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LOW-IMPACT SPACE WEATHER SENSORS AND THE U.S. NATIONAL SECURITY SPACECRAFT

by

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LOW-IMPACT SPACE WEATHER SENSORS AND THE U.S. NATIONAL SECURITY SPACECRAFT

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ADC	analog-to-digital converter
ADCS	Attitude Determination and Control Subsystem
AER	Atmospheric and Environmental Research, Inc.
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AI&T	assembly, integration, and test
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
APL	Applied Physics Laboratory
AU	astronomical unit
C&DH	command and data handling
CDR	critical design review
CIA	Central Intelligence Agency
CME	coronal mass ejection
CMG	control moment gyros
COT	commercial-of-the-shelf
CPA	charge plate assembly
CPU	central processing unit based
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DOD	Department of Defense
DSP	Defense Support Program
ECSS	European Cooperation for Space Standardization
EMI	electromagnetic interference
EPS	electrical power system
ESD	electrostatic discharge
FFRDC	federally funded research and development centers
GEO	geosynchronous orbit
GPS	Global Positioning System
GUI	Graphical User Interface

HEO	high earth orbit; highly elliptical orbit
HUMINT	Human Intelligence
HWCI	hardware configuration items
IC	intelligence community
ICBM	intercontinental ballistic missile
ICD	initial capabilities document
IMU	inertial measurement units
ISS	International Space Station
JCIDS	joint capabilities integration and development system
JROC	Joint Requirements Oversight Council
LANL	Los Alamos National Laboratory LEO low earth orbit
LRV	last recorded value
MEO	mid-earth orbit
MIT-LL	MIT Lincoln Laboratory
MMOD	micrometeoroid/orbital debris
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOPS	National Reconnaissance Office Operations Squadron
NPT	navigation, pointing, and timing
NRO	National Reconnaissance Office
NSF	National Science Foundation
NTM	National Technical Means
OAM	orbit adjust maneuvers
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
PDR	preliminary design review
PNT	positioning navigation and timing
QZSS	Quasi-Zenith Satellite System
R_E	earth radii
RF	radio-frequencies
RWA	reaction wheel assemblies
SAA	South Atlantic Anomaly

SBIRS	Space Based Infrared System
SOC	satellite operations center
SOPS	Space Operation Squadron
SPO	system program office
SV	space vehicle
SWAP	size, weight and power
SWPC	Space Weather Prediction Center
TDRS	Tracking and Data Relay System
TID	total ionizing dose
TT&C	telemetry, tracking and command
USSR	Union of Soviet Socialist Republics

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EXECUTIVE SUMMARY

The objective of this thesis is to explore the potential benefits of equipping U.S. national security spacecraft with low-impact and inexpensive targeted space environment sensors, review the systems engineering and acquisition challenges that exist in executing this proposal, and provide recommendations for overcoming these challenges to meet the needs of national security space.

In the earliest days of space exploration, the Soviet's Sputnik 2 and the United States' Explorer 1 observed the earth's magnetic field and its trapped charged particles, now known as the Van Allen radiation belts. As the number of spacecraft on orbit increased, so did the United States' understanding of space weather and its effects on technology. Today, it is understood that "energetic particles and plasma in the space environment can be hazardous to space systems, causing system outages, shortening mission lifetimes, reducing functional capabilities, and potentially masking hostile actions" (O'Brien et al. 2008, 8). Despite these known threats, "the ability to observe, predict, and warn of impending solar activity is in its childhood" (Poppe and Jorden 2006, 1).

The United States is limited in its ability to understand current environmental conditions in space and forecast space weather and its effects partly due to the relatively small number of environment sensors currently on orbit. Two classes of sensors are employed to track the near-earth space environment:

> (1) Targeted sensors capable of measuring the environment and effects at a level sufficient for providing situational awareness for the host spacecraft; and (2) Comprehensive sensors capable of providing detailed environment measurements that can be mapped to a broad region of near-Earth space, providing global situational awareness and quantitative characterization of the environment. (O'Brien et al. 2008, iii)

Additionally, due to the lack of space weather situational awareness, determining if environmental factors contributed to an on-orbit spacecraft anomaly is "time-consuming, inaccurate, and of a low confidence level" (O'Brien et al. 2008, 7). Finally, U.S. national security is increasingly dependent on the capabilities of space systems.

Space is now a recognized domain of warfare (White House 2010, 22). In this increasingly contested environment, “real-time, spatially accurate space environment data from a targeted sensor is critical to determining whether a specific anomaly event might be the result of hostile activity rather than natural phenomena” (O’Brien et al. 2008, 7).

National security space system development, deployment, and operations would benefit greatly from improved space environment situational awareness; however, at this time, a comprehensive strategy to improve U.S. capabilities has not been approved. Sensor technology is at a readiness level that accommodates multiple targeted sensors incorporated onto the spacecraft structure with minimal impact to the host. Currently, monitoring the environment around individual spacecraft is rarely a requirement. Without a requirement, program managers are not able to invest in this capability despite the known benefits.

To overcome these challenges, a low- to no-cost schedule impact integration plan is recommended. This strategy will allow the spacecraft operators to benefit immediately from the data provided by targeted spacecraft sensors. Over time, it will improve the general understanding of the space radiation and plasma environments over all orbital regimes where national security spacecraft operate. This comprehensive amalgamation of targeted spacecraft sensors will improve space weather models that influence both space weather forecasting and spacecraft design. These immediate and comprehensive improvements to the understanding of the space environment will allow space operators to respond proactively to space weather threats, differentiate between space weather and adversarial impacts, and allow spacecraft designers to engineer spacecraft with more accurate margins to survive space weather effects. These benefits ultimately improve spacecraft operational availability and space weather monitoring resiliency, and will help drive down spacecraft cost.

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I. INTRODUCTION

The U.S. space program matured from a need to understand the unknown. The desire to expand this nation's reach outside the earth's atmosphere was not only inspired by the desire to explore unknown new worlds or gain familiarity with the little understood natural environment outside Earth's atmosphere, but also was driven more from the fear of the unknown residing on the other side of the planet. The former Union of Soviet Socialist Republics (USSR) had detonated their first atomic weapon in 1949 and launched their first satellite in 1957. If the Soviets had the ability to launch a radio transmitter into orbit over the United States, then they could potentially launch a nuclear weapon on a ballistic trajectory to U.S. military targets and population centers, as well as this country's allies. Instantly, the vast oceans on either side of North America that had provided some level of isolation and security for almost the last two centuries became significantly less protective.

Japan's surprise attack on Pearl Harbor was still fresh in the minds of U.S. political and military leadership during the early years of the Cold War. The United States was confronted with the conditions for yet another surprise attack, this time coming from high above the outer edges of Earth's atmosphere and over the North Pole instead of across the Pacific. The Soviet's launch of Sputnik displayed advanced aerospace technology superior to the American's, and U.S. national security was perceived to be critically at risk. Even more problematic, the United States did not know just how far advanced the Soviet technology was over its own technology. Human intelligence (HUMINT) had its limitations and overflight of denied Soviet territory to gain insight into current activities could possibly result in shooting down an American pilot, at best, and at worst, provoke war. The United States needed to kick-start its aerospace development programs to contest and counter the Soviet Union's capabilities and gain intelligence on Soviet advancements in development.

The U.S. Air Force, led by General Curtis E. Lemay, was focused on building more and more strategic bomber aircraft to penetrate Soviet borders as a method of deployment for nuclear weapons instead of investing in rocket technology and developing intercontinental ballistic missiles (ICBM). The Air Force was also not yet interested in overhead reconnaissance. The Central Intelligence Agency (CIA), intent on gaining insight into Soviet military posture and aerospace advances, developed the U-2 Dragon Lady with Lockheed's Skunk Works to overfly Soviet territory and gain key intelligence. After early program success, both the Navy and the Air Force embraced overhead reconnaissance as a means to gain intelligence, and with timely and accurate information, they hoped to prevent the war that seemed inevitable. Unfortunately, Soviet advances in anti-aircraft missiles allowed for the embarrassing shoot down of Francis Gary Powers in a U-2 aircraft over the USSR. Soviet advanced missiles limited the capabilities of both strategic bombers and high-flying reconnaissance aircraft. Even the CIA's supersonic and stealthy A-12 Oxcart and the Air Force's SR-71 were vulnerable by the time they became operational. The Sputnik crisis in 1957 followed by the "U-2 Incident" in 1960 only intensified the pervasive fear of impending nuclear war. The edges of the Earth's atmosphere were vulnerable and the Soviets had the advantage in space; the United States needed to invest in the ultimate high ground.

The president of the United States and Congress prioritized U.S. space capabilities by establishing and heavily investing in both civil and military organizations whose mission was to push the limits of aerospace technology. Despite trailing Soviet capabilities in early years and having to overcome the continuous challenges inherent to advanced aerospace activities, the United States' private and government space industries are flourishing today. U.S. national security is no longer dependent on beating the Soviets in space; however, assured access and a continuous operational presence in space remains pervasively critical to U.S. national security and an average citizen's current way of life:

> Satellites contribute to increased transparency and stability among nations…The utilization of space has created new markets; helped save lives by warning us of natural disasters, expediting search and rescue operations, and making recovery efforts faster and more effective; made agriculture and natural resource management more efficient and sustainable; expanded our frontiers; and provided global access to advance medicine, weather forecasting, geospatial information, financial operations, broadband and other communications, and scores of other activities worldwide. (White House 2010b)

The national security interests of the United States, military, political, and economic, are all increasingly reliant on the capabilities space systems provide. As a result, “no other state spends as much on its space activity (75 percent of global space funding is by the United States), or has a greater stake in a safe and secure space (43 percent of all active satellites are U.S. owned)” (Zenko 2014, 6).

A consequence of U.S. dependence on space-based capabilities is the emergence of a constant threat to U.S. national security, the space environment. Today, it is understood that “energetic particles and plasma in the space environment can be hazardous to space systems, causing system outages, shortening mission lifetimes, reducing functional capabilities, and potentially masking hostile actions” (O’Brien et al. 2008, 1). Despite these known threats, “the ability to observe, predict, and warn of impending solar activity is in its childhood” (Poppe and Jorden 2006, 1).

Partly due to the relatively small number of environment sensors currently on-orbit, the United States is limited in its ability to understand current environmental conditions in space and forecast space weather and its effects. Two classes of sensors are employed to track the near-earth space environment:

> (1) ***Targeted*** sensors capable of measuring the environment and effects at a level sufficient for providing situational awareness for the host spacecraft; and (2) ***Comprehensive*** sensors capable of providing detailed environment measurements that can be mapped to a broad region of near-Earth space, providing global situational awareness and quantitative characterization of the environment. (O’Brien et al. 2008, iii; emphasis added)

Additionally, due to the lack of space weather situational awareness, determining if environmental factors contributed to an on-orbit spacecraft anomaly is “time-consuming, inaccurate, and of a low confidence level” (O’Brien et al. 2008, 7). Finally, U.S. national security is increasingly dependent on the capabilities of space systems, and space is now a recognized domain of warfare (White House 2010a, 22). In this increasingly contested environment, “real-time, spatially accurate space environment data from a targeted sensor is critical to determining whether a specific anomaly event might be the result of hostile activity rather than natural phenomena” (O’Brien et al. 2008, 7).

National security space system development, deployment, and operations would benefit greatly from improved space environment situational awareness; however, at this time, a comprehensive strategy to improve U.S. capabilities has not been approved. Sensor technology is at a readiness level that accommodates multiple targeted sensors incorporated onto the spacecraft structure with minimal impact to the host. Currently, monitoring the environment around individual spacecraft is rarely a requirement. Without a requirement, program managers are not able to invest in this capability despite the known benefits.

Increasing space environment situational awareness does require an investment. Traditionally, investment in emerging space capabilities is prioritized to those deemed critical to national security. Astronomer and astrophysicist Carl Sagan was acutely aware of this paradigm:

> The lesson to me seems clear: there may be no way to send humans to Mars [or back to the Moon] in the comparatively near future, despite the fact that it is entirely within our technological capability. Governments do not spend vast sums just for science, or merely to explore. They need another purpose, and it must make real political sense. (Sadeh 2002)

Significant scientific value can be gained in increased space situational awareness; however, pure scientific interests not directly supporting military, economic, or political security are not considered during this study. This paper focuses on the operational benefits critical to national security space systems realized from increased space weather situational awareness.

A. PROBLEM STATEMENT AND OBJECTIVE

The U.S. national security is increasingly dependent on the capabilities of space systems. Space weather poses a threat to national security space systems. The United States is limited in its ability to counter space weather and its effects. National security space system development, deployment, and operations would benefit greatly from targeted and local space environment situational awareness around each spacecraft. Equipping spacecraft with low-impact and inexpensive space weather sensors may help solve this problem.

This paper first assesses the current space environmental situational awareness capability. Then, it addresses the operational benefits realized from increased space weather situational awareness. Finally, it examines and addresses the dimensions of an acquisitions strategy, both programmatic and technical, to equip U.S. national security spacecraft with low-impact and inexpensive space weather sensors.

B. RESEARCH QUESTIONS

This research is divided into primary and secondary research questions that are addressed throughout each chapter and summarized in the conclusion. The intent of the primary questions is to provide decision makers the information required to decide if investing in targeted space weather sensors on all national security space satellites is worth their consideration and investment. While answering the secondary questions, this research will provide the decision makers with a foundational understanding of the environmental conditions that affect U.S. spacecraft, what technology exists today that supports the U.S. national security interests, and a response to how the proposed architecture of proliferated low-impact sensors will advance operations for each spacecraft with integrated sensors and the entire national security space enterprise.

1. Primary Research Questions

- What are the expected benefits of increased space weather situational awareness local to the space vehicle?
- If the national space community desires those benefits, what are the dimensions of an acquisitions strategy, both programmatic and technical, that must be addressed?

2. Secondary Research Questions

- What is space weather and how does it affect space systems?
- What are the current operational space weather monitoring capabilities?
- What technology exists today or in the near future that could provide real-time local space environment data for individual space vehicles?
- How can localized sensors contribute to a comprehensive understanding of space weather conditions and forecasting?

C. BENEFIT OF STUDY

This thesis would benefit the national security space enterprise by defining the benefits of localized space vehicle environment situational awareness and laying the groundwork for an approach to achieve those benefits. The study examines how low-cost, low-impact targeted sensors when combined with data from comprehensive sensors and space weather models can significantly increase near earth space environment situational awareness.

The recommendations of this study could also improve operational responsiveness to satellite anomalies from space weather effects and adversarial attacks. Organizations that could benefit from this study include the Department of Defense (DOD), national space programs, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the larger government and commercial space community.

D. SUMMARY OF CHAPTERS

To serve as a foundation for understanding national security space assets, space weather, and their interaction, this thesis starts with an overview of the types of satellites the United States currently deploys for this nation’s national security. The next chapter is a brief overview of the satellite subsystems that can be affected by space weather. The following chapter then introduces space environmental physics and the space weather architecture that exists today. This thesis then introduces inexpensive low-impact space environment sensors that may be integrated into all of today’s national security spacecraft and discusses the benefits provided. This integration is not without challenges; this paper recommends strategies for overcoming the technical and acquisition challenges of integrating low-impact space environment sensors on all national security spacecraft.

II. U.S. NATIONAL SECURITY SPACECRAFT—THE HIGH GROUND

To serve as a foundation for understanding the benefits and challenges of incorporating low-impact targeted space weather sensors on all national security satellites, this chapter provides a brief overview of the type of spacecraft critical to U.S. national security and their subsystems that can be affected by space weather effects.

A. TYPES OF SPACECRAFT

The spacecraft described as follows are currently deployed by the U.S. national security space enterprise. Each type of vehicle operates in different orbital regimes and is affected by the space weather environment differently relative to their orbits. These vehicles are introduced to help the reader understand, at a general level, what vehicles are in operations, where they operate, and the next chapter introduces how their environment affects them.

1. Launch Vehicles

Satellites require a "velocity of at least 18,000 miles per hour to stay in orbit" (Nelson and Lenehan 1993, 18). This velocity requires a significant amount of energy to propel spacecraft out of the earth's atmosphere and into a usable orbit. For context, a successful launch requires about "400 pounds of rocket propellant to put 10 pounds of spacecraft into [Low Earth Orbit] LEO" and "1600 pounds of rocket propellant to put 10 pounds of spacecraft into [Geosynchronous Orbit] GEO" (18). For a typical launch vehicle, the "rocket's weight is 90% propellant, 10% structure and electronics" (18). Many innovative systems have been proposed to place satellites into orbit more efficiently, including space elevators that run along carbon fiber nanotubes and electrical powered magnetic rail guns; however, rocket powered launch vehicles continue to be the only assured vehicles for accessing space.

2. Communications

National security communications satellites provide data links to locations across the globe that are impossible or inconvenient to reach by terrestrial systems. Wireless communications can be obscured when line of sight between the transmitter and receiver is blocked by terrain, such as mountains and natural or urban canyons, or even by the curvature of the earth. Terrestrial wired communication is impractical over great distances over the oceans or poles, and may be impossible in denied territory. Communications satellites can loiter with coverage of most of the earth for a significant amount of time. Most communications satellites are in a geosynchronous (GEO) and geostationary orbit, about 22,300 miles above the earth's equator, where they maintain a consistent position over the same region of earth. Four or five communication satellites dispersed in GEO orbit can provide coverage of almost the entire planet. The polar regions are not well covered by GEO satellites. Communications satellites in a highly elliptical orbit (HEO) have long dwell times over the poles and can fill this gap.

In addition to providing direct communications to denied regions on earth, communications satellites also provide a link between other spacecraft and the earth, especially those flying in low earth orbit (LEO). For spacecraft like the International Space Station (ISS) that travel at high rates of speed less than a few hundred miles from the surface, it is often inefficient to transmit communications through direct downlink to ground antennae. A constellation of communications satellites in GEO or HEO orbits are almost always visible from the LEO vehicle and data from that vehicle passed through the relay down to a corresponding ground station can provide consistent communications. This relayed communications link is often referred to as a "bent pipe." Spacecraft are expensive but constructing, maintaining, and staffing a large number of ground stations to support constant contact with LEO vehicles is cost prohibitive. One communications relay on orbit can support many different types of other satellites.

3. Positioning Navigation and Timing

Perhaps, the most familiar positioning navigation and timing (PNT) satellite system currently on orbit is the United States' Global Positioning System (GPS). This system is used worldwide by a very diverse set of users. Other space fairing nations are developing competing and complimentary systems, including the European Union (Galileo), Russia (GLONASS), China, India, and Japan. These satellites utilize a synchronized onboard atomic clock to keep time and transmit their signals back toward earth. A user with four satellites in view and a compatible receiver can know their coordinate position through triangulation, and then know their exact location in time and space.

This capability is critical to national defense. The DOD uses GPS for naval navigation, coordination of troop movements, assistance with friend vs. foe determination, and targeting munitions deployment. The DOD, which develops, deploys, and maintains the GPS constellation, sustains an additional encrypted message format for precise PNT on the GPS constellation. The unencrypted format, however, is still very critical to national security as the world’s financial system is reliant on GPS for precise timing worldwide.

4. Remote Sensing

Remote-sensing satellites are comprised of a wide range of vehicles with a wide range of payloads. NASA, NOAA, the DOD and the National Reconnaissance Office (NRO) all fly satellites critical to U.S. national security. NOAA and DOD weather satellites help military mission planners determine the best location and time to engage the enemy. NRO’s surveillance, reconnaissance, and intelligence spacecraft provide overhead intelligence products of denied territories. The DOD’s Space Based Infrared System (SBIRS) provides constant surveillance of missile launch activity across the globe while providing missile warning, missile defense, technical intelligence, and battlespace awareness (Chaplain 2014).

The NRO flies a constellation of satellites often referred to the nations “eyes and ears” in space. These remote-sensing satellites, such as the declassified HEXAGON system seen in Figure 1, are critical to gaining intelligence in denied areas across the globe.

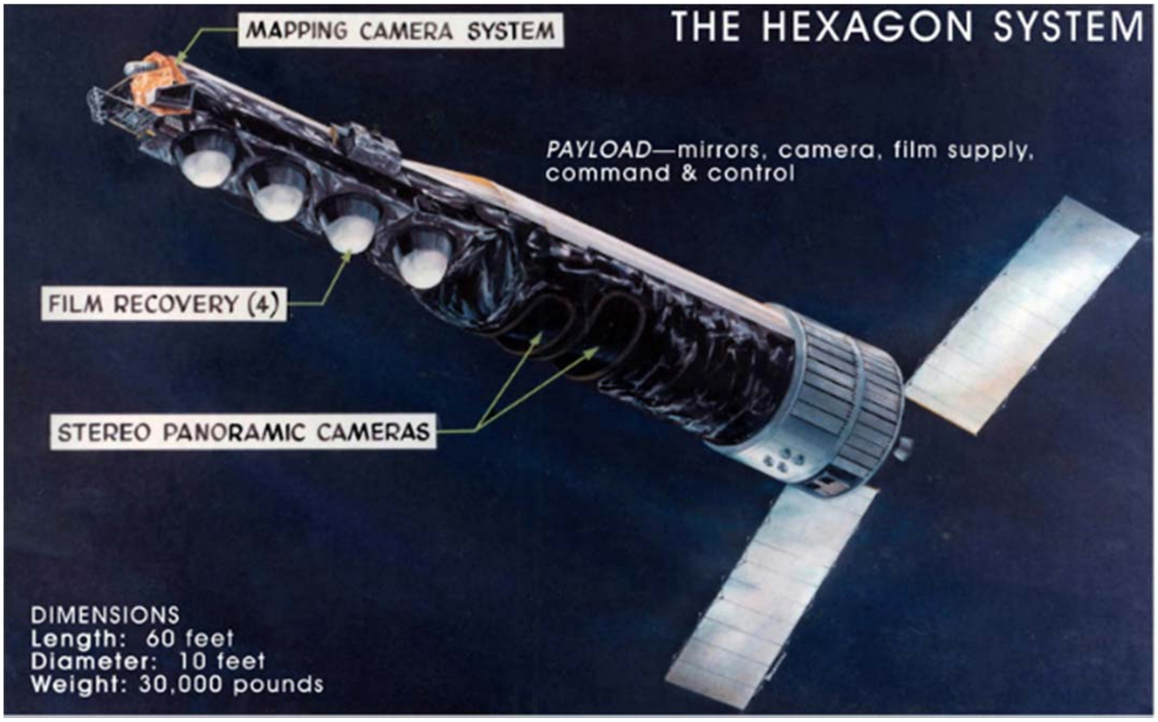

Figure 1. NRO Hexagon System. Source: Center for the Study of National Reconnaissance (2011).

B. SATELLITES: SYSTEM OF SYSTEMS

Space systems are true systems of systems comprised of not only the vehicle on orbit but also a significant amount of ground components, both hardware and software, that support the vehicle.

1. Space Vehicle Segment

The space vehicle can be decomposed functionally into lower level functional components in a few common ways. For the purposes of this summary, the space vehicle subsystems, represented in Figure 2, are decomposed by function into components consistent with "The New SMAD" (Wertz, Everett, and Puschell 2011, 397).

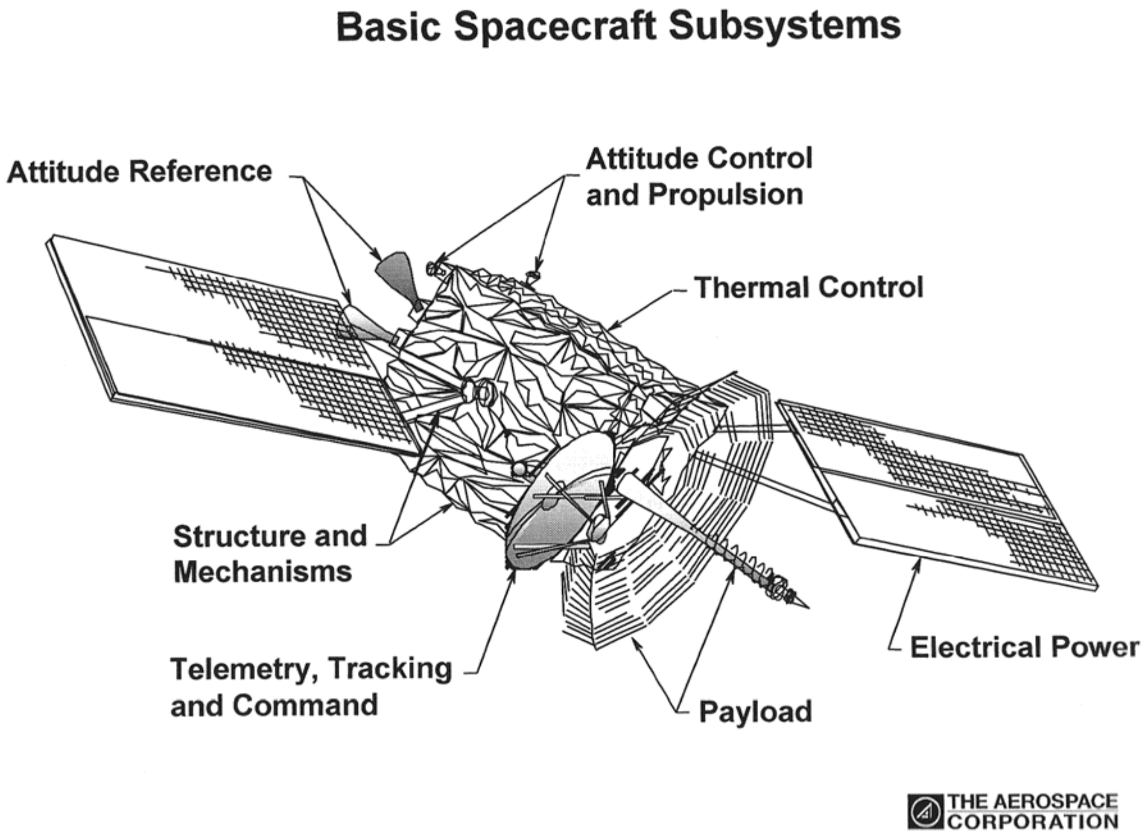

Figure 2. Basic Spacecraft Subsystems.
Source: Nelson and Lenehan (1993, 26).

a. Payload

Payloads are the primary reason the space vehicle is put into orbit. These payloads can vary significantly from communications relays to remote sensing payloads. The payload and its intended mission often drive the majority of requirements throughout the rest of the system. These requirements may determine the orbit of the space vehicle, the power required to operate the system, and the pointing accuracy the vehicle must maintain to achieve the mission.

b. Attitude Determination and Control Subsystem

A space vehicle needs to be able to control its orientation in space. First, one requirement may be pointing the payload at a specific reference point. Additionally, the communications payload may need to point back to a ground station or a relay satellite, such as the Tracking and Data Relay System (TDRS), to receive commands from mission operators or transmit data back for processing. The space vehicle, unless it has a thermonuclear power supply (usually reserved for deep space missions), also needs to orient its solar arrays toward the sun, none of which can be accomplished without the ability to control the vehicle's three-dimensional orientation. Attitude Determination and Control Subsystem (ADCS) systems "include the sensors, actuators, avionics, algorithms, software, and ground support equipment used to determine and control the attitude of a vehicle" (Wertz, Everett, and Puschell 2011, 565).

The vehicle recognizes its attitude in reference to known objects, which is accomplished with sensors designed to recognize the earth and the sun, as well as the catalog of visible stars. After the spacecraft separates from the launch vehicle, or possibly after the satellite experiences an anomaly, the spacecraft must acquire these reference points to establish attitude control. Star trackers are a commonly integrated subsystem that employs optical sensors and flight software that compares what these sensors see to "a star sensor based stellar inertial reference system" (The Aerospace Corporation 2005, 491), a catalog of known stars, and reorient into a safe configuration where the space vehicle is power and thermal stable.

In addition to these optical sensors, a variant of inertial measurement units (IMU) monitors the vehicle's attitude continuously. The units use accelerometers and gyroscopes to track the vehicle's movements. When the space vehicle knows its location, and tracks any changes with the IMU, then it can determine its current attitude in relation to its previous known attitude.

A passive means to maintaining attitude while on orbit is to set the vehicle into a spin about a single axis. Like a spinning bicycle tire, the space vehicle remains stable while spinning about this axis; however, the agility of the vehicle to slew and point in different directions is limited. In this case, the spacecraft mission must allow for a fixed payload or the payload must have the ability to point itself. Control moment gyros (CMG) or reaction wheel assemblies (RWA) are a more modern approach for attitude control.

CMGs and RWAs both use spinning rotors to control the vehicle's attitude. CMGs consist of a wheel and one or more gimbals that manipulate the consistently spinning wheel, and as a result, its angular momentum generates a torque to maneuver the vehicle. RWAs actually manipulate the wheel's speed to generate a torque. Most applications use multiple wheels; at least three are needed to provide three-axis stabilization, and more may be incorporated for redundancy. Over time, these CMGs and RWAs can build up a significant amount of momentum that needs to be "dumped" from the system to operate safely and efficiently. The ADCS system can use magnetic torque rods that use an electrical current that creates a magnetic dipole along their length that counters the Earth's magnetic field to remove momentum from the system. This method is preferred over using the propulsion subsystem to remove momentum since fuel is in limited supply and electricity is renewable. These attitude reference subsystems work in combination with the attitude control and propulsion system to orient the vehicle as commanded.

c. Propulsion

The propulsion system and ADCNS work together to maintain attitude control. Typically, thrusters use onboard stored fuel to position and orient the vehicle. Propulsion systems contain an energy source and a means to produce thrust. They are used for spacecraft orbit adjustments, station keeping maneuvers, collision avoidance, attitude control, and removing momentum from onboard attitude control systems like control moment gyros, reaction wheels, and magnetic torque rods. The propulsion subsystem includes the fuel used to supply energy, the tanks that store that fuel, the plumbing and regulatory mechanisms that manipulate the fuel, and the thrusters that expel the energy providing thrust. Multiple sources of energy can be used for propellant, including solid and liquid fueled thrusters to electronic ion engines.

d. Command and Data Handling

Command and data handling (C&DH) is the system responsible for on board processing, the storing and sending of payload data, and telemetry through the communications system to the ground segment. This subsystem contains the spacecraft computers and flight software responsible for managing all the other subsystems.

e. Telemetry, Tracking, and Command

The communications payload and telemetry, tracking, and command (TT&C) subsystems are the "lifeline of the space vehicle" (The Aerospace Corporation 2005, 541). They are the data link between the ground operators and the vehicle. Radio frequencies (RF) are transmitted in the form of commands to the vehicle (uplink), and the vehicle responds with vehicle telemetry and mission data through RF back to the ground site (downlink). The system may include wideband and narrowband receivers, and transmitters, power amplifiers, RF modulators, and the antenna. It does not matter how well the payload performs if the vehicle cannot communicate that data back to the ground.

f. Electrical Power System

The electrical power system (EPS) system is the subsystem that "provides, stores, regulates, and distributes electrical power to payloads/instruments, and other flight subsystems (i.e., thermal, communication, guidance, and navigation)" (Wertz, Everett, and Puschell 2011, 641). The space vehicles typically use a combination of photovoltaic solar arrays and batteries to generate and maintain electrical power requirements for the system. For maximum efficiency, the space vehicle may adjust its attitude toward the sun to increase access to direct sunlight or have moveable arrays that can maneuver toward the sun independent of where the vehicle is pointing. The solar arrays can provide a direct energy supply to the electrical distribution unit for immediate consumption by other subsystems; however, batteries are typically used for power stability and continued electrical power while the spacecraft is in an eclipse of the Sun. Design considerations need to be made for spacecraft with an orbit that transfers through the Earth's shadow. Enough power budget must exist to transfer through this eclipse and continue its mission while the batteries have an opportunity to recharge while in view of the Sun. Battery technology has changed over the last several decades, and the space industry is currently moving toward space-rated lithium ion cells to store energy. A series of electronics then regulates and controls the power output from the batteries and distributes power to the other spacecraft subsystems.

Nuclear power has been used in space but is usually reserved for interplanetary or interstellar missions, as these systems cannot utilize the Sun's energy efficiently do to their ever-increasing distance from the Sun, or they have long duration missions that will not re-enter the Earth's atmosphere, such as a Mar's lander.

g. Structure, Mechanisms, and Thermal Control

The spacecraft structure consists of the bus frame, brackets, and fasteners. Weight is an important design consideration; honeycomb composites and lightweight aluminum structural components are typically used to keep weight to a minimum. This structure must support the payload and all other subsystems during the space vehicle's design life. The most stressing environment for space vehicle structures is the launch environment. During launch, the vehicle "load cases are typically provided as combination of axial and lateral loading" (Wertz, Everett, and Puschell 2011, 670) where the most violent load factors are observed during launch and maximum dynamic pressure (referred to as Max Q) when the launch vehicle and space vehicle experience the harshest coupled loads environment upon ascent.

Mechanisms include those moveable elements of the structure that support the spacecraft functions that include solar arrays, deployable antennas, and booms, radiators, motors, and actuators. These mechanisms have a "relatively high incidence on orbit failure" (Wertz, Everett, and Puschell 2011, 680) and are designed to be as simple as possible to reduce the risk of failure.

All subsystems have requirements for acceptable temperature ranges to function properly. The thermal control subsystem manages these temperatures. Several active and passive mechanisms are used to maintain these temperature ranges. Protective coatings and insulation are used, as well as heat pipes that transfer heat from hot electronics to cold areas of the space vehicle in addition to radiators that dispense waste heat into space; all help manage the thermal environment. Active electric heaters are used throughout the spacecraft to warm mechanisms for deployments and regulate the temperature of electronics. Also, “various military, commercial, and scientific projects require cooling of infrared sensors and spectrometers, optical elements, low-noise amplifiers, superconducting devices, and other instruments over a range of temperatures from below 10 K to more than 150 K” (Donabedian 2003, 121).

2. Ground Segment

Unlike the Hubble Space Telescope, or the ISS and other previously manned orbital space stations that were both designed from the beginning to be serviced and resupplied while on orbit, most satellites on orbit will not have an opportunity to be repaired, serviced for extended life, or upgraded to improve future mission capabilities. The limited ability to perform maintenance on the space vehicle while on orbit requires the system be reliable without hands-on intervention, often for many years. For this reason, it is prudent to design the vehicle with no more complexity than absolutely necessary. Design trades are made early in a satellite system’s development to assess the complexity, reliability, and associated risks between the space and ground segments.

The “European Cooperation for Space Standardization (ECSS) [defines the ground segment] as composed of ground operations organizations, with the personnel involved in the mission, and ground systems, that group together all ground infrastructure required to support the mission from its preparatory stage to completion” (Fortescue, Swinerd, and Stark 2011). All ground segments provide for TT&C operations while on orbit, as well as support test, launch, and initialization activities of the satellite. The complexity trades done during satellite design, however, result in a diverse range of complexity in satellite ground segments. Ground segments may be single stations with a small footprint and no operators on console maintaining the mission, health, and safety of the vehicle. This approach is often referred to as “lights out” ops; in other words, no reason exists to leave the lights on since operators will not be on site. Another ground segment approach, typically used for more complex or critical satellites, is to have multiple connected ground stations providing additional capabilities and a more resilient architecture.

This architecture and implementation is common for most national security space systems. The Air Force currently maintains a primary consolidated satellite operation center (SOC) at Schriever Air Force Base outside Colorado Springs, Colorado, as well as backup SOC facilities and a series of ground stations with antennas around the world to communicate with a variety of military satellites in multiple orbits known as the Air Force satellite control network. Figure 3 is an aerial photograph of the Defense Support Program's (DSP) ground station located at Buckley Air Force Base, an Air Force Space Command (AFSPC) base located just east of Denver in Aurora, Colorado. The DSP constellation provides overhead persistent infrared coverage in support of an early missile warning. The large white radomes seen supporting the DSP constellation, sometimes referred to as "golf balls," cover antenna used to communicate with satellites providing both protection from the weather, as well as concealing their pointing direction. The large building contains the SOC where operators are in contact with the space vehicles and on constant watch for threats across the globe.

Figure 3. Defense Support Program Control Site. Source: Sellers (2004).

A simplified ground segment is comprised of two components. One component on the "front end" commands the vehicle and one component on the "back end" receives information from the satellite.

a. Mission Management and Command and Control Element

The front end of the system is the Mission Management and Command and Control System element. This element "flies" the satellite. This element generally encompasses a scheduling component to plan and deconflict future activities of the satellite or a constellation of satellites, as well as an element that contains executable scripts, libraries, databases, and space vehicle constraints specific to each spacecraft. The scheduler accesses these vehicle unique features to deconflict and plan the activities for the command and control element to execute.

b. Processing Element

The back end of the ground segment is the processing element. This element receives space vehicle telemetry, ephemeris, and mission data. A combination of hardware and software receives, demodulates, and formats the downlinked data, then in the case of many national security space assets, the downlink data may be encrypted and need to be decrypted. Mission operators use vehicle telemetry and ephemeris to ensure nominal health and the safety of the vehicle. Mission data from the payload may be processed onsite or sent to an offsite location for final processing. Depending on the size of mission data being processed, a simple central processing unit based (CPU) computer can handle the volume; however, it may require significantly larger "monolithic" sized computer systems. In addition, a significant amount of vehicle or mission specific processing code and algorithm chains must be computed before the data is transformed into its final product.

C. CHAPTER SUMMARY

This chapter introduced at a high level the types of spacecraft employed by U.S. national security and their supporting subsystems, in space, and on the ground, that are susceptible to space weather effects. Both space and ground segments are susceptible to interference and damage from space weather. The ground systems are generally well protected by the Earth’s magnetic field and atmosphere. National security spacecraft, however, are expected to execute their mission consistently through the harsh space environment. The next chapter discusses that environment.

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III. SPACE WEATHER AND ITS IMPACTS TO SPACECRAFT

To understand the effects and impacts to space vehicles from space weather, it is important to understand the physical relationship between these spacecraft and the near Earth space environment. The Sun’s energy interacting with the Earth’s magnetic field and atmosphere dominate this environment. This discussion supports the recommendation for integrating low-impact space weather sensors on national security satellites.

A. THE SPACE ENVIRONMENT

The space environment has routinely been characterized as harsh and unforgiving. In addition to space weather, vehicles unprotected by the Earth’s atmosphere must contend with micrometeoroids and man-made debris, the effects of operating in a vacuum, and the ever-present effects of gravity. Space weather is primarily influenced by the relationship between the Sun’s activity and the Earth’s magnetic field (Figure 4). It is worth briefly discussing the interaction between the Sun and the geomagnetic field, as well as galactic cosmic rays and their impact on the environment in which U.S. national space satellites operate.

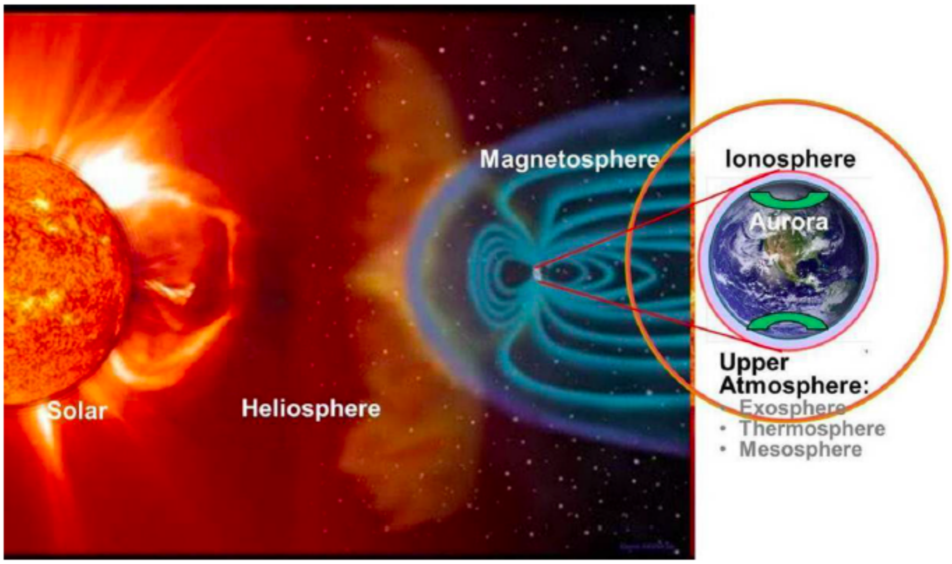


Figure 4. Space Weather Domains. Source: White House Office of Science and Technology Policy (2013).

1. The Sun

The Earth’s closest star, the Sun, is the origin of the most dynamic space weather. At its core, this great ball of gas produces significant energy through nuclear fusion that converts hydrogen to helium, the two majority elements of the Sun. The Sun is moderately sized relative to the billions of other stars in the universe, but it is still massive, 1.99 x 1030 kg, and dense, 1.4 x 103 kg/m3. At the edge of the Sun, highly energized plasma radiates in all directions. This “solar wind is similar to the composition of the Sun’s upper atmosphere (~90% protons, ~10% He++)” (Olsen 2005, 72) and travels at speeds of up to “~700 kilometers per second” (72).

The surface of the Sun’s gaseous equator spins at a faster rate than the poles. This differential rotation causes the Sun’s magnetic field to warp and twist, causing disturbances at the Sun’s surface that result in prominences, which are “extrusions of ‘cold’ chromospheric gas into the corona from active regions of enhanced magnetic field strength” (Olsen 2005, 57). The twisted magnetic field also leads to the highly energetic “hot” solar flares often from areas of activity called sunspots (Figure 5). Less frequently, a coronal mass ejection (CME) can manifest and eject coronal material at speeds exceeding 1,000 km/s.

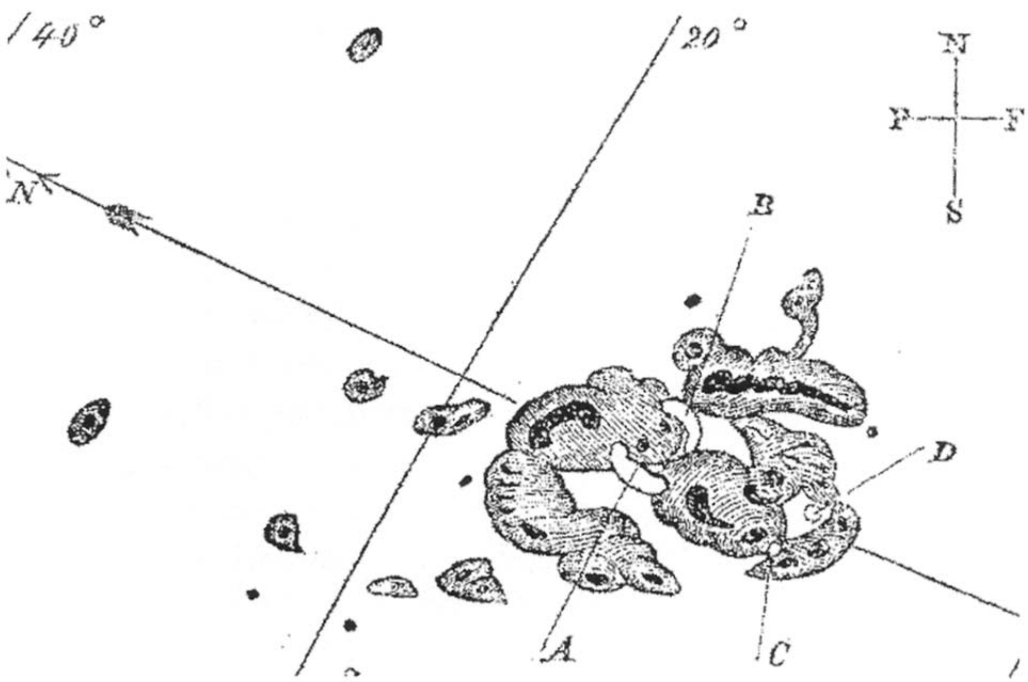


Figure 5. Sunspots as Sketched by Richard Carrington of Sunspots on September 1, 1859. Source: Carlowicz and Lopez (2002, 54).

2. Heliosphere

The solar wind creates a barrier, or bubble, between our solar system and the interstellar matter that exists between our Sun and the other stars, with their own heliosphere. The distance between the earth and the Sun is just a fraction of the extent of the heliosphere. One astronomical unit (AU) represents the distance between the Sun and the Earth, about 150 million km. Voyager 1 was launched in 1977 to study the deep space environment and crossed the heliopause in 2012. The heliopause is the edge of the heliosphere, a distance of about 120 AU or “18 billion kilometers” (White House Office of Science and Technology Policy 2013, 9) from the Sun. National security space satellites do not operate at these great distances; however, its interaction with the Earth’s magnetosphere is the source of dynamic near Earth space weather. “It takes approximately eight minutes for solar photons traveling at the speed of light to reach Earth, whereas it can take up to several days for the solar wind and intermittent solar gases emitted from the Sun in the form of CMEs to cover the same distance” (10).

3. Magnetosphere

This “region of space surrounding the earth in which the geomagnetic field plays a dominant role” is the magnetosphere (Olsen 2005, 109). The interaction between the solar wind and the Earth’s magnetic field is the primary cause of space weather (Figure 6). Significant amounts of energy are transferred into the near earth environment. The robust and inconsistent fluctuations in the speed of the radiative output from the Sun cause great distortions in the magnetosphere, and with it, inconsistencies and variations in the radiation and charged environment. Often associated with CME impacts with the Earth, “geomagnetic storms occur when energy transferred from the solar wind is deposited in the magnetotail, sometimes building up to the point whereby a fraction of the energy is dumped into the near-Earth space environment in the form of a magnetic substorm” (White House Office of Science and Technology Policy 2013, 10).

Explorer I, the first U.S. satellite, was equipped with sensors that discovered the geomagnetic field and the trapped ionized high-energy particles of the Van Allen radiation belts named for the experiment’s lead physicist. Radiation energy varies in this region from ~1,000 to 60,000 kilometers but some particles can reach relativistic speeds. These particles “have velocities near the speed of light and carry tremendous amounts of kinetic energy” (Moldwin 2008, 53).

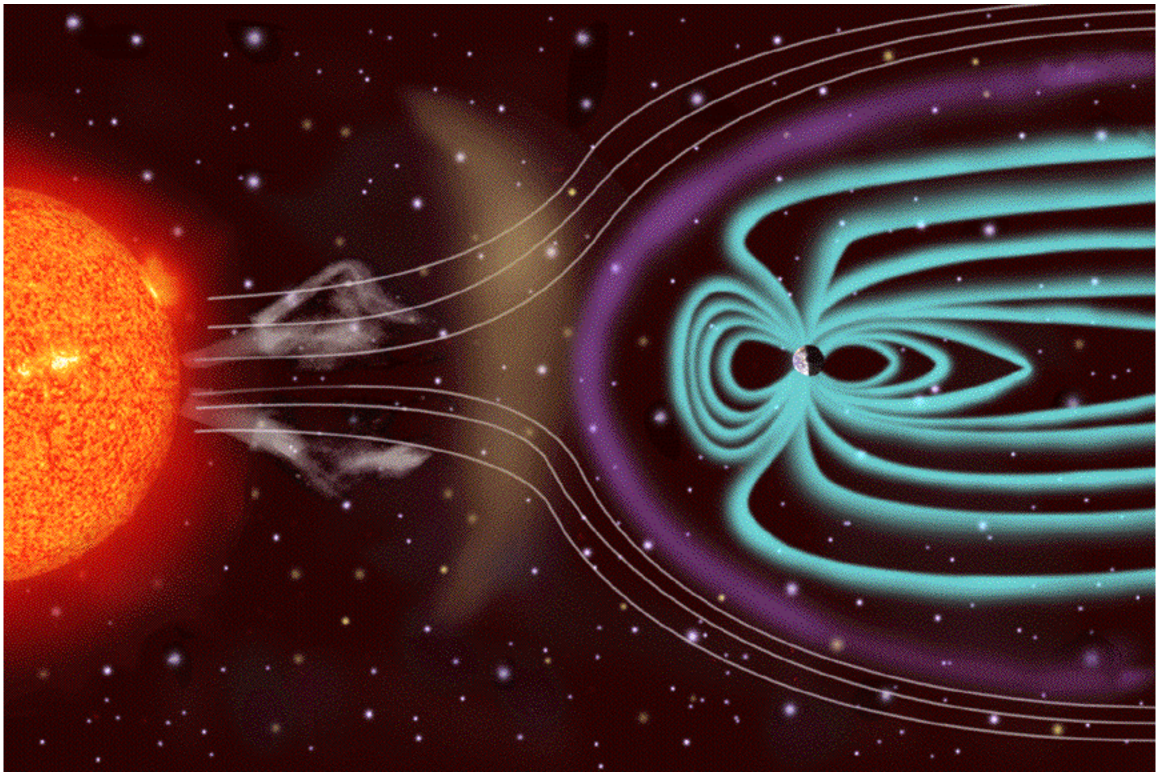


Figure 6. Artist Depiction of the Magnetosphere.
Source: ESA and NASA (2015).

4. Van Allen Radiation Belts

Energetic particles trapped in the Earth's magnetic field were hypothesized and later proven by American astrophysicist James Van Allen. His advocacy to host a scientific experiment perceptive to energetic particles on the United States' first and follow-on satellites led to the discovery of two rings of charged particles consisting of protons and electrons trapped in the Earth's magnetic field. These rings "are comprised of two regions of electrons, peaking at about 3,000 km and 25,000 km, and a single region of protons, peaking at about 3000 km" (Tribble 2003, 158). These two rings are usually referred to as the inner and outer belts. The "valley between them is sometimes called the slot region" (158).

This traditional understanding of the two-belt arrangement has recently been modified, as it is now proven that these belts are manipulated along with the Earth's magnetic field from the effects of space weather. Two probes named after the man who discovered these belts were “launched on August 30, 2012…[and] just days after the special twin spacecraft soared into orbit…the mission has answered one long-standing question about the nature and behavior of the belts, and revealed that the outer belt, depicted in Figure 7, can split into two separate belts” (Zell 2013). Despite being one of the first astronomical discoveries for U.S. satellites, scientists continue to explore and learn new impacts from space weather in the near Earth space environment.

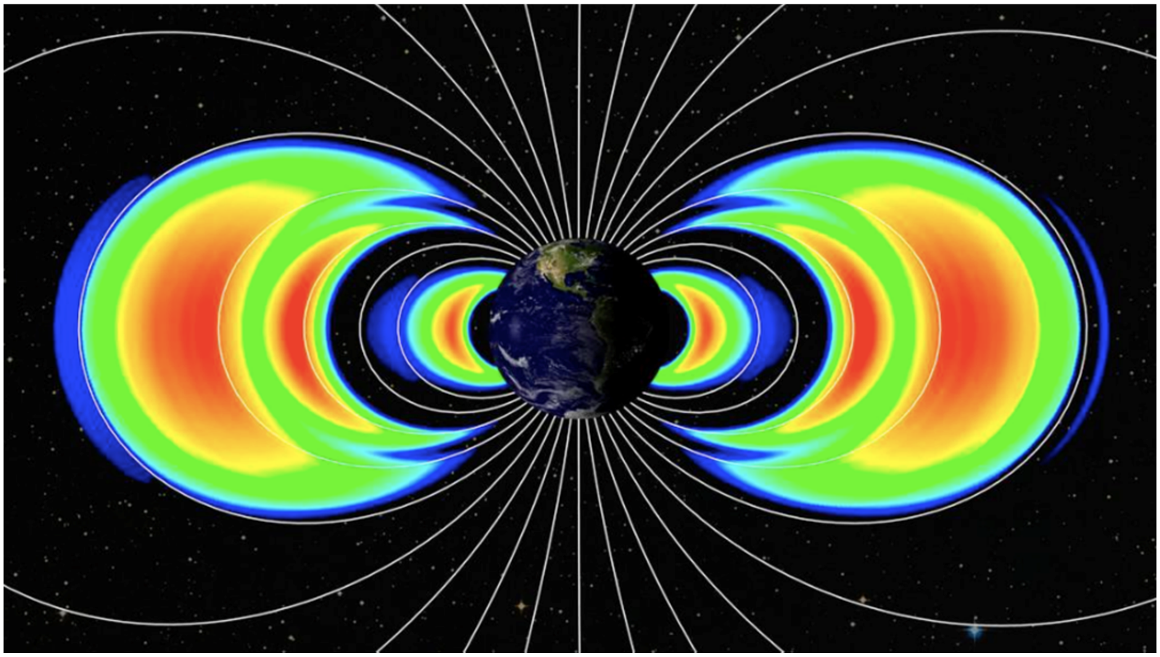


Figure 7. New Representation of the Van Allen Radiation Belts.
Source: Zell (2013).

5. South Atlantic Anomaly

A region of enhanced radiation is a feature at lower altitudes in the South Atlantic region “because of the offset and tilt of the geomagnetic axis relative to Earth’s rotation axis” (Fortescue, Swinerd, and Stark 2011, 27). Low altitude space vehicles traversing through this region are exposed to a higher density of charged particles, particularly high-energy protons. As a result, a strong correlation of reported spacecraft anomalies has occurred while flying through the South Atlantic Anomaly (SAA). Figure 8 shows the density of these protons and their penetration into the Earth’s atmosphere with an altitude as low as 200 km.

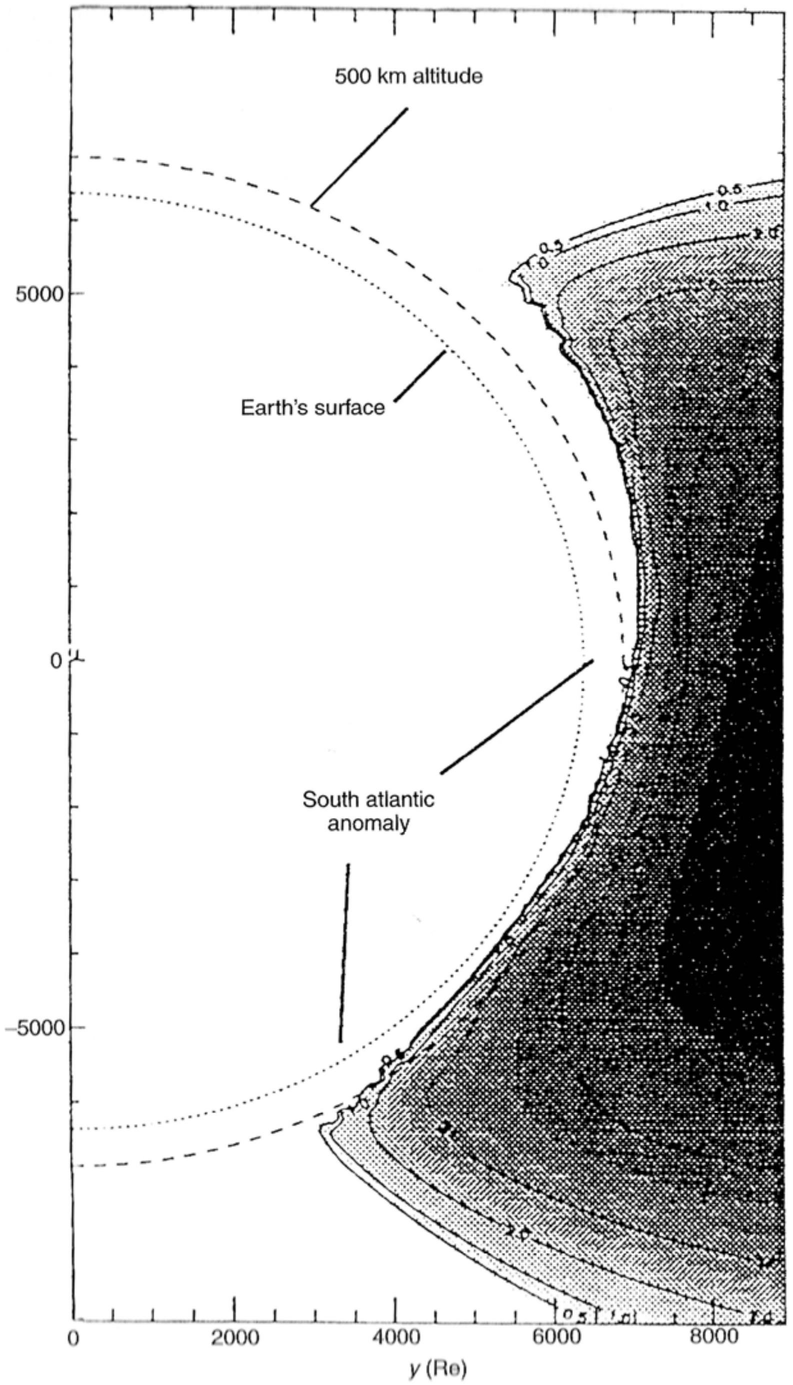


Figure 8. South Atlantic Anomaly Proton Radiation Belt. Source: Fortescue, Swinerd, and Stark (2011, 29).

6. Ionosphere

The region of the Earth’s upper atmosphere from about 50 km to 1,000 km is a region of free ions and electrons called the ionosphere. The charged particles have been photoionized primarily by ultraviolet energy from the Sun. This layer is particularly important for high-frequency communications that bounce off this layer and back to earth. RF transmissions from communications satellites and those of the GPS can also be influenced by the changing conditions of the ionosphere and design considerations for these systems must be implemented to operate through these conditions.

One visual example of the interaction of geomagnetic storms can be seen in this atmospheric layer. The dancing lights of the Aurora flow along the magnetic field lines radiating out of the poles when atmospheric gasses are excited by charged particles near the E-Region (Figure 9).

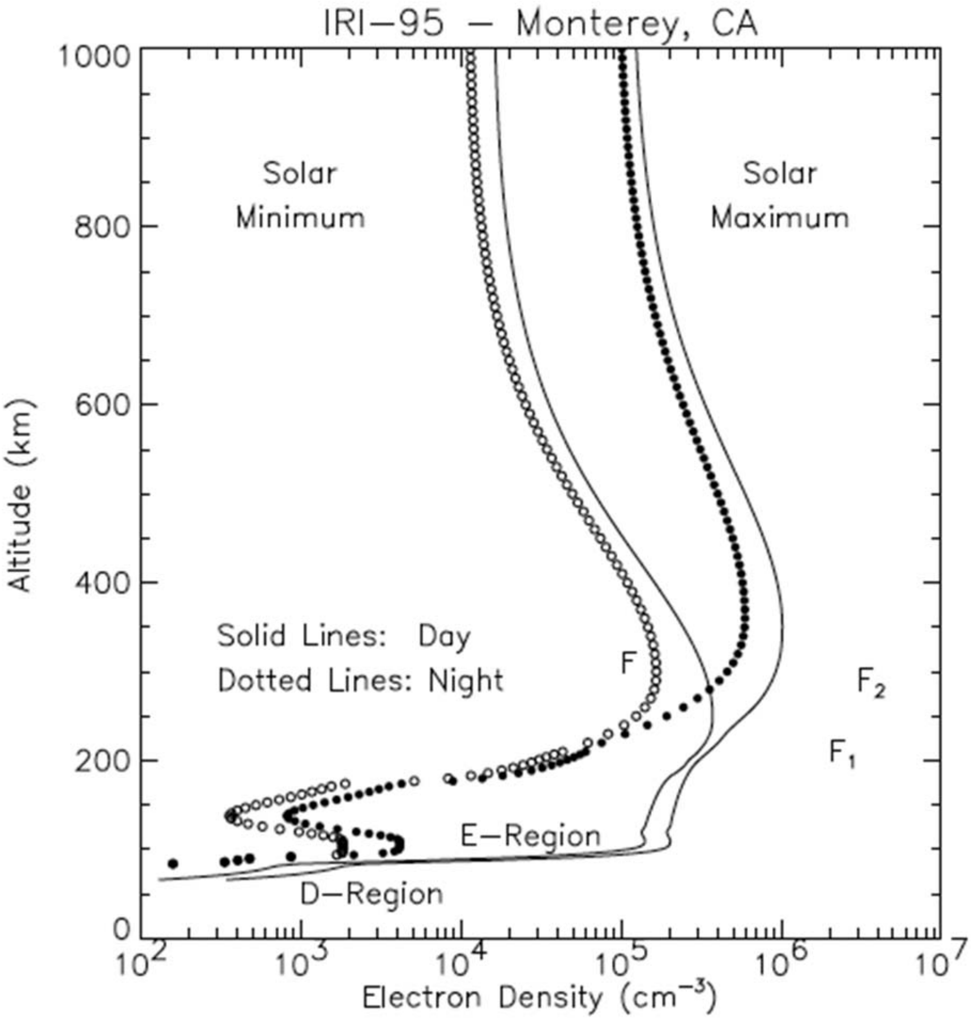


Figure 9. Electron Density as a Function of Altitude.
Source: Olsen (2005, 160).

B. AREAS OF OPERATION

> Like ships at sea, satellites sail the ocean of space. And, like their terrestrial counterparts, satellites must endure severe storms in the environment in order to perform their mission.
>
> —NOAA (2008, 1)

National security spacecraft operate in a variety of orbits (Figure 10). Spacecraft operating in each of these orbits are exposed to different space environment conditions and must be designed and built to withstand these conditions. To design and build a spacecraft to operate through these varying conditions, the engineering team must understand the orbits and their relationship with space weather. A general understanding of the space environmental conditions in each orbit is understood, but limited sensor data restricts the ability to optimize each national security spacecraft for each specific orbit. Each orbit presents a unique space environment challenge.

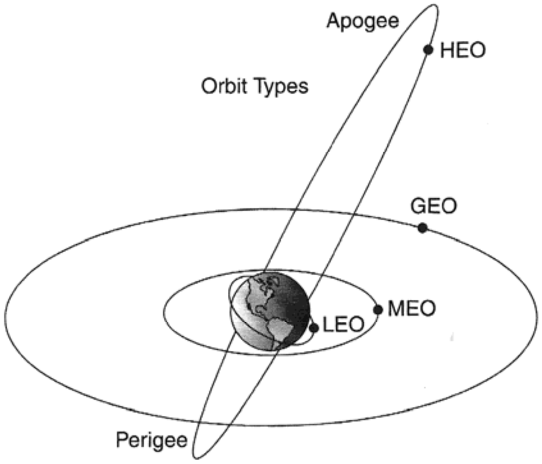


Figure 10. The Four Main Types of Orbits.
Source: Moldwin (2008, 80).

1. Low-Earth Orbit

Space vehicles with an orbit below ~2,000 km are considered to be in LEO. Spacecraft must orbit above an altitude of ~160 km to maintain a sustainable orbit due to the drag induced by the upper atmosphere at that altitude. Most LEO vehicles maintain an orbit somewhere between 300 and 1,000 km to take operational advantage of this orbit.

The advantage of this orbit is its relative closeness to the Earth’s surface, particularly for remote sensing satellites. For example, DigitalGlobe’s WorldView panchromatic (black and white) electro-optical and shortwave infrared imagery satellites operate in this orbit. A disadvantage of this orbit is the spacecraft’s relative fast overflight speed and short dwell time across the landscape below. A space vehicle in this orbit has a very short dwell time “over the horizon” and may require multiple ground stations for direct downlink of data or require a cross-link communications satellite at GEO or HEO to provide a bent-pipe communications capability. Additionally, depending on the apogee and perigee, seen in Figure 10, of the orbit, the vehicle may encounter drag resistance and encounter the highly energetic charged particles of the upper atmosphere.

2. Medium-Earth Orbit

By far, the most recognizable space vehicles in mid-earth orbit (MEO) are position, navigation, and timing space vehicles, including the United States' GPS. In addition to GPS, the European Union's GALILEO and the Russian Federation's GLONASS PNT systems are also deployed in MEO. This orbit at ~20,000 km results in about a 12-hour orbital period (the time it takes to complete one orbit). While most of the satellites in MEO reside around 20,000 km, MEO is considered the appropriate category for any space vehicle operating between LEO from ~2,000 km to GEO at 42,000 km.

3. Geosynchronous Orbit

This orbit shares a special relationship with the rotation of the Earth. A space vehicle placed in a circular orbit about 35,000 km away from the Earth's surface, about 6.6 RE, with low inclination along the equatorial plane, will track over the same relative position on the ground. This orbit is both GEO and geostationary orbit. Geostationary refers to the space vehicle's ground track staying relatively constant over the same spot on Earth along the equator. From this vantage point, one ground station with a fixed antenna can communicate with the vehicle and the vehicle has line-of-site communications to most areas over that side of the globe. For this reason, GEO "has become the world standard for most communications satellites" (Gordon and Morgan 1993, 5). A constellation consisting of four or five evenly spaced vehicles at GEO can provide almost worldwide coverage. The northern and southern most latitudes are the exception, where space vehicle transmissions must pass through significantly more atmosphere, which degrades signal strength.

Not all GEO orbits are also geostationary. Some space vehicles are placed in a GEO orbit with an inclination that creates a ground track oscillating between either side of the equator into the northern and southern hemispheres. An advantage to this orbit can be a longer dwell time over specific regions or better direct line-of-site to a ground target; however, this architecture would require multiple satellites for persistent coverage.

An example of this architecture is the Quasi-Zenith Satellite System (QZSS) in an asymmetric figure-8 GEO seen in Figure 11. QZSS is designed to be a NPT and communications augmentation satellite that improves NPT accuracy over Japan. The vehicle loiters at higher altitudes longer over the area of Japan.

Figure 11. Asymmetric Figure-8 Geosynchronous Orbit Ground Track. Source: Japan Aerospace Exploration Agency (2003).

This system, made up of “at least four satellites” (Japan Aerospace Exploration Agency 2003), also allows for a more advantageous angle of incidence than the GPS system to improve accuracy in the “urban canyons,” seen in Figure 12 that are created by tall high-rise buildings.

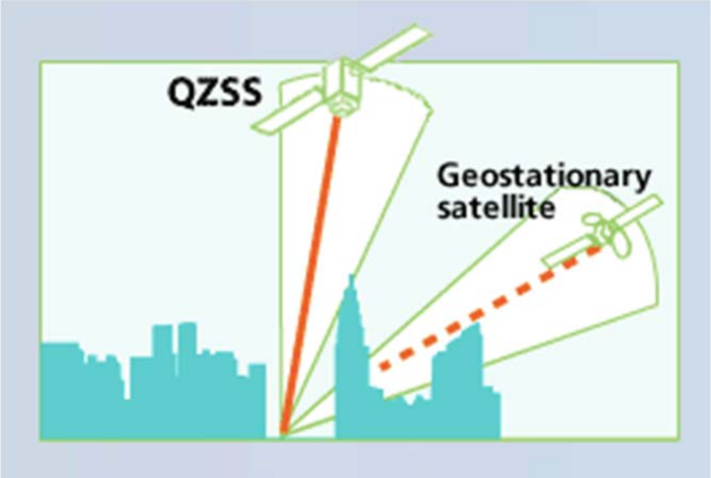


Figure 12. NPT Improvement in Japanese Urban Canyons.
Source: Japan Aerospace Exploration Agency (2003).

4. High-Earth Orbit

In the same way the asymmetric figure-8 geosynchronous orbit provides specific regional advantages, the HEO orbit provides longer dwell times over high latitudes. Due to the disproportionate population density in the northern hemisphere, these orbits are often characterized by long dwell times over the northern latitudes. A space vehicle in this orbit meets its perigee at high speed over the Antarctic and loiters near apogee over the northern hemisphere at very high altitudes.

A specific HEO orbit has often been utilized for Soviet and Russian communications satellites, referred to as Molniya. This orbit allows the space vehicles to dwell over the Soviet states for many hours throughout the day. HEO orbits can complement GEO satellites for full earth coverage. SBIRS, the U.S. missile warning constellation, combines GEO vehicles with HEO payloads to allow perceptivity to missile launches from polar regions where Russian nuclear submarines patrol.

C. THE SPACE WEATHER ENVIRONMENT AND EFFECTS

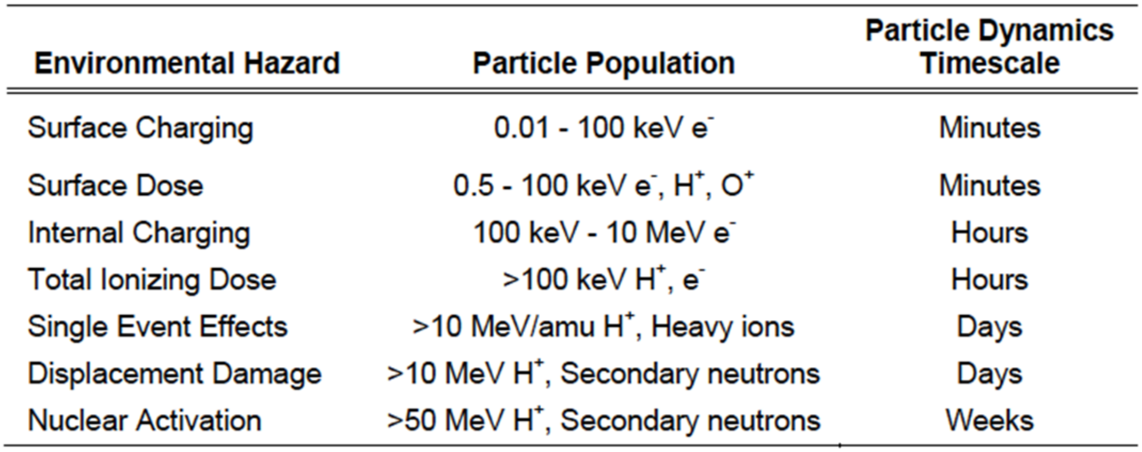
The United States invested a significant amount of resources during the Cold War to develop and deploy satellite systems in support of national security; however, while “developing [space] technology provided an unprecedented vantage point for the United

States, [it] also posed unprecedented technological challenges” (Berkowitz 2011, V). The harsh environment of space requires distinct design considerations for the space environment. Space environment effects can be divided into “five categories: vacuum, neutral, plasma, radiation, and micrometeoroid/orbital debris (MMOD)” (Tribble 2003, 3).

The plasma and radiation environments are a significant contributor to spacecraft anomalies. From 1974 to 1999, “the National Geophysical Data Center recorded over 4500 spacecraft anomalies or malfunctions that have been traced to the effects of the space radiation environment” alone (Howard and Hardage 1999, 11). The neutral environments also contribute to spacecraft anomalies, to a lesser degree, and are briefly discussed later. Vacuum and MMOD environments are not significantly affected by the Sun’s variable activity and are not relevant to the recommendations made in this paper, and for these reasons, are not discussed. The primary focus of this paper’s recommendation is concerned with the plasma and radiation environmental effects on spacecraft.

For comparison, Table 1, from Aerospace Corporation report number ATR-2008(8073)-5, lists the hazards of the plasma and radiation environment effects, the particle population that causes these problems, and the time it takes for these the effects to impact the spacecraft.

Table 1. Space Environment Hazards. Source: O’Brien et al. (2008, 1).



Environmental Hazard	Particle Population	Particle Dynamics Timescale
Surface Charging	0.01 - 100 keV e$^-$	Minutes
Surface Dose	0.5 - 100 keV e$^-$, H$^+$, O$^+$	Minutes
Internal Charging	100 keV - 10 MeV e$^-$	Hours
Total Ionizing Dose	>100 keV H$^+$, e$^-$	Hours
Single Event Effects	>10 MeV/amu H$^+$, Heavy ions	Days
Displacement Damage	>10 MeV H$^+$, Secondary neutrons	Days
Nuclear Activation	>50 MeV H$^+$, Secondary neutrons	Weeks

1. Neutral Environment

Space vehicles in LEO are still affected by the uppermost regions of the Earth’s atmosphere. Despite the very low atmospheric density hundreds of kilometers above the Earth’s surface, LEO vehicles traveling close to eight kilometers per second still interact with enough atoms, mostly atomic oxygen, to affect the vehicles’ velocity. Atomic oxygen levels also vary dependent on solar activity and react chemically with some space vehicle materials.

a. Aerodynamic Drag

Aerodynamic drag is a real threat to LEO space vehicles as this “frictional force causes the spacecraft to lose altitude, which moves it into a denser neutral atmosphere… [causing] increased drag, which lowers the satellite into even denser atmosphere” (Moldwin 2008, 81), thus worsening the problem. Many LEO vehicles, to include the ISS, have a propulsion system with enough fuel onboard to increase their orbital altitude periodically through the design life of the vehicle. These orbit adjust maneuvers (OAM) are a part of basic planned space vehicle maintenance activities for many LEO vehicles. Sun activity can affect the atmospheric density and cause problems for satellite tracking. See Figure 13.

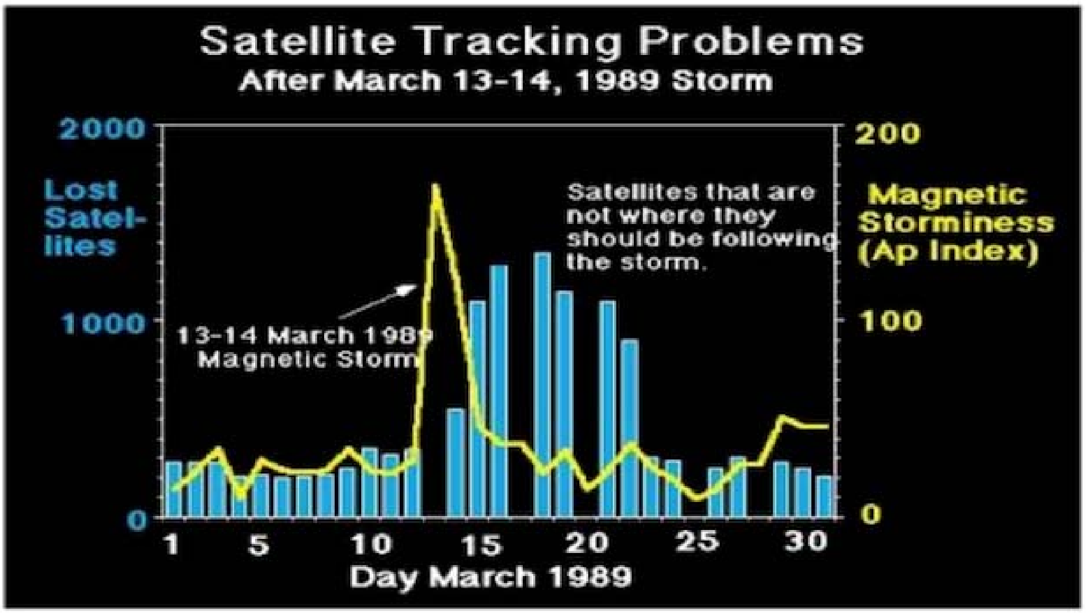


Figure 13. Number of Satellites Lost in Connection with the March 13–14, 1989, Storm. Source: Space Weather Prediction Center (2015).

b. Atomic Oxygen

Ultraviolet radiation from the Sun "dissociates molecular oxygen, above 100 kilometers" (Wertz and Larson 2007, 211) from the Earth's surface. Atomic oxygen is known to cause "oxidation or erosion and general degradation of materials properties" (Tribble 2003, 84). The amount of radiation from the sun varies with the solar cycle and directly relates to the amount of atomic oxygen in the upper atmosphere.

c. Plasma Environment

The least prevalent fundamental state of matter on Earth is actually incredibly abundant outside the Earth's atmosphere; in fact, "over 99% of the universe, the Sun, and the stars, is a plasma" (Tribble 2003, 115). This plasma made of very high energy negatively charged electrons and positively charged ions can cause problems for the spacecraft that operate in this environment. Components on the vehicle, built of differing material, "conductors and dielectrics, will charge to different potentials in the presence of plasma" (Tribble 2003, 115). Additionally, "an object that is subjected to an unequal flux of ions and electrons will develop a net charge" (129). This electric potential can grow to the point where an electrostatic arc occurs between components, which is often referred to as an electrostatic discharge (ESD) event. An ESD event can generate "electromagnetic interference (EMI) from such arcs [that] can cause spacecraft to operate erratically" (Wertz and Larson 2007, 213). When "the potential difference across a dielectric exceeds the material's inherent breakdown characteristics," the dielectric can break down as seen in Figure 14.

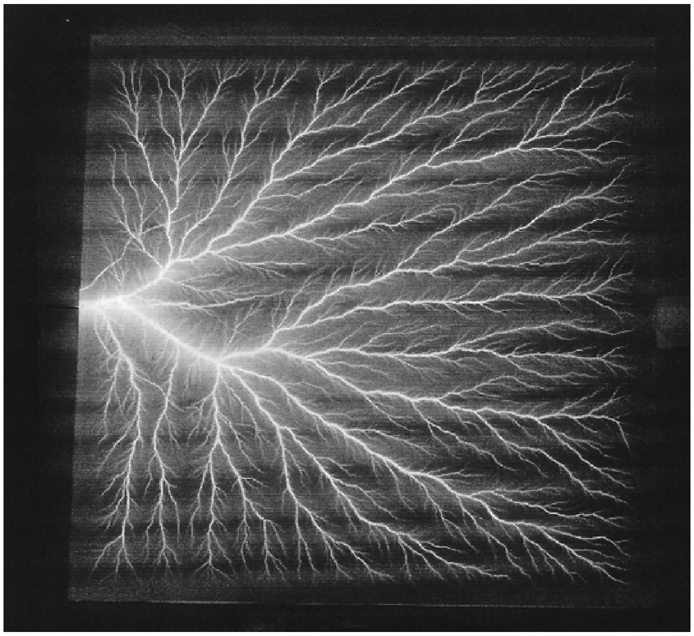


Figure 14. Defects in Dielectric Material after Exposure to Electric Field.
Source: Moldwin (2008, 84).

Spacecraft designers can minimize charging by preventing the "buildup of large potentials by actively balancing currents to spacecraft surfaces [or] prevent differential charging of surfaces by insuring that the entire surface is of uniform conductivity" (Tribble 2003, 145). These techniques are summarized in Table 2.

Table 2. Plasma Environment Effects Design Guidelines.
Source: Tribble (2003, 145).

Uniform Surface Conductivity	Make exterior surfaces of uniform conductivity if possible
ESD Immunity	Utilize uniform spacecraft ground, electromagnetic shielding, and filtering on all electronic boxes
Active Current Balance	Consider flying a plasma contactor or a plasma thruster

2. Radiation Environment

The radiation trapped in the Van Allen belts "differ significantly from the lower-energy particles that compose the plasma environment" (Tribble 2003, 153), and deserve special consideration for the impact they have on spacecraft. In the field of spacecraft design, radiation impacts must always be considered because a space vehicle will interact with trapped particles or transient particles from the Sun or interstellar sources in any orbit (Figure 15).

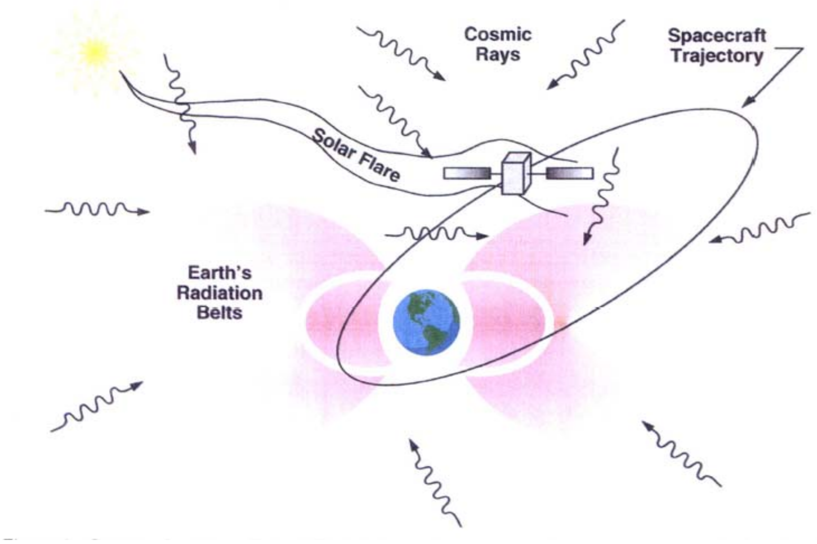


Figure 15. Cartoon Depicting All the Radiation Types that a Spacecraft Can Experience. Source: Howard and Hardage (1999, 2).

In Figure 16, the trapped particles in the Van Allen belts are illustrated in the Earth's radiation belts along with the impacts from solar flares and galactic cosmic radiation. The primary source of radiation to space vehicles is "comprised of two regions of electrons, peaking at about 3000 km and 25,000 km, and a single region of protons, peaking at about 3000 km (Tribble 2003, 158)" as presented in Figure 16. The Van Allen radiation belts, "proton energies range from 0.01 to 400 MeV [and] electron energies are in the range from 0.4 to 4.5 MeV" (Fortescue, Swinerd, and Stark 2011, 27). These particles "have a large amount of kinetic energy and can have a permanent effect upon the material through which they pass" (30).

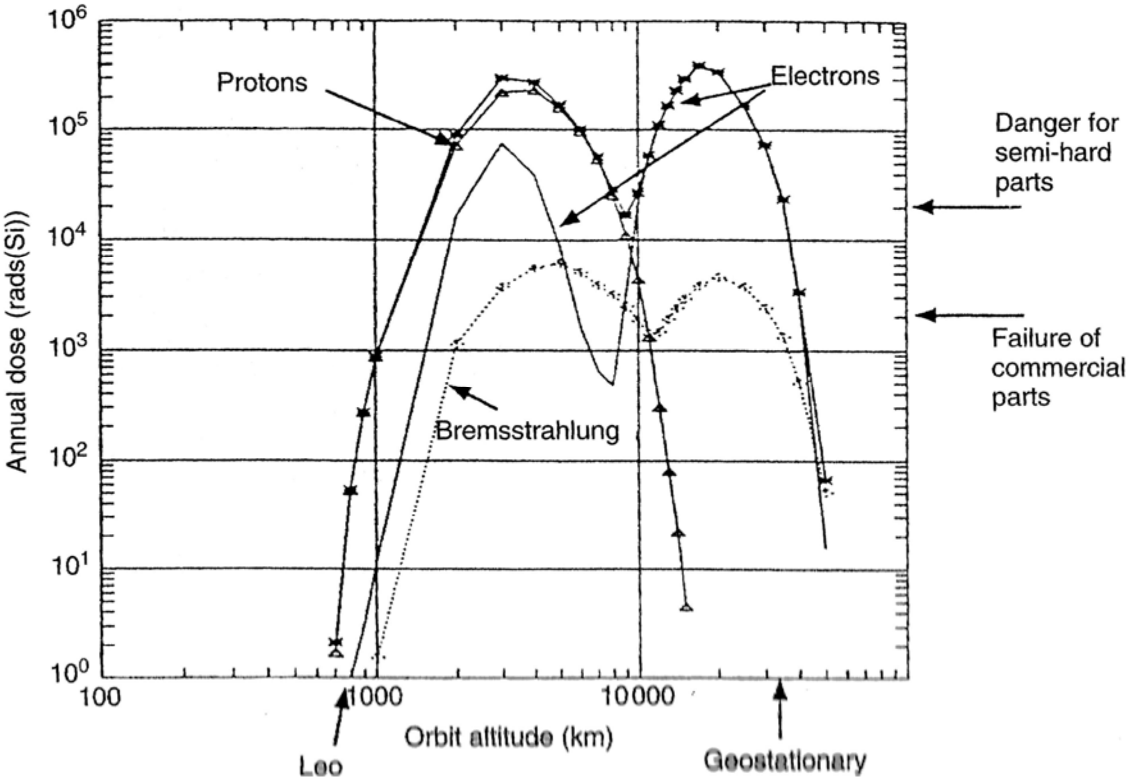


Figure 16. The Structure of the Van Allen Radiation Belts.
Source: Fortescue, Swinerd, and Stark (2011, 30).

The relatively consistent solar wind is a secondary source of radiation, and "consists of low energy electrons and protons and is typically only energetically significant for externally mounted spacecraft components" (Howard and Hardage 1999, 3). Compared to other radiation sources, the solar wind is relatively insignificant. Solar flares and galactic cosmic radiation pose more significant challenges for spacecraft engineers.

At times, magnetic disruptions on the Sun's surface can lead to an explosion of energetic particles in the form of solar flares that reach the Earth a day or two after their release. This activity can have significant influences on the magnetosphere and the radiation environment where national security spacecraft operate. The "flare can produce energetic protons and heavy ions that will produce effects in electronics" (Howard and Hardage 1999, 3) Solar activity, to include sun spots and their associated solar flares, trend on an 11-year solar cycle, as seen in Figure 17.

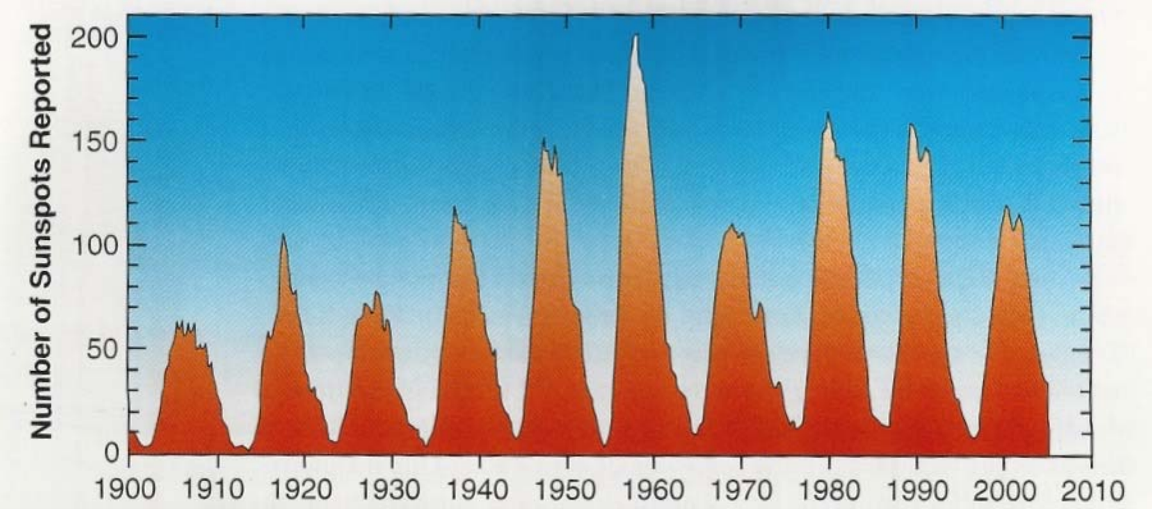


Figure 17. Sunspot Activity. Source: Poppe and Jorden (2006, 25).

Finally, galactic cosmic radiation appears to exist uniformly across the universe and "consists of a low flux, ~4 particles/cm2s of energetic, 108–1019 eV, ionized nuclei" (Tribble 2003, 161). These particles have an ever-present impact to spacecraft on orbit, but their effects tend to be most present in times of solar minimum. Figure 18 presents the relationship between particle flux and particle energy for the different energetic particles in the near earth environment. These range from the high flux, low energy solar winds to low flux, high energy galactic cosmic rays.

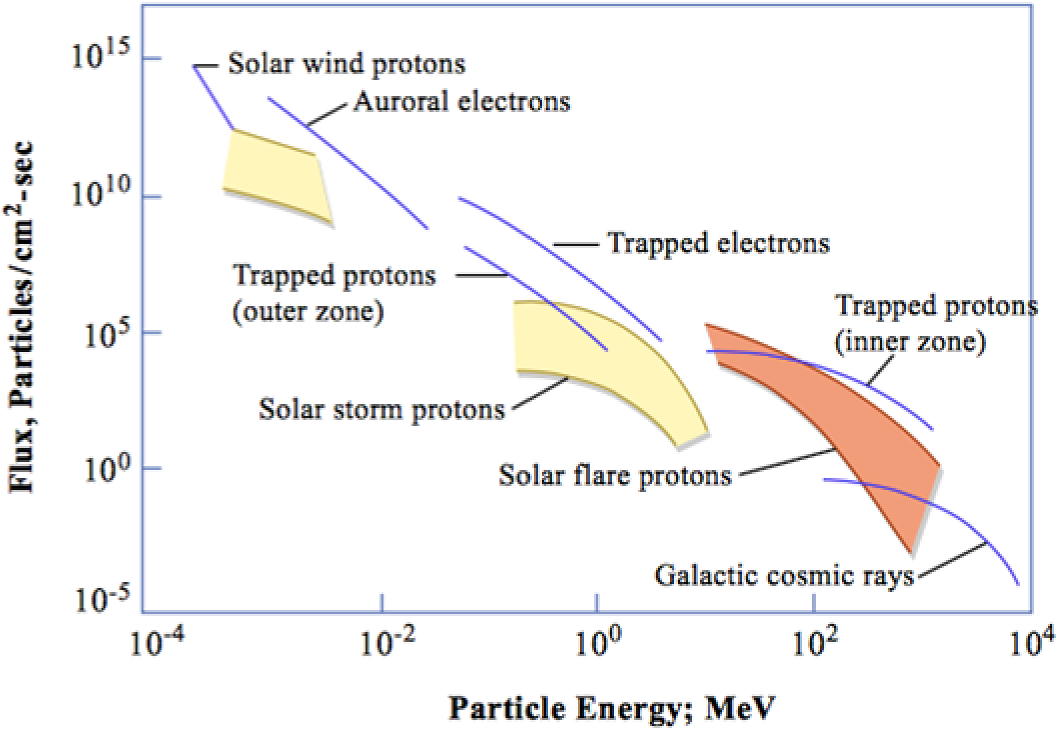


Figure 18. Particle Flux and Particle Energy.
Source: MIT OCW (2006).

Energetic electrons, protons, and heavy ions can wreak havoc on a spacecraft. Figure 19 shows how electronic and nuclear integrations can lead to total ionizing dose, displacement damage, and single event effects.

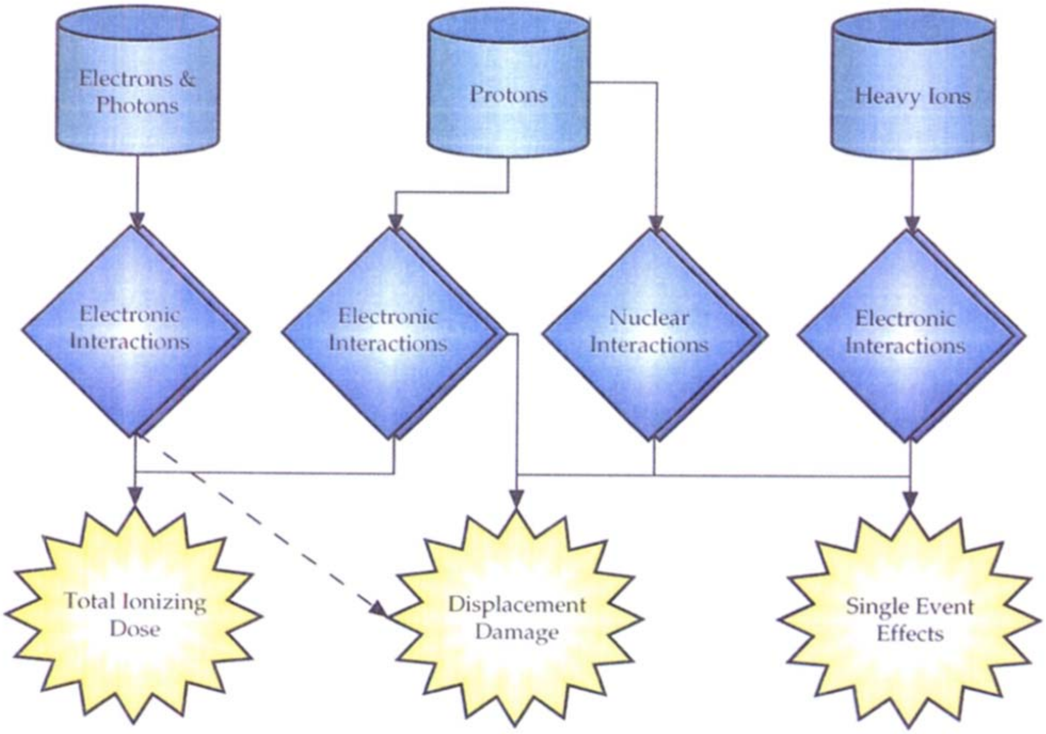


Figure 19. Diagram of Radiation Environment Effects on Electronic Systems. Source: Howard and Hardage (1999, 8).

The amount of energy received by a material that results in ionization of the material is the total ionizing dose (TID). Energy from the radiation environment can excite an atom's electrons into a higher energy state that frees them from the now positively charged ion; "these electrons, or more correctly the positive charge created by ionization, are the prime cause of the total ionizing dose effects" (Howard and Hardage 1999, 9). When spacecraft electronics are exposed to radiation, and this ionization effect takes place within their semiconductors, the properties of the dialectic material change and may "allow small leakage currents to flow,…although this sounds fairly benign, it can lead to long-term consequences" (Tribble 2003, 181). Elaboration of these consequences on spacecraft electronics is summarized in NASA Technical Paper-1999-209373:

> In general, all types of electronics are susceptible to ionization but the charge generated inside the semiconductor material can quickly be collected and removed without ill effect (assuming the radiation interaction rate is at a low level of the space environment). If a semiconductor device contains, for example, a silicon dioxide/silicon

> interface (as in all modern integrated circuits based on complementary metal oxide semiconductor (CMOS) technology), charge generated inside the oxide can become trapped at the interface. This trapped charge, by charging the potential of the interface structure, can lead to increased "leakage" current or changed operational characteristics of any device using this structure. (Howard and Hardage 1999)

The dose of radiation absorbed by a material is referred to as rad, and is defined as "that amount of any kind of radiation which deposits 10–2 J per kg of material" (Tribble 2003, 176).

Excited by radiation, the entire atom's energy level can increase, "increasing vibrational motion of the atoms" (Howard and Hardage 1999, 11) to a state where that atom actually escapes the influence of the nearby atoms and flows out of its position in the material's crystalline structure. This displacement of the atom is known as displacement damage. The crystalline structure's "regular order gives semiconductor materials their unique properties, the disturbance causes changes in the operation of any device exposed to this environment" (11). Over time, radiation induced displacement damage degrades the performance of the semiconducting material.

One of the more susceptible components on a spacecraft to displacement damage is the solar cell. This displacement damage is disconcerting considering the primary means for generating electricity to power near Earth satellites are solar arrays comprised of many small solar cells. The degradation in solar cell performance, caused by the total dose effects, is a life limiting consideration during spacecraft design.

The ionized particles carry a charge and "a number of detectors, switches, and current and voltage regulators can observe a pulse of charge as the particle interacts with the circuit" (Moldwin 2008, 85) known as a single event effect. Several specific effects are defined in Table 3 and can cause anomalies that may degrade or remove the spacecraft from operations for a period of time, or also have the potential for devastating effects that cause a premature end of mission.

Table 3. Listing of Single Event Effects.
Source: Howard and Hardage (1999, 13).

Acronym	Effect	Description
SEU	Upset	Digital circuit changes logic state
SEL	Latchup	Device switches to a destructive, high current state
SEGR	Gate Rupture	Destructive failure of a power transistor
SEB	Burnout	Another mode of destructive failure for a power transistor
SEFI	Functional Interrupt	Device enters mode where it is no longer performing the designed function
SEMBE	Multiple Bit Error	More than one logic state change from one ion
SET	Transient	Transient current in circuit
SEIDC	Induce Dark Current	Increased dark current in CCD arrays

Single event effects occur when “a heavy ion is incident on the sensitive area of an integrated circuit, producing sufficient charge in the form of electron—hole pairs to cause a change in the logic state of the device” (Fortescue Swinerd, and Stark, 2011, 43). These effects can cause a minor non-permanent upset in operations but they also have the potential to impact “critical circuitry such as a control system or decision-making logic, [where] it can have serious consequences on the spacecraft operation—generating false commands such as thruster firings” (43). Such events can be life limiting or life ending for national security spacecraft.

D. CHAPTER SUMMARY

This chapter covered the space environment and the effects it can have on all spacecraft including those deployed for U.S. national security. Vacuum, the neutral environment, the plasma environment, radiation, and orbital debris all impact spacecraft design and operations. The plasma and radiation environments have the potential to disrupt national security space satellite operations significantly. The current space weather situational awareness architecture, discussed in the next chapter, is inadequate to meet the emerging space situational awareness needs of national space systems.

IV. CURRENT SPACE WEATHER SITUATIONAL AWARENESS

The White House explicitly acknowledges that U.S. space capabilities are critical to U.S. national security interests:

> The United States will pursue the following goals in its national space programs: Improve space-based Earth and solar observation capabilities needed to conduct science, forecast terrestrial and near-Earth space weather, monitor climate and global change, manage natural resources, and support disaster response and recovery. (White House 2010b, 4)

A. STAKEHOLDERS

The United States is currently and increasingly reliant on space-based capabilities. This paper is focused on national security space systems but the U.S. government deploys many space-based satellites that support many aspects of an American's day-to-day life. The Department of Commerce (DOC), NASA, and the National Weather Service are primary stakeholders concerned with current and forecasted space weather. The DOC provides an expanded list of consumers of space weather data. The following list from NOAA summarizes some of these consumers and their respective uses of weather data:

> <u>Electric Power Grid Operators</u> use geomagnetic storm detection and warning products to maximize power grid stability and to mitigate power grid component damage and large-scale blackouts.
>
> <u>Spacecraft Launch Operators</u> use radiation products to avoid electronic problems on navigation systems, preventing launch vehicles from going off course and being destroyed.
>
> <u>Spacecraft Operations and Design</u> staff rely on space weather products to avoid electronic problems. Space weather effects on satellites vary from simple repairs to total mission failure.
>
> <u>Manned Spaceflight</u> activities are altered to avoid or mitigate effects of radiation storms impacting crews and technological systems.
>
> <u>Navigation Systems</u> depend on space weather information to ensure the integrity and safe use of electronic navigational systems, such as GPS.
>
> <u>Aviation Operators</u> use crucial information on space weather impacts—such as communication outages, potentially harmful radiation, and navigation errors—to adjust routes and altitudes.

> Communications Operators anticipate and react to space weather activity to mitigate impacts occurring over a wide range of communications frequencies used by emergency management officials, search and rescue systems, and many others.
>
> Surveying and Drilling Operations rely on accurate and timely space weather products for safe and efficient high-resolution land surveying and sea drilling. (2012, 4)

These stakeholders represent the larger domestic community that is reliant on space for day-to-day operations. U.S. national interests and national security are reliant upon these stockholders' uninterrupted access to space. This diverse community is increasingly dependent on space-based capabilities vulnerable to space weather effects.

B. REQUIREMENTS

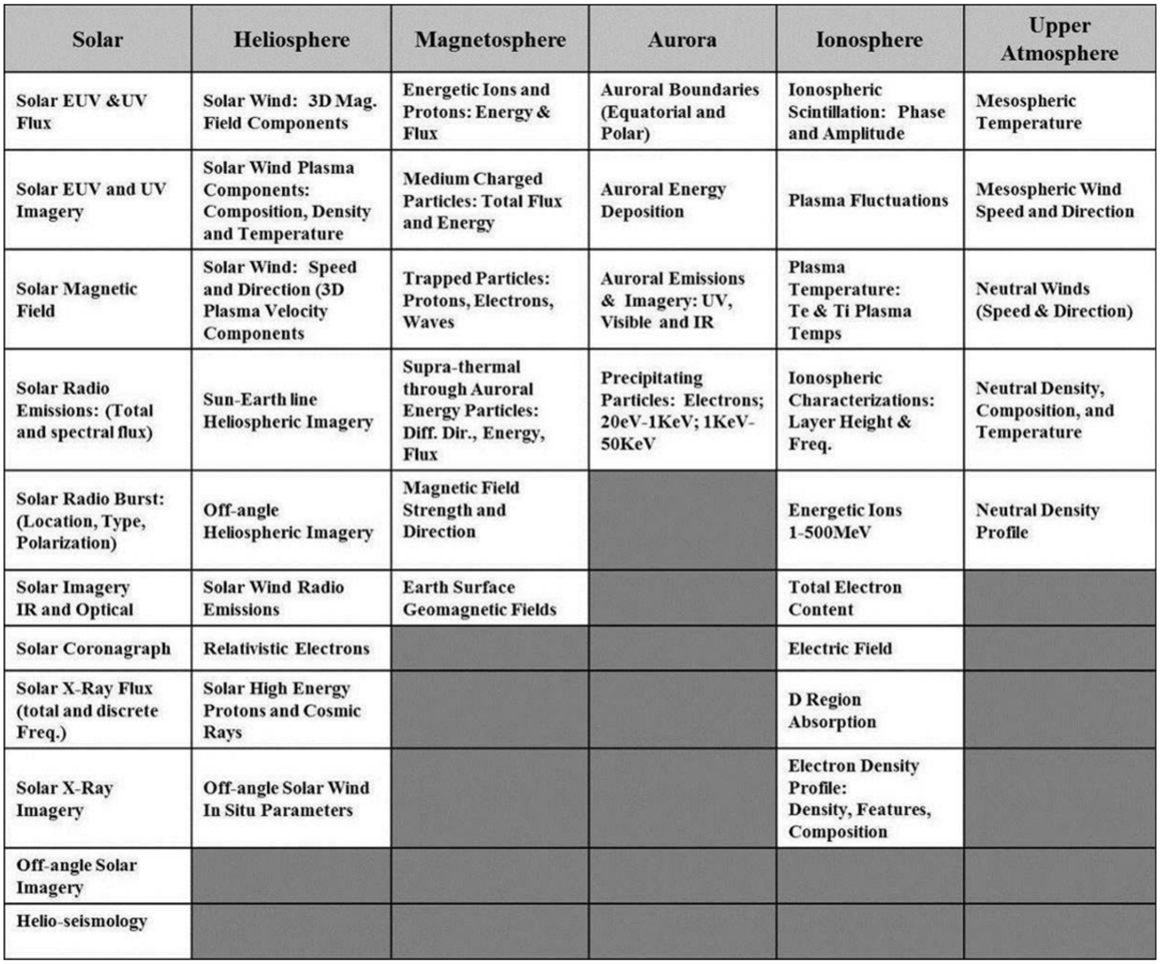
National security space systems support the United States' ability to project power in the diplomatic, information, military, and economic domains. In 2013, the Executive Office of the President requested the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) "to lead a study to assess (1) the current and planned space weather observing systems and (2) the capacity of those systems to meet operational space weather forecasting requirements over the next 10 years" (White House Office of Science and Technology Policy 2013, iii). The study assessed the following DOD, DOC, and NASA documents to consolidate space weather observation requirements:

- NOAA Consolidated Operations Requirements List, 2011 (DOC).
- NOAA Program Observation Requirements Document—Space Weather Program, 2009 (DOC).
- Air Force Weather Space Weather Implementation Plan, Oct 2010 (DOD).
- Initial Capabilities Document for Meteorological and Oceanographic Environment, 2009 (DOD).
- Integrated Space Weather Analysis System Data Requirements, 2011 (NASA).
- Space Radiation Analysis Group Requirements, 2011 (NASA).

- Four-Dimensional Weather Functional Requirements for NexGen Air Traffic Management, 2008 (Joint Planning Development Office Weather Functional Requirements Study Group 2013, 12).

From these documents, the OFCM generated Table 4 to consolidate the United States' space weather observing requirements.

Table 4. Observing Requirements by Space Weather Domain Space Weather Observing Systems. Source: White House Office of Science and Technology Policy (2013, 13).



Solar	Heliosphere	Magnetosphere	Aurora	Ionosphere	Upper Atmosphere
Solar EUV &UV Flux	Solar Wind: 3D Mag. Field Components	Energetic Ions and Protons: Energy & Flux	Auroral Boundaries (Equatorial and Polar)	Ionospheric Scintillation: Phase and Amplitude	Mesospheric Temperature
Solar EUV and UV Imagery	Solar Wind Plasma Components: Composition, Density and Temperature	Medium Charged Particles: Total Flux and Energy	Auroral Energy Deposition	Plasma Fluctuations	Mesospheric Wind Speed and Direction
Solar Magnetic Field	Solar Wind: Speed and Direction (3D Plasma Velocity Components	Trapped Particles: Protons, Electrons, Waves	Auroral Emissions & Imagery: UV, Visible and IR	Plasma Temperature: Te & Ti Plasma Temps	Neutral Winds (Speed & Direction)
Solar Radio Emissions: (Total and spectral flux)	Sun-Earth line Heliospheric Imagery	Supra-thermal through Auroral Energy Particles: Diff. Dir., Energy, Flux	Precipitating Particles: Electrons; 20eV-1KeV; 1KeV-50KeV	Ionospheric Characterizations: Layer Height & Freq.	Neutral Density, Composition, and Temperature
Solar Radio Burst: (Location, Type, Polarization)	Off-angle Heliospheric Imagery	Magnetic Field Strength and Direction		Energetic Ions 1-500MeV	Neutral Density Profile
Solar Imagery IR and Optical	Solar Wind Radio Emissions	Earth Surface Geomagnetic Fields		Total Electron Content	
Solar Coronagraph	Relativistic Electrons			Electric Field	
Solar X-Ray Flux (total and discrete Freq.)	Solar High Energy Protons and Cosmic Rays			D Region Absorption	
Solar X-Ray Imagery	Off-angle Solar Wind In Situ Parameters			Electron Density Profile: Density, Features, Composition	
Off-angle Solar Imagery					
Helio-seismology					

These requirements are generally comprehensive in nature and do not support direct measurements from targeted sensors integrated on national security spacecraft.

C. ARCHITECTURE

The space weather observation architecture includes systems both on the ground and on orbit (Figure 20). These systems are poised ready to sense changes in space weather conditions and report those changes to ground operation centers. These operation centers receive and process the data from multiple sensors, and using models and analytical tools, the teams at these operations centers can provide useful products to the end users. These products include current conditions, future forecasts, and notifications of potential space weather threats.

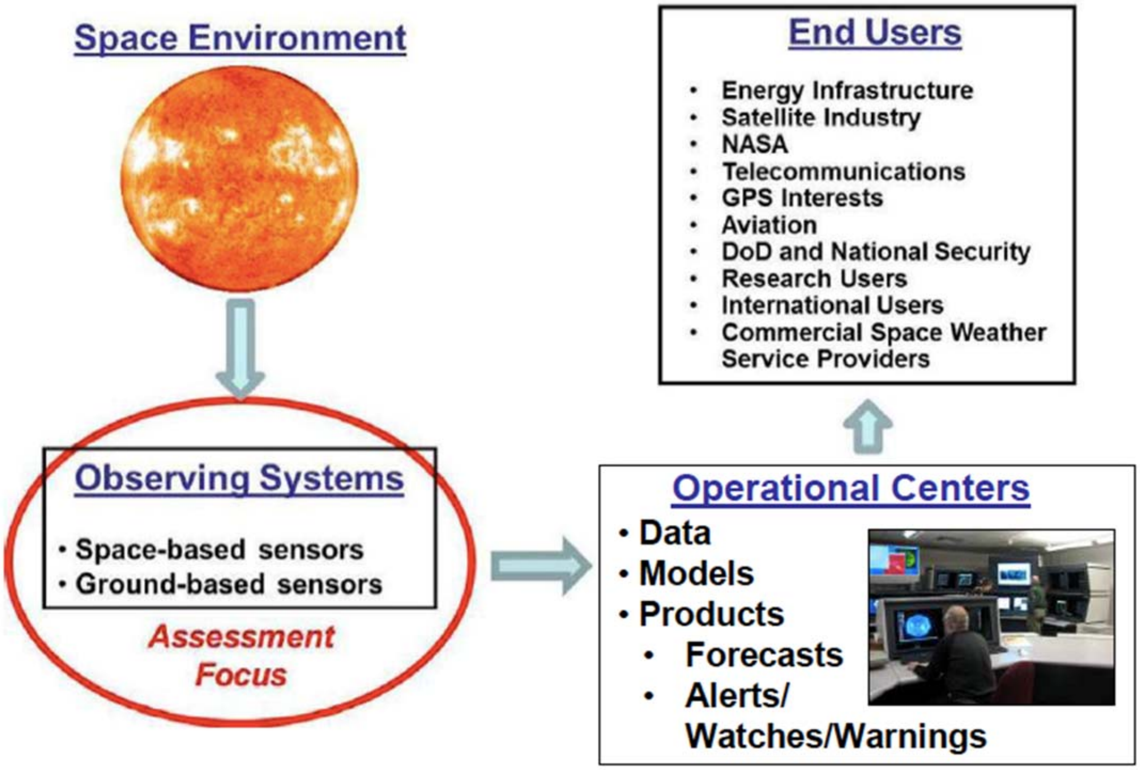


Figure 20. Space Weather Architecture. Source: White House Office of Science and Technology Policy (2013, 8).

1. Observation Systems

The United States and its allies attempt to fulfill the requirements outlined in Table 4 with both ground-based and space-based observing systems. The DOD, NASA, civil and foreign space sensors, and ground-based-sensors depicted in Figure 21 help form a comprehensive understanding of the space weather environment.

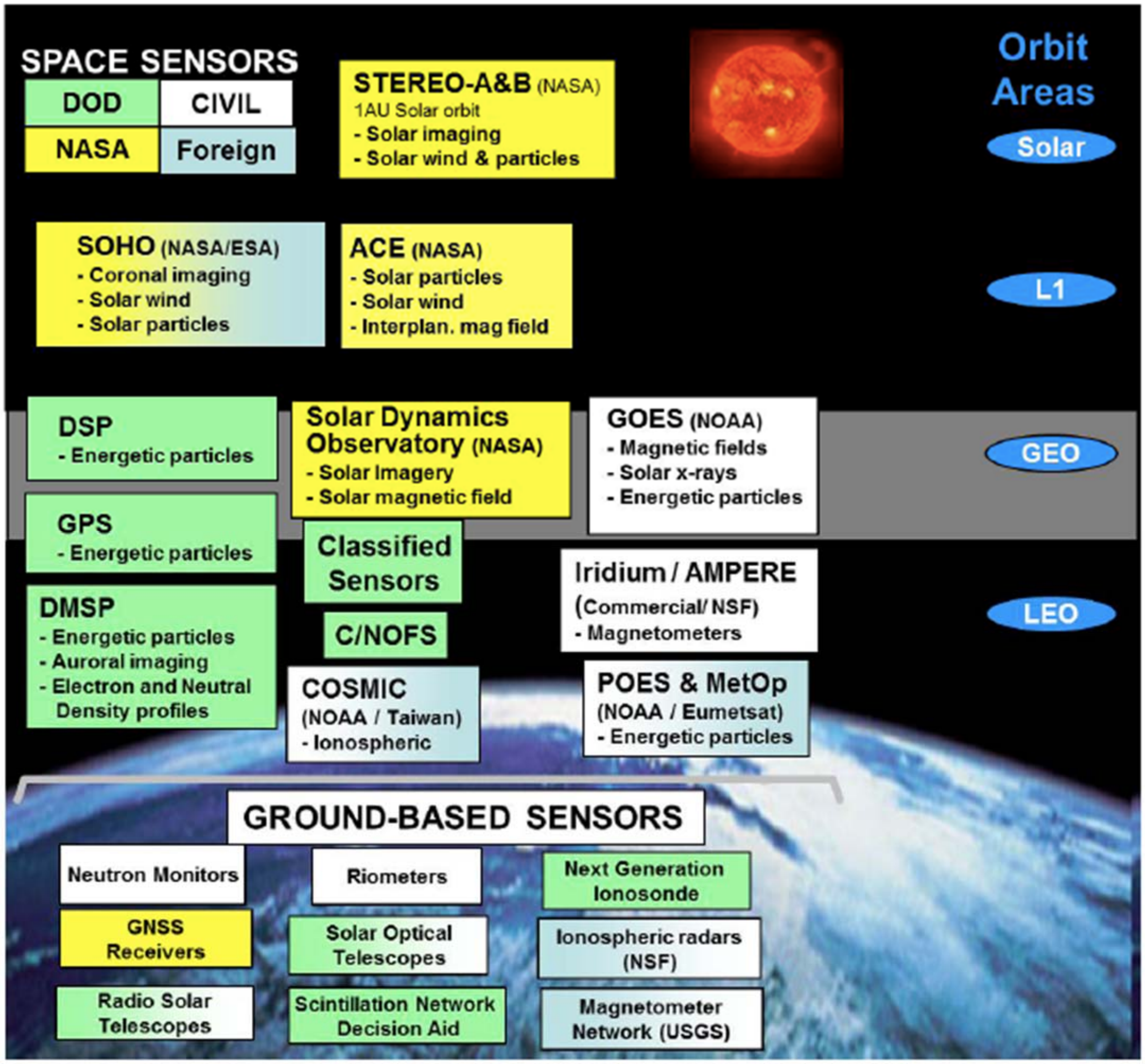


Figure 21. Space Weather Observing Systems. Source: White House Office of Science and Technology Policy (2013, 13).

a. *Ground-Based Sensors*

The ground-based collection of space weather sensors are mostly comprised of sensors intended to understand better ionosphere conditions and optical telescopes used to monitor the Sun’s activity. Ground-based sensors provide critical information to space weather operation centers, particularly information about the ionosphere, but ground-based sensors “sparse coverage limits their utility meeting operational requirements” (White House Office of Science and Technology Policy 2013, 30).

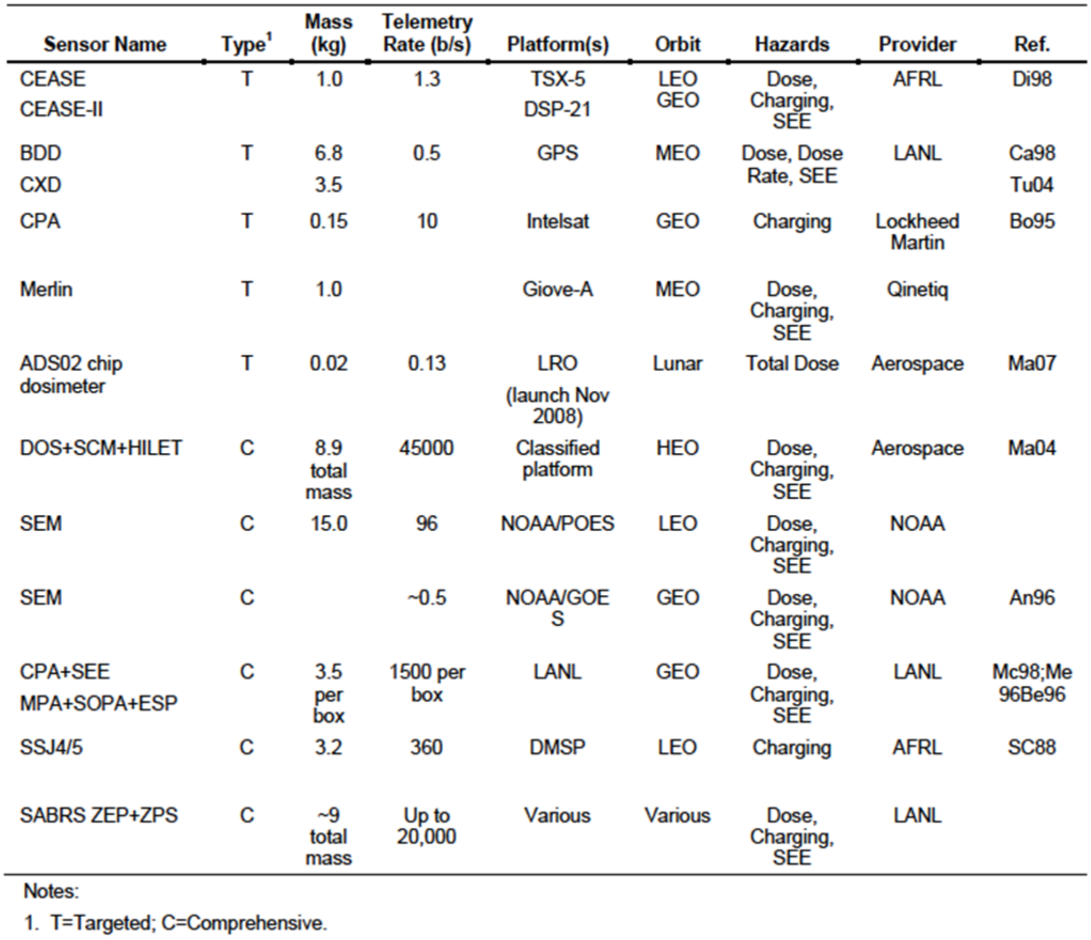
b. Space-Based Sensors

Space-based weather sensors can be divided and defined in two categories, comprehensive space weather sensors and targeted space weather sensors. From Aerospace Corporation technical report ATR-2008(8073)-5, both targeted sensors and comprehensive sensors are defined:

> (1) Targeted sensors that are capable of measuring the environment and effects at a level sufficient for providing situational awareness of specific effects for the host spacecraft; and (2) Comprehensive sensors that are capable of providing detailed environment measurements for a wide variety of effects and to map those measurements to a broad region of near-Earth space, providing global situational awareness and quantitative characterization of the environment climatology for the design of future space systems. (O’Brien et al. 2008, iii)

From that same report, Table 5 provides a list of comprehensive and targeted space weather sensors.

Table 5. Examples of Space Environment Sensors for Operational Vehicles. Source: O’Brien et al. (2008, 2).



Sensor Name	Type[1]	Mass (kg)	Telemetry Rate (b/s)	Platform(s)	Orbit	Hazards	Provider	Ref.
CEASE CEASE-II	T	1.0	1.3	TSX-5 DSP-21	LEO GEO	Dose, Charging, SEE	AFRL	Di98
BDD CXD	T	6.8 3.5	0.5	GPS	MEO	Dose, Dose Rate, SEE	LANL	Ca98 Tu04
CPA	T	0.15	10	Intelsat	GEO	Charging	Lockheed Martin	Bo95
Merlin	T	1.0		Giove-A	MEO	Dose, Charging, SEE	Qinetiq	
ADS02 chip dosimeter	T	0.02	0.13	LRO (launch Nov 2008)	Lunar	Total Dose	Aerospace	Ma07
DOS+SCM+HILET	C	8.9 total mass	45000	Classified platform	HEO	Dose, Charging, SEE	Aerospace	Ma04
SEM	C	15.0	96	NOAA/POES	LEO	Dose, Charging, SEE	NOAA	
SEM	C		~0.5	NOAA/GOES	GEO	Dose, Charging, SEE	NOAA	An96
CPA+SEE MPA+SOPA+ESP	C	3.5 per box	1500 per box	LANL	GEO	Dose, Charging, SEE	LANL	Mc98;Me96Be96
SSJ4/5	C	3.2	360	DMSP	LEO	Charging	AFRL	SC88
SABRS ZEP+ZPS	C	~9 total mass	Up to 20,000	Various	Various	Dose, Charging, SEE	LANL	

Notes:

1. T=Targeted; C=Comprehensive.

Comprehensive sensors, like those aboard the Defense Meteorological Satellite Program (DMSP), provide a broad understanding of the space weather environment. These sensors, typically aboard dedicated weather satellites, are used to help inform the stakeholders on general space weather conditions. Comprehensive sensors flown in multiple orbits not only help current operational users adjust their activities based on current and expected conditions but also help inform developers on how to build future space vehicles to be more resilient to their expected environments. These vehicles can provide a general understanding of space weather conditions, as well as a local understanding specific for that specific vehicle.

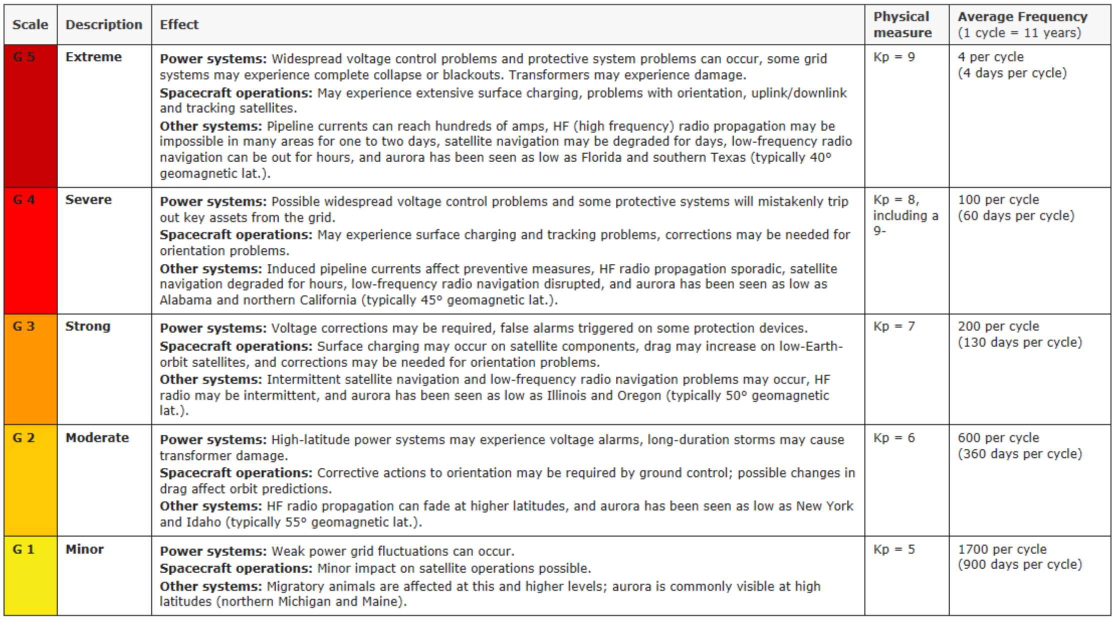
Targeted space weather sensors are used primarily to provide localized space weather situational awareness around the host vehicle. Targeted space weather sensors are important because like the weather on Earth, where the current weather conditions can vary significantly county by county, in the great vastness of space, current space weather conditions can vary dramatically from spacecraft to spacecraft. The combination of temporal variations created by the Earth's own magnetic field, spatial variations created by the influence of the Earth's rotation about the Sun allowing solar winds to manipulate the magnetosphere, and trapped energetic particles in the Van Allen radiation belts, create a dynamic space environment. If people wish to understand the current conditions surrounding a space vehicle at the local level, targeted space weather sensors that measure the current plasma and radiation environments are required.

2. Operation Centers

The DOD, NOAA, international partners, and some U.S. adversaries maintain space weather operation centers that consolidate information gathered by ground and space-based sensors to understand U.S. current space weather conditions, as well as attempt to forecast space weather events and issue alerts, watches, and warnings to stakeholders. For the DOD, the responsibility for monitoring and communicating current and expected space weather conditions falls to the 2nd Weather Squadron, under the 2nd Weather Group, part of the 557th Weather Wing stationed at Offutt Air Force Base, home of the U.S. Strategic Air Command. The Air Force maintains its own set of comprehensive space weather sensors, and some targeted, to provide national security stakeholders with relevant space weather data.

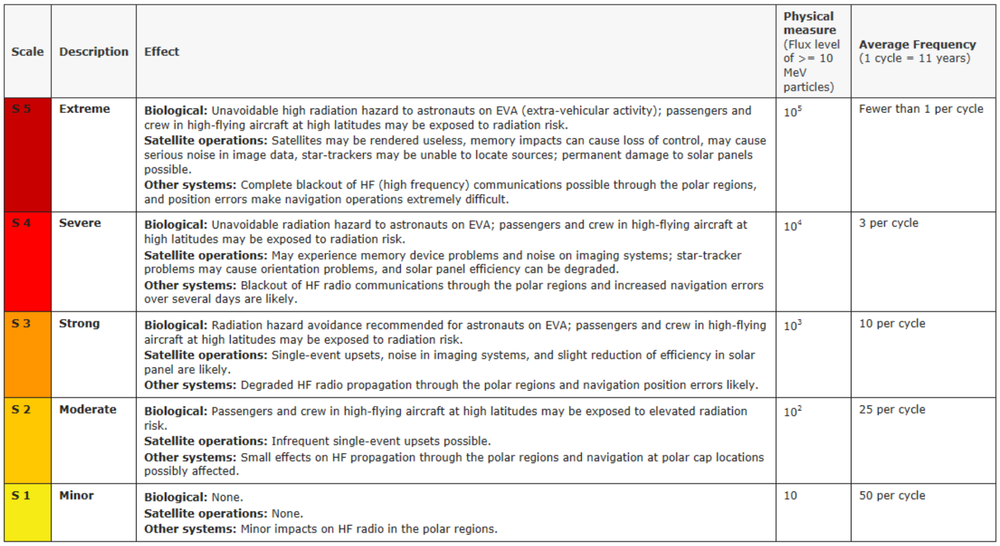
The Space Weather Prediction Center (SWPC), part of NOAA, located in Boulder, Colorado is the civilian hub for space weather data collection, product development, and information dissemination. The SWPC teams with the U.S. Air Force to provide current comprehensive space weather conditions and forecasts.

The most recognized space weather communication tool is the "NOAA Space Weather Scales, designed in 1999, which list three types of storms on Earth as measured by three physical parameters of solar activity" (Poppe and Jorden 2006, 122). These scales are presented in Figure 22, Figure 23, and Figure 24. The three types of storms monitored by NOAA are geomagnetic storms, solar radiation storms, and radio blackout storms. Geomagnetic storms are the disruptions of the Earth's magnetosphere, disturbed by solar activity that can lead to both increased radiation and plasma effects on spacecraft. A "k-value" has been established to provide a physical measurement value to the significance of these expected magneticspheric impacts. Solar radiation storms are a result of increased solar activity that disturbs the nominal radiation environment and can increase the potential for spacecraft impacts by increased radiation effects. This parameter is measured simply by radiation flux. Finally, the possibility of radio blackouts is reported by the SWPC with parameters ranging from "M1 to X20." These forecasted potential blackouts can range from intermittent communications to several hours of complete blackouts. The Air Force typically supplies users a simple red, yellow, or green scale for radio blackout impacts, solar radiation storm impacts, and geomagnetic storm impacts. These crude scales give space vehicle anomaly team directors a "quick look" opportunity to see if space weather is a contributing factor to their current problem.



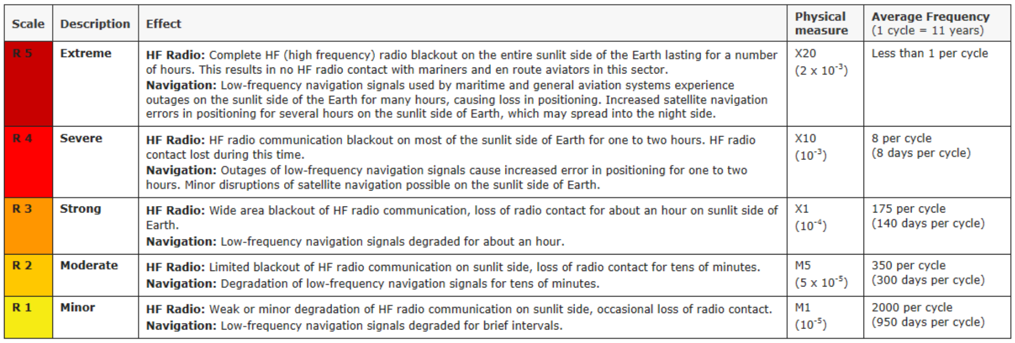
Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Figure 22. Geomagnetic Storms. Source:
Space Weather Prediction Center (2015).



Scale	Description	Effect	**Physical measure** (Flux level of >= 10 MeV particles)	**Average Frequency** (1 cycle = 11 years)
S 5	**Extreme**	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	**Severe**	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	**Strong**	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

Figure 23. Solar Radiation Storms. Source: Space Weather Prediction Center (2015).



Scale	Description	Effect	Physical measure	**Average Frequency** (1 cycle = 11 years)
R 5	**Extreme**	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Figure 24. Radio Blackouts. Source: Space Weather Prediction Center (2015).

D. CHAPTER SUMMARY

The systems currently deployed to monitor the space weather environment are primarily comprehensive in their approach. This data is critical for the stakeholders defined previously; however, for national security space systems, this comprehensive approach does not provide targeted space environment situational awareness. Inexpensive low-impact space environment sensors, currently available from industry could be integrated into all national security spacecraft today to provide local and targeted space weather data for each satellite.

V. ASSESSMENT OF INEXPENSIVE LOW-IMPACT TARGETED SPACE WEATHER SENSORS

Previous chapters have introduced the types of satellites deployed by the U.S. national security organizations, the spacecraft subsystems, the space environment, and the potential negative effects this environment can have on these systems. The current space weather monitoring system is comprehensive in its approach, providing a general temporal understanding of the current space weather conditions. This approach is not sufficient to meet the current and emerging needs of national security spacecraft. This chapter defines low-impact space weather sensors, acknowledges their inexpensive availability in industry today for both the plasma (spacecraft charging) and radiation environments, and their benefits to both the individual spacecraft and the enterprise at large.

A. REQUIREMENTS TO BE LOW IMPACT

A low-impact sensor should use minimal space vehicle resources and is easily integrated into the space vehicle with minimal impact to the system's cost, schedule, and performance. A size, weight, and power "SWAP" analysis is one of the techniques often used during spacecraft design to understand the impacts of changes to the rest of the system. Each of these qualities is particularly important to understand fully during spacecraft design, as each of these resources is highly constrained on satellites. For comparison, large electro-optical telescope systems have significantly different constraints, depending on if they are earth-based or on-orbit observatories. For example, the Hubble space telescope orbiting about 550 kilometers above the Earth, and the Hiltner telescope at the MDM Observatory outside Tucson Arizona, both have 2.4-meter primary mirrors. From a size comparison, they both have the same diameter mirrors; however, their weight differs significantly. The Hubble's primary mirror weighs 828 kilograms (NASA 2008) compared to the Hiltner's 2,000 kilograms (Thorstensen and Halpren 2016). Additionally, while power management on the Hubble was carefully designed to meet but not exceed system requirements to save battery weight, the Hiltner is simply supplied by commercial power. Much of the size and weight constraints for satellites are driven by the cost per pound for sending a satellite to its final orbit and the capabilities of the launch vehicles.

The Hubble was launched on the Space Transportation System, better known as the Space Shuttle. NASA has estimated the cost of a shuttle launch to average “out to be about $450 million per mission” (Morgan 2000). Independent estimates have declared that price to be much higher, but if NASA’s figure is used, then the Hubble weighing in at 11,110 kilograms costs about $40,500 per kilogram. At these costs, every gram counts. Therefore, a low impact space weather sensor must be very small and very lightweight.

Batteries, solar arrays, and power management systems are also very heavy. For this reason, low impact sensors must not consume much energy from the rest of the system. To justify incorporating low impact sensors, the sensors must be able to operate at the standard bus power supply levels to eliminate the need for additional power management, and battery and solar array sizing must not be impacted. In addition to SWAP concerns, the sensors must also be simply integrated into standard C&DH systems for minimal impact to the host vehicle. They must also remain stable at the temperatures expected on the host vehicle without the need for active or passive thermal management, again to reduce weight and cost. Finally, all these low impact requirements reduce system assembly, integration and test (AI&T) impacts. Their low impact nature is similar to the integration impacts of a common thermistor. Low impact sensors can be integrated off the critical path, while other integration activities are ongoing, and not impact the overall spacecraft delivery schedule.

These requirements keep costs low and ensure “doing-no-harm” to the space vehicle. This is key to justify the incorporation of low impact sensors on national security space systems. Today, existing technology meets these low impact requirements.

B. EXISTING TECHNOLOGIES

Two types of space environment sensors exist today that meet the aforementioned low-impact definition and are ready for integration onto today’s national security space systems. Small inexpensive spacecraft charging and radiation sensors integrated into the space vehicle can provide a targeted look at the conditions around the vehicle and monitor the effects the environment may have on the vehicle. Similar to spacecraft thermistors that are proliferated about many locations on typical spacecraft, these sensors operate on standard bus voltages, communicate with TT&C systems via standard simple interfaces, maintain a readied supply chain to not impact schedule, and have relatively insignificant cost compared to the host system.

1. Surface Charging Sensors

An example of a spacecraft-charging sensor flown operationally today is the Lockheed Martin built charge plate assembly (CPA). This instrument detects charging developing on surfaces, which can lead to differential voltage potentials, and possibly electrical arcing, causing damage. It has flown on many Lockheed built SES and INTELSAT space vehicles. These vehicles have electronic propulsion systems that may influence the plasma environment around the space vehicle (SV); thus, Lockheed developed integrated CPAs onto the system to study those potential effects. These CPAs “design included a 5 cm × 5 cm (2 in × 2 in) aluminum plate painted with Chemglaze Z306 dielectric paint bonded to the spacecraft with nonconductive CV2946 adhesive” (Likar 2009), as shown in Figure 25. These instruments were also, “configured to provide a 0 V to 5 V output compatible with typical spacecraft telemetry format” (Likar 2009), which allows for simple integration onto almost any spacecraft. The instrument weighs only 0.15 kg. The small exposed panel with minimal support electronics mounted just below the space vehicle structure’s surface could be mounted in multiple locations around the SV, as seen in Figure 26.

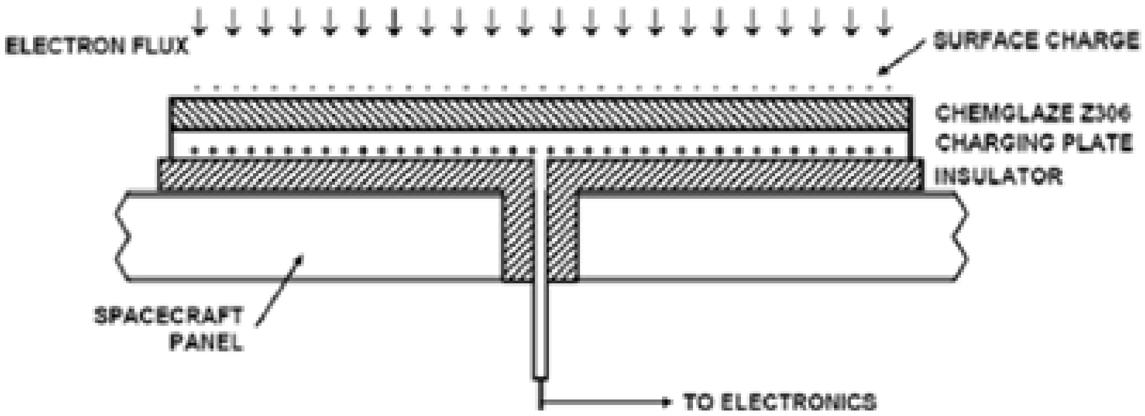


Figure 25. CPA Diagram. Source: Mazur et al. (2010).

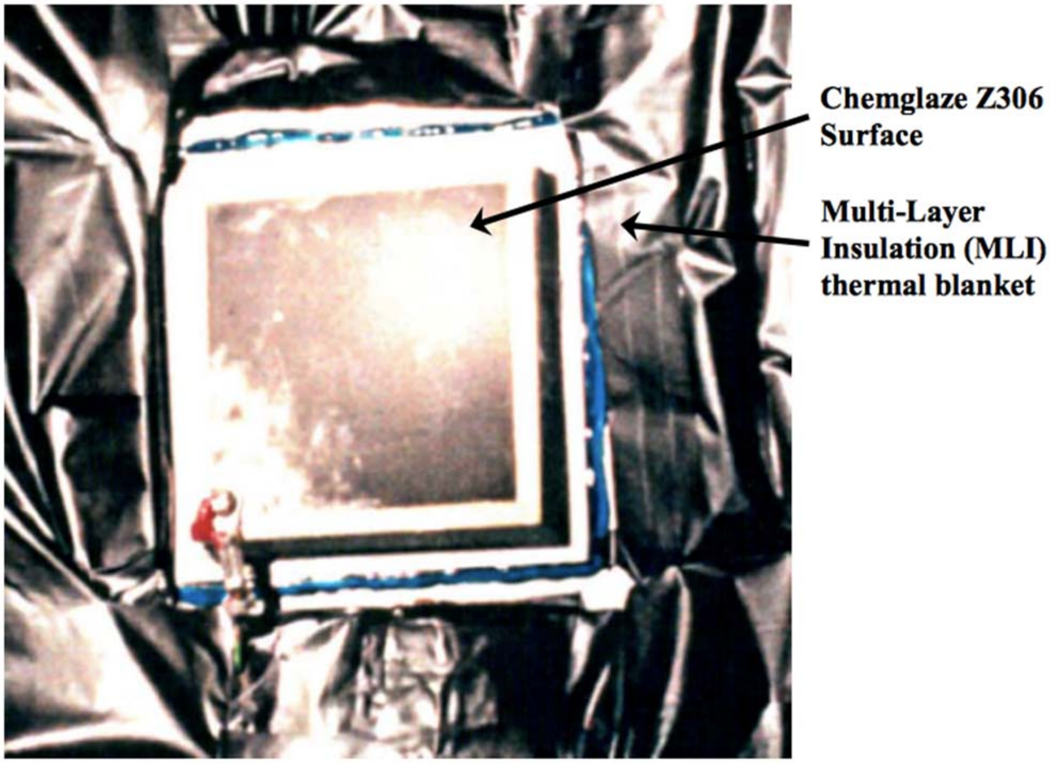


Figure 26. CPA Mounted to Spacecraft Panel. Source: Likar (2009).

The data collected from the CPAs on orbit today have shown that not only do spacecraft charging conditions vary significantly from spacecraft to spacecraft that are in relatively close proximity, but from one physical structure on the vehicle to the next. Due to data collected from this spacecraft, Lockheed concluded that the specific surface properties on U.S. national security satellites “are poorly known, making extrapolation of environmental data from scientific spacecraft difficult and somewhat uncertain” (Likar 2009). Large comprehensive environmental monitoring satellites fail to provide the needed targeted charging data that small low-impact sensors, like the CPA, could provide.

2. Radiation Sensors

As previously noted, “the radiation environment is among the more critical environments faced by a spacecraft” (Tribble 2003), and this environment also varies from spacecraft to spacecraft dependent on astronomical conditions and the vehicle’s position relative to the protective magnetosphere and trapped radiation belts. Like spacecraft charging sensors, small inexpensive and low-impact radiation sensors can be integrated into national security spacecraft to achieve the desired understanding of the local and temporal radiation environment and its potential effects to that specific spacecraft. A low impact radiation sensor must effectively observe the total dose and the conditions present for potential single event upsets, "the dominant radiation effects under space environment resulting in integrated circuit damage" (Daglis 2004). Today, commercial-off-the-shelf (COT) instruments exist that meet these requirements.

Dosimeters have been used for many years on the Earth's surface and in space to measure the radiation environment. These dosimeters, even for space applications, "required significant resources" (Mazur et al. 2010) needing significant power and weighed several kilograms. These do not meet the requirements of low-impact space environment sensors as defined earlier in this chapter. Recent advancements in manufacturing have led to the development of the micro dosimeter; "a compact hybrid microcircuit that directly measures TID absorbed by an internal silicon test mass" (Teledyne Microelectronic Technologies 2015). These devices weigh only 20 grams, have a standard 10V to 40V input and standard outputs, "intended to be directly connected to most analog-to-digital converters (ADCs) or spacecraft housekeeping analog inputs (0–5V range), which makes minimal demands on the host vehicle" (Teledyne Microelectronic Technologies 2015). With standard power requirements and costing approximately only hundreds to thousands of dollars for all sensors incorporated into a single spacecraft, similar to thermistors already prolifically integrated across all national security spacecraft today, these sensors meet the low-impact definition introduced in this paper. The size of the instrument can be seen in Figure 27 compared to a U.S. dime coin. As a result of the instrument's small size and low-impact requirements, it can be installed in multiple locations around spacecraft, and specifically, near radiation sensitive payloads and electronics.

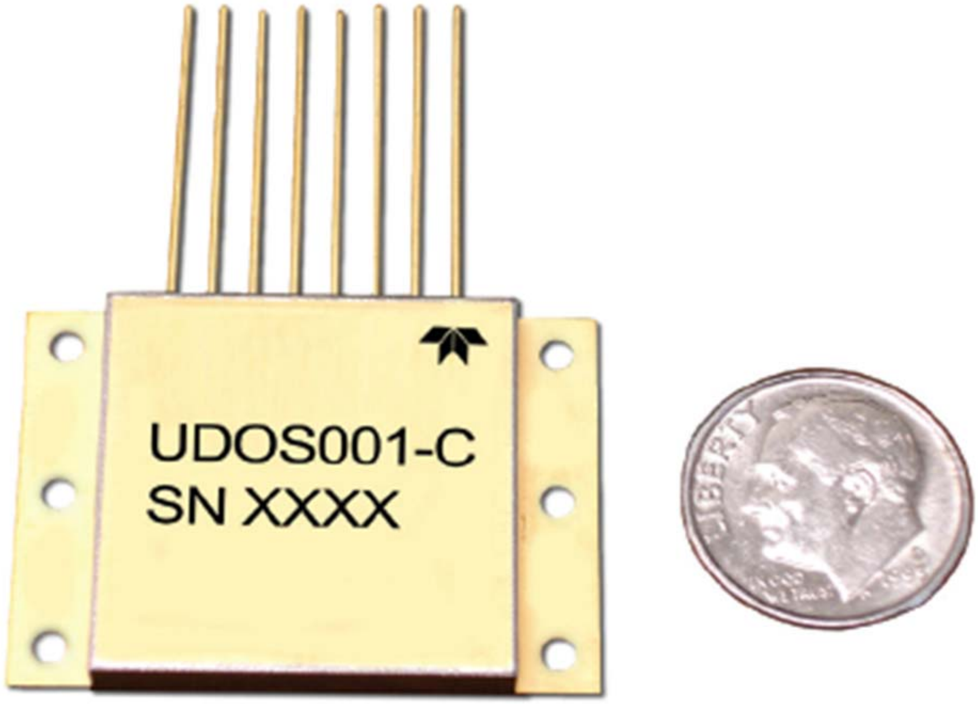


Figure 27. Teledyne Micro Dosimeter Size Comparison. Source: Teledyne Microelectronic Technologies (2015)

These low-impact space environment sensors would provide significantly greater targeted situational awareness of the space environment, as well as real time data for "alerts for hazardous conditions (radiation events), alarms for hostile action, anomaly diagnosis real time, [and] allow an operator to shutdown spacecraft until the condition passes" (Teledyne Microelectronic Technologies 2015). Integrating these sensors on national security satellites would provide great benefits to the acquirer and the warfighter.

C. BENEFITS OF TARGETED SENSORS

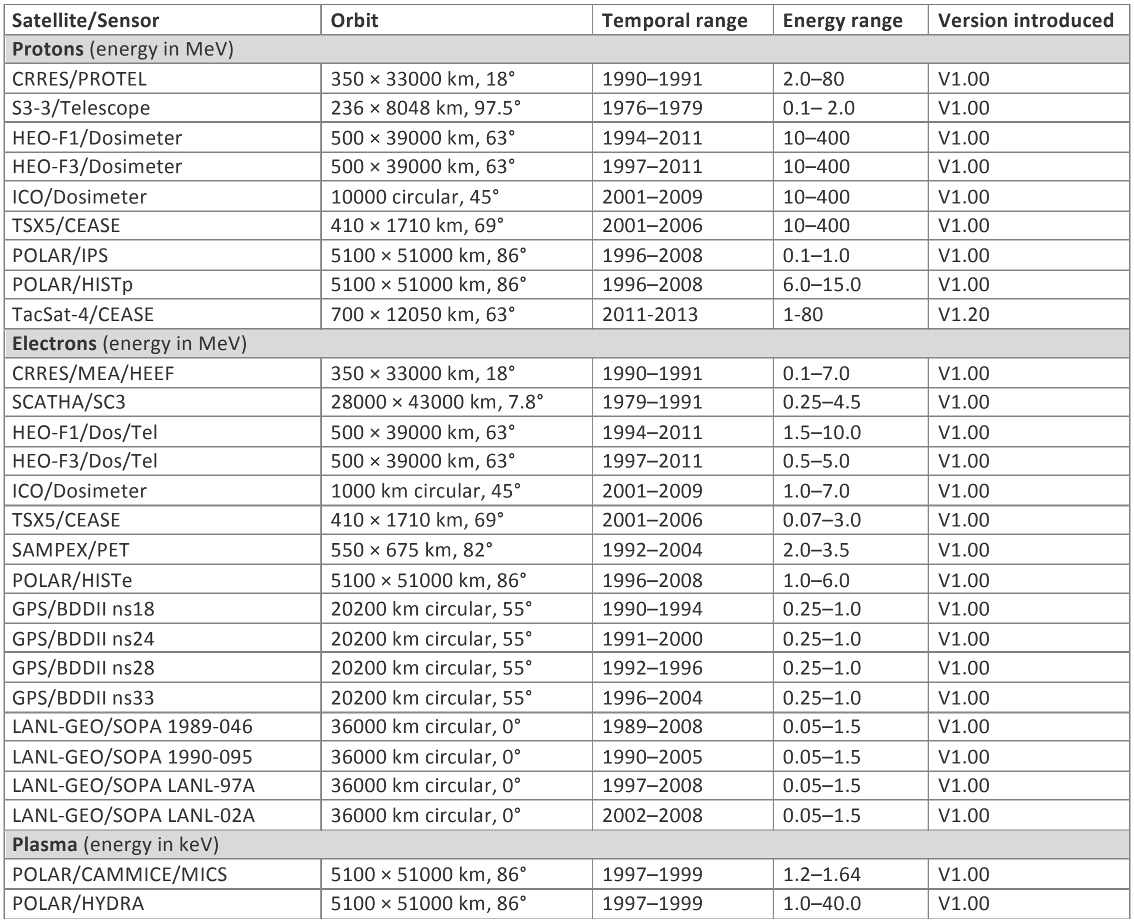
Today, with the systems previously discussed, the national space community has a good understanding of the comprehensive space weather environment; however, much like terrestrial weather, space weather can vary significantly from one location to the next around the Earth. In the same way, the morning weather forecast in Washington, DC may not be as useful to those in Los Angeles getting ready for work in the morning. Comprehensive space weather satellites may be able to give spacecraft controllers a general understanding of the physical conditions their satellites may have to operate through that day but are not able to provide data on the specific conditions around each individual spacecraft.

In the case where the forecast for solar radiation storms may be moderate, some satellites may still see an increased radiation environment while others may encounter a nominal environment depending on their orbit and current transition through that orbit. The magnetosphere and trapped radiation within the Van Allen belts are constantly stressed by the Sun's activity. Today, using only comprehensive sensors and space weather models without information from targeted space weather sensors, it is difficult to extrapolate the specific local weather conditions for individual spacecraft. As a result, targeted space weather sensors are vital, and have several associated benefits.

1. Lower Life cycle Costs

One associated benefit is lower overall life cycle costs. Space weather models are used to predict and forecast space weather events and impacts, and they are also used to influence the engineering of the space vehicle to ensure that vehicle can survive expected design life in predicted conditions. Today's standard model used to assist in spacecraft design is the AE9/AP9/SPM. The AE9 model's energetic electrons, the AP9 model's energetic protons, and SPM are the standard plasma model. These models, derived from the data of 37 space-based environment sensors, shown in Table 6, in multiple orbits, were "developed by a collaboration led by Air Force Research Laboratory (AFRL) and including Aerospace Corporation, Atmospheric and Environmental Research, Inc. (AER), Los Alamos National Laboratory (LANL), MIT Lincoln Laboratory (MIT-LL), and Boston College" (Visual Distributed Laboratory 2015). Unfortunately, "the space weather community has been held back from modeling the space environment, partly because of the shortage of observations and partly because the space environment is immense" (Poppe and Jorden 2006, 125).

Table 6. AE9/AP9/SPM: Data Sets.
Source: Visual Distributed Laboratory (2015, 7).



Satellite/Sensor	Orbit	Temporal range	Energy range	Version introduced
Protons (energy in MeV)				
CRRES/PROTEL	350 × 33000 km, 18°	1990–1991	2.0–80	V1.00
S3-3/Telescope	236 × 8048 km, 97.5°	1976–1979	0.1– 2.0	V1.00
HEO-F1/Dosimeter	500 × 39000 km, 63°	1994–2011	10–400	V1.00
HEO-F3/Dosimeter	500 × 39000 km, 63°	1997–2011	10–400	V1.00
ICO/Dosimeter	10000 circular, 45°	2001–2009	10–400	V1.00
TSX5/CEASE	410 × 1710 km, 69°	2001–2006	10–400	V1.00
POLAR/IPS	5100 × 51000 km, 86°	1996–2008	0.1–1.0	V1.00
POLAR/HISTp	5100 × 51000 km, 86°	1996–2008	6.0–15.0	V1.00
TacSat-4/CEASE	700 × 12050 km, 63°	2011-2013	1-80	V1.20
Electrons (energy in MeV)				
CRRES/MEA/HEEF	350 × 33000 km, 18°	1990–1991	0.1–7.0	V1.00
SCATHA/SC3	28000 × 43000 km, 7.8°	1979–1991	0.25–4.5	V1.00
HEO-F1/Dos/Tel	500 × 39000 km, 63°	1994–2011	1.5–10.0	V1.00
HEO-F3/Dos/Tel	500 × 39000 km, 63°	1997–2011	0.5–5.0	V1.00
ICO/Dosimeter	1000 km circular, 45°	2001–2009	1.0–7.0	V1.00
TSX5/CEASE	410 × 1710 km, 69°	2001–2006	0.07–3.0	V1.00
SAMPEX/PET	550 × 675 km, 82°	1992–2004	2.0–3.5	V1.00
POLAR/HISTe	5100 × 51000 km, 86°	1996–2008	1.0–6.0	V1.00
GPS/BDDII ns18	20200 km circular, 55°	1990–1994	0.25–1.0	V1.00
GPS/BDDII ns24	20200 km circular, 55°	1991–2000	0.25–1.0	V1.00
GPS/BDDII ns28	20200 km circular, 55°	1992–1996	0.25–1.0	V1.00
GPS/BDDII ns33	20200 km circular, 55°	1996–2004	0.25–1.0	V1.00
LANL-GEO/SOPA 1989-046	36000 km circular, 0°	1989–2008	0.05–1.5	V1.00
LANL-GEO/SOPA 1990-095	36000 km circular, 0°	1990–2005	0.05–1.5	V1.00
LANL-GEO/SOPA LANL-97A	36000 km circular, 0°	1997–2008	0.05–1.5	V1.00
LANL-GEO/SOPA LANL-02A	36000 km circular, 0°	2002–2008	0.05–1.5	V1.00
Plasma (energy in keV)				
POLAR/CAMMICE/MICS	5100 × 51000 km, 86°	1997–1999	1.2–1.64	V1.00
POLAR/HYDRA	5100 × 51000 km, 86°	1997–1999	1.0–40.0	V1.00

The models used today that inform design decisions are conservative because of the relatively few sensors contributing to model development. Conservative models translate directly to overly engineered and very expensive space vehicles. In today’s fiscally constrained environment, national security space systems cannot afford to be built with unnecessary margin. The model developers designed the AE9/AP/SPM models “to support periodic updates with new data sets” (Visual Distributed Laboratory 2015). Incorporating data from proliferated targeted sensors on national security spacecraft would contribute to more realistic models that help better inform future spacecraft design, close the design boundaries to more realistic margins, and could lead to lowering cost.

2. Improved Anomaly Resolution and System Resiliency

In the event of a spacecraft anomaly, operators monitoring the health and safety of the vehicle need to take steps if necessary to “safe” the vehicle. Most national security space vehicles have some form of fault protection to allow the vehicle, in an event of an anomaly, to safe itself; however, dependent on the hardware and software condition, it may require human input to ensure the continued mission capability of the vehicle.

Once initial steps have been taken, either by the space vehicle’s autonomous fault architecture or by commands sent by operators on the ground, and the vehicle is safe for an extended period of time, a “war room” is established to address the continued safety of the vehicle and return to nominal mission if possible. This anomaly resolution team consists of vehicle operators and vehicle engineers, usually comprising both government and contractor support. One of the earliest questions the team addresses, before capturing additional observables and establishing a path forward, is recording the current space weather environment conditions and the defensive counter space condition.

National security space system’s support organizations have access to DOD, NASA, civil and international space observation systems through DOD Space Operation Squadrons (SOPS) and National Reconnaissance Office Operations Squadrons (NOPS) using NOAA and DOD space weather centers. These centers keep the engineering teams supporting on orbit vehicles informed of the potential space weather threat condition.

The team assesses the “green, yellow, red—quick look.” If space weather is a potential contributing factor, the anomaly director may request additional information from the space weather squadron to help assist in anomaly resolution. If their anomalous space vehicle is not equipped with a targeted space weather sensor, the anomaly response team must make an assessment using comprehensive space weather data and models of the environment. This data may not contribute enough information to adjudicate definitively if space weather was an actual contributor to the anomaly. If the spacecraft was not traversing the SAA at the time of a single event upset or other anomalous event, then it is very unlikely that space environmental effects can be definitively attributed to be the source of the spacecraft anomaly. Even if the vehicle was traversing the SAA, the root cause, the analysis team may wrongly contribute space weather effects to be a contributing factor to the spacecraft anomaly. The space weather architecture, as it exists today, simply leaves too much ambiguity as to the current radiation and plasma environments around national security spacecraft to implicate or exonerate space weather and its effects definitively to a current spacecraft anomaly. Targeted space weather sensors installed on all national security spacecraft would help to reduce this ambiguity significantly.

The space domain is evolving into an increasingly contested environment. Kinetic and non-kinetic threats against U.S. national security space assets are advancing, and targeted space weather sensors can assist in quickly discriminating between space weather interference and nefarious activity from U.S. advisories. The anomaly response team, if their vehicle is equipped with a targeted sensor, could assess actual real-time telemetry from their vehicle at the time of the event and more definitively rule in or out the possibility of space weather interference.

The integration of targeted space weather sensors on national security satellites would increase the resiliency of U.S. space weather architecture to assure consistent access to space weather data. A disaggregated architecture of inexpensive but prolific space weather sensors would significantly reduce U.S. reliance on relatively few large and complex space weather satellites, where a single failure of one of these spacecraft would significantly reduce U.S. space weather situational awareness. This approach aligns with the strategic approach recommended by Air Force Space Command Commander, General William L. Shelton, in a statement to the Senate Armed Services Committee, where he advocated for a disaggregated architecture for strategic space systems as one potential approach to increase their resiliency. He argued, “disaggregated or dispersed constellations of satellites will yield greater survivability, robustness and resilience in light of environmental and adversarial threats” (United States Air Force Space Command 2013). The same concept is true for disaggregated and dispersed space weather sensors.

D. CHAPTER SUMMARY

Over the last several years, as U.S. dependence on space and the need for improved space environment situational awareness has increased correspondingly. While low impact space weather sensors exist today, their incorporation on to national security space systems is still presented with acquisition and integration challenges. Both of these challenges, if addressed smartly, can be overcome and are discussed in the next chapter.

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VI. INTEGRATING TARGETED SENSORS ON NATIONAL SECURITY SPACECRAFT

The previous chapter defined and introduced inexpensive and low-impact space weather sensors and their benefits if integrated into all national security spacecraft. This chapter discusses the acquisition challenges associated with this integration and the relatively simple technical hurdles that must be overcome. This chapter defines and addresses two problems. The problems relating to the lack of local space weather data for each individual spacecraft are presented followed by the negative impacts at the national system level. After defining the problems, the national security space stakeholders are defined and an approach to incorporating low-impact targeted sensors to meet these stakeholders' needs is discussed.

A. ACQUISITION CHALLENGES AND REQUIREMENTS

The benefits of incorporating low-impact space weather sensors on national security satellites solve multiple problems at two levels, at the national system level and at the individual spacecraft level. The entire national system acquisitions and operations community can benefit from fusing the data from the proliferated sensors to improve space weather models to help reduce design margin to the space weather environment, which ultimately reduces system cost. Additionally, the nation can benefit from a more resilient space weather architecture. At the individual spacecraft level, operators can benefit from faster anomaly resolution by exonerating space weather effects or nefarious activity, thus increasing spacecraft mission availability. Problems in general exist for "a need or a want of a solution that accomplishes something that cannot be done due to some objective reason(s), that is, availability, technology, science, opportunity, resources, or desire" (Langford 2012). Today, inexpensive low-impact space weather sensors are available, the technology exists, the science is proven, and an opportunity and desire exist to incorporate these sensors on all national security spacecraft. Aerospace Corporation acknowledges there "is a growing consensus in the satellite operations and acquisition community that new technologies, new orbits, and new threats will continue to expand the need for space environment sensors" (O'Brien et al. 2008, 7). The challenge then for acquiring and incorporating these sensors is recourses, perceived schedule, and cost impacts. If these perceived schedule and cost can be overcome, then both the national system level and the spacecraft level problems can be solved.

Resources are not allocated to solve these problems because a formal, written requirement does not exist for targeted space environment sensors to be incorporated on all national security space systems. The system program office (SPO) responsible for developing and deploying new spacecraft does not invest in integrating targeted space environment sensors into their systems without a requirement. SPOs receive their requirements through the joint capabilities integration and development system (JCIDS) process. Stakeholders use this process to flow their requirements to the Joint Requirements Oversight Council (JROC) and Chairman of the Joint Chiefs of Staff (CJCS), and are responsible for "identifying, assessing, validating, and prioritizing joint military capability requirements" (Goldfein 2015, A-1). This process is outlined in Figure 28.

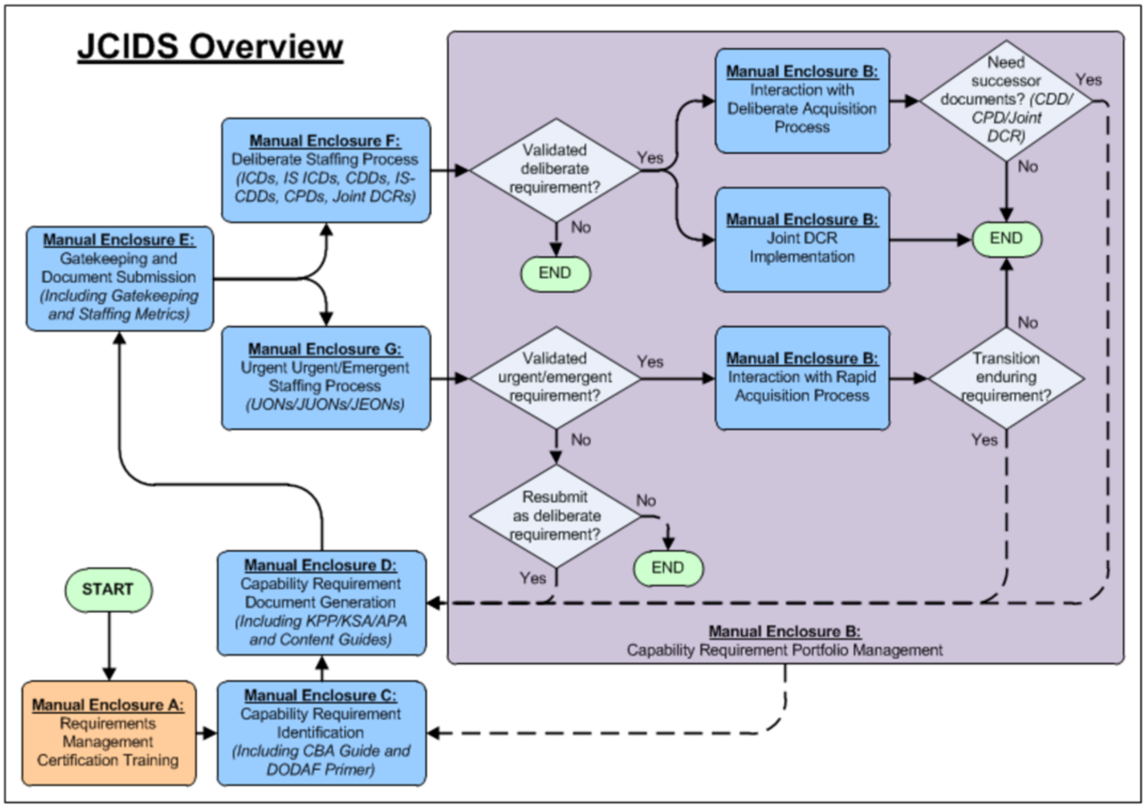

Figure 28. Overview of JCIDS Process and Manual Enclosures. Source: Goldfein (2015, A-2).

From this process, an initial capabilities document (ICD) is drafted, and when approved, the responsible acquisition office initiates the space acquisition process outlined in Figure 28. An ICD should tell the office what to accomplish through the requirements definition, not how to accomplish it, and then the SPO can decide through the acquisition process how to meet their requirements. Unfortunately, it is unlikely that a requirements document for any given system includes a requirement for targeted space environment monitoring unless that system's main mission payload is particularly sensitive to environmental effects. That system would then likely be designed to be protected from those effects and the program office may decide the integration of targeted sensors are a "nice to have" item rather than a requirement. Multiple stakeholders are not realizing the benefits of incorporating inexpensive low-impact targeted sensors because these resources are not being applied to solve the problems.

1. National Security Space Weather Stakeholder Definition

Today’s space weather architecture is inadequate to meet the national and spacecraft level problems identified. Part of the reason why resources have not been allocated to solve these problems is the national space community is large, and in many ways, organizationally fractured. Additionally, each stakeholder may perceive these problems and the benefits realized by solving these problems differently. A stakeholder is “one who has a stake in the outcome, is most typically an entity (a person either acting alone or representing an organization who can influence the conceptualization or funding of the development project” (Langford 2012, 259). Despite each of these stakeholders seeing the problem differently, the integration of inexpensive low-impact space environment sensors onto all national security satellites can help solve these problems both at the spacecraft level, and can also contribute at the national level. Table 7 provides a list of stakeholders and their definitions.

Table 7. Stakeholders Defined.

Stakeholders	**Definition**
On-console Operators	Team currently monitoring vehicle state of health and planning and executing scheduled maintenance.
On-call Support	Engineering team at the ready to support space vehicle anomalies.
Engineering Support Team	Technical support for on orbit vehicles that includes contractor, government, and federally funded research and development centers (FFRDC) support.
System Program Office	Acquisitions and engineering professionals responsible for procuring new satellite technology and ensuring the success of current on-orbit assets.
End User of Space Vehicle Data	The consumers of the service provided by the satellite system. Examples of end users are users of GPS receivers, satellite communications, and remote sensing product analysists.
NOAA Space Weather Prediction Center	The agency, part of NOAA’s National Weather Service, in Boulder Colorado responsible for monitoring space weather

Stakeholders	Definition
	activity through both ground and space-based sensors. The agency publishes current conditions, as well as future forecasts.
Air Force Weather Agency (AFWA)	Under the Air Force's 557th Weather Wing and responsible for coordinating with the NOAA SWPC and disseminating current space weather conditions and projections to operators of national security space satellites.
Government and University Modeling Centers	"Developmental test-beds, and prototyping/ transition centers [such as the] Community Coordinated Modeling Center, NSF Center for Integrated Space Weather Modeling and Naval Research Laboratories, Air Force Research Laboratory and SWPC" (White House Office of Science and Technology Policy 2013, 8) focused on improving current forecasting models to predict future space weather conditions.
Space Weather Researchers	Those individuals and teams dedicated to improving the scientific understanding of space weather and its interactions.

This set of stakeholders is a subset of the space weather stakeholders previously described in Chapter IV. These stakeholders are specific to the national security space enterprise and have specific needs that can be addressed by incorporating inexpensive low impact sensors on each national security satellite. An analysis of their needs is captured in the stakeholder analysis.

2. Stakeholder Analysis

These stakeholders perceive the problem differently relative to their relationship to the space system and the benefits they receive from the integration of targeted space weather sensors on national security satellites (Figure 29). For those closest to the spacecraft, the on-console operators, their perceived benefit is primarily realized at the space vehicle level from the real-time space environment data coming down in a stream of telemetry being monitored by those operators. For those furthest away from the spacecraft, space weather researchers, the benefits they receive are primarily from the combined data from proliferated sensors over many years. They benefit most from a resilient sensor system that gathers data from multiple orbital regimes over many solar cycles.

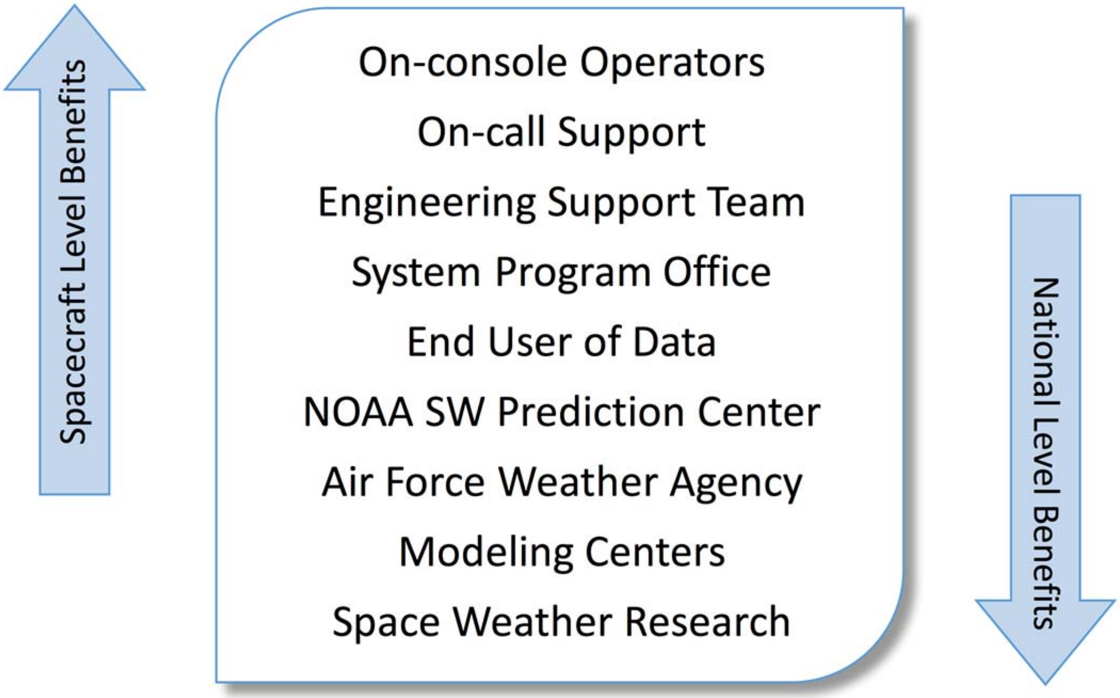

Figure 29. Stakeholder Benefit Relationship

On-console operators are typical of national security satellite systems, as it is preferred that any abnormalities in their performance be addressed as quickly as possible. The team monitors the telemetry displayed at workstations transmitted from the spacecraft to the ground element. This team is typically responsible for on-orbit scheduled maintenance, planned orbit adjust maneuvers, and are the first responders to work anomalies. Integrated space weather sensors on the vehicle would be used the same way as other sensors, such as temperature, voltage, and pressure sensors, to monitor the vehicle’s state of health. In the event of an anomaly, this team is primarily responsible for placing the vehicle into a safe mode of operation and calling in the on-call support team. The spacecraft and this team benefits most from targeted space weather sensors by giving the on-console operator the capability to monitor the spacecraft environment in real-time and prepare for potential hazardous environmental effects by turning off sensitive spacecraft electronics. This preventative, rather than reactionary, approach to operating in the hazardous space environment is significantly improved with the incorporation of targeted environment sensors. The space environment is vast and environmental conditions around specific satellites vary greatly. Relying on comprehensive sensors for proactive vehicle safety can be unreliable. At best, it can lead to situations where the spacecraft is taken out of service unnecessarily. At worst, it can lead to missed opportunities to put the vehicle in a safer configuration and result in damaged and degraded hardware and loss of on-orbit capability. On-console operators are not the only ones who benefit at the spacecraft level from having targeted sensors incorporated into the system.

On-call and engineering support teams are the next immediate users of localized space weather conditions. The targeted sensors can provide environment information to support anomaly root cause and corrective action. The on-call team is a smaller group of operators and engineers trained to ensure the safety of an on-orbit satellite and return that vehicle to normal operations. This team is available 24 hours a day, 7 days a week, and may also call in additional support from a larger engineering support team who are experts in the satellites multiple sub-systems. Local space weather data can help the teams quickly adjudicate if space weather was a potential contributing factor to the anomalous event by retrieving the space weather sensors telemetry at the time of the event with the ability to state definitively if space weather effects may have contributed to the current anomaly.

Local space weather data can assist project officers responsible for on-orbit vehicles, as well as developers of future spacecraft in the government system program offices. A better, more comprehensive understanding of the specific conditions the spacecraft are subjected to can help the team assess impacts to that system and others. Specifically, the program office must “address reach back (reactive), reach forward, (proactive), horizontal (across adjacent products and programs), and reach across (spanning various lines of business within an enterprise, or even across different companies and corporations within the industry)” (Hecht 2011, 9) to ensure the success of current and future national space systems. The program office, along with support from the engineering support team, determines if design modifications can be made to future systems, and if on-orbit operations can be modified to prevent the realized environmental impacts. The SPO starts to realize the benefits of targeted space weather sensors at both the vehicle level and the greater national system level.

The NOAA SWPC and AFWA can use localized space weather data from individual satellites and incorporate that data with the constellation of comprehensive space weather sensors to warn operators better of current space weather conditions, as well as improve their forecasts for future space weather activity. These stakeholders realize the benefits at the national level where the combined data from each spacecraft's targeted sensors help provide a more comprehensive and real-time understanding of the space weather environment to improve space weather forecasting. As a result, spacecraft operators, engineering teams, and the program office realize benefits to their specific spacecraft with the ability to safe the vehicle proactively from space weather effects, and prevent and recover from anomalies, which all contribute to improved mission availability. These stakeholders overlap in their combined benefits from integrated inexpensive low-impact space weather sensors.

One of the most compelling uses for the local space weather data is to help improve U.S. current space weather models. Government and university modeling centers, in collaboration with the SWPC and AFWA, could have access to significantly more data than just what the DOD, NASA, and foreign comprehensive space weather observing systems currently provide. Trending the data from local space weather sensors over time, in addition to the data collected by comprehensive sensors, could significantly improve U.S. ability to predict space weather and accurately forecast expected weather to the greater community. In addition, improved models can allow the development of spacecraft with less margin to realistic environment conditions that ultimately drive down cost.

B. LOW-RISK, NO-IMPACT SENSOR INTEGRATION

The systems engineering and sensor integration approach outlined in this paper would allow for the incorporation of targeted space weather sensors on all national security spacecraft with low, approaching no impact, to cost, schedule, and performance of the system, as well as a great benefit to both the system and the national security space enterprise. The primary intent is to "do-no-harm" to the host vehicle with negligible cost and schedule impacts and no mission performance impacts. This approach contributes to resolving one of the two significant challenges preventing targeted sensors from being incorporated onto all national security satellites; the perception of potential significant cost and schedule impacts to each individual program.

1. Functional Architecture

The architecture proposed to support the incorporation of targeted sensors on all national security spacecraft does not differ much from the architecture in place today that supports both nominal spacecraft command control and processing, as well as the consolidation of comprehensive space weather data. In support of defining the differences between the proposed architecture and the current architecture, a functional model for national security targeted space monitoring is captured in Figure 32. System "functionality is a set of functions that is required to produce a particular output" (Buede and Miller 2016, 205). The model begins with the function of "sense environment" with charged particles, within the plasma environment, and radiation flux as inputs to this function. The final output serves to overcome the two problems defined earlier in Chapter VI. Targeted data is displayed on the operator's user interface to support command and control decisions and anomaly resolution for individual spacecraft. The larger national level problem defined in this chapter is resolved with the function F.7 "perform data fusion for multiple spacecraft." The aggregated targeted data is combined with comprehensive data with the output being "fused data for AFWA and NOAA for situational awareness and forecasts." Stepping through this functional architecture and the specifics of the physical architecture in the next section proves little modification is required to today's space weather situational awareness architecture, Figure 20. The intent is to acknowledge the areas that require little to no changes and focus on the integration approaches where changes must be made.

In the IDEF0 model, Figure 30, each function of the system is identified within the box. For example, the first function, “F.1” is to sense the environment, and “F.2,” or the second function of the system, is to capture the sensor output. These functions have inputs that are identified coming into the left side of the box and outputs coming out of the right side of the box. In this model, the physical mechanisms that perform these functions are identified coming into the bottom of the box. No controls are identified in this model, as they are not unique to this system, and already accounted for in the current space weather architecture.

The unique function of this proposed architecture is found in F.1, Sense Environment. The addition of targeted space weather sensors on all national spacecraft is a new function supported by the radiation and spacecraft charging sensors identified in Chapter V. F.2 through F.6 are not unique to this proposed architecture. All spacecraft capture sensor output, transmit that sensor data to the ground where telemetry is processed, stored, and displayed for the operators. In this scenario, the targeted spacecraft weather data is just an additional telemetry point that can be passively or actively monitored by the operator in the same way a spacecraft’s multiple thermistors are monitored. F.7, perform data fusion for multiple spacecraft, is not unique. This function already exists in today’s space weather monitoring architecture, but it is important to acknowledge the physical modifications that need to be made to support addressing the national problem earlier identified.

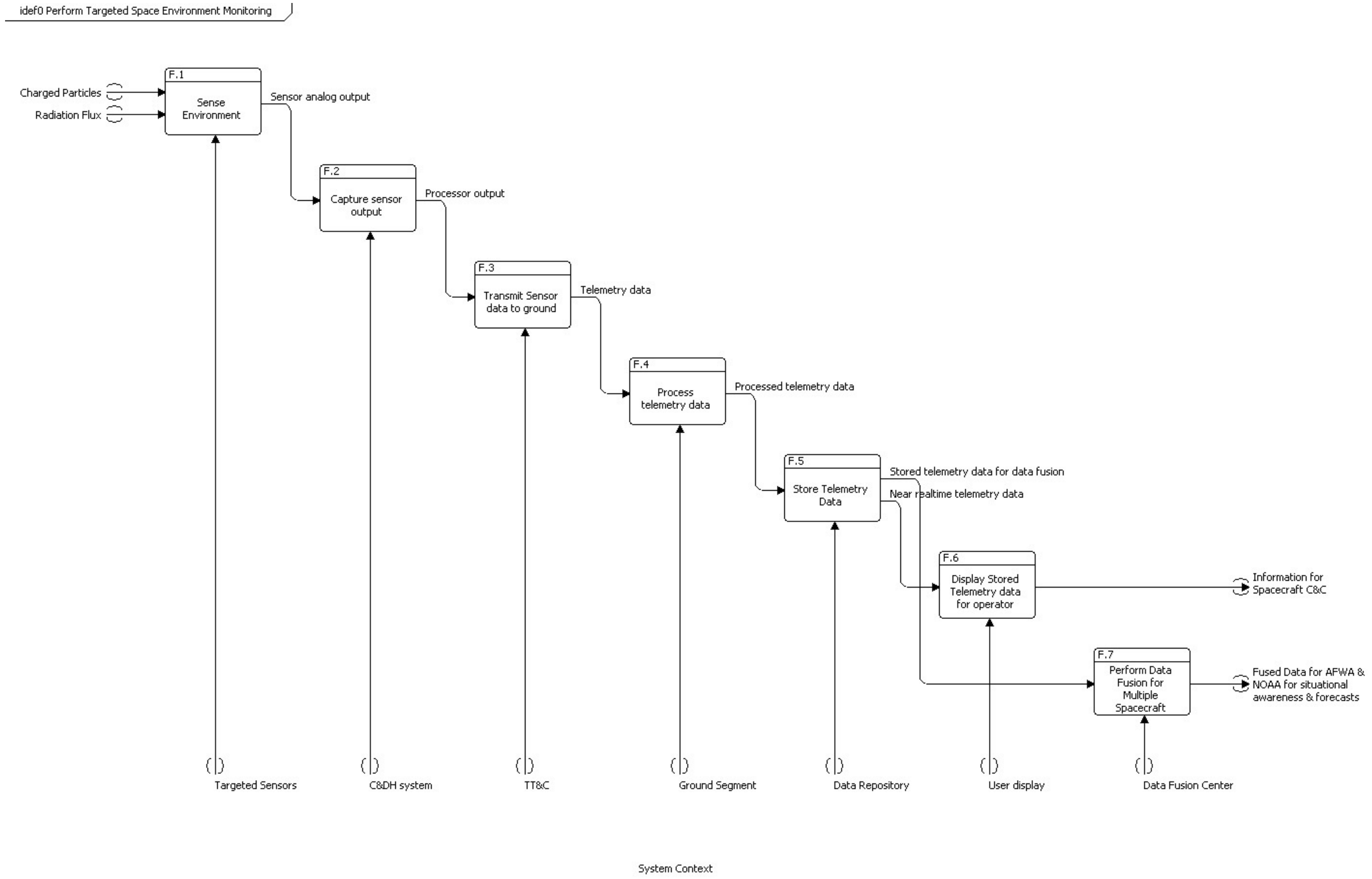

Figure 30. IDEF0 Model for Targeted Space Environment Monitoring.

2. Physical Architecture

The functional architecture proposed requires some modification to the physical architecture. In this model, “the physical architecture provides resources for every function identified in the functional architecture” (Buede and Miller 2016, 242). It was noted that relatively few modifications to the current satellite physical architecture are required to put the mechanisms in place to provide the desired effects at the spacecraft and national levels. The mechanisms that support F.2 (Capture sensor output) through F.7 (Perform data fusion) for multiple spacecraft are mostly in place today and require slight modifications.

The targeted sensors required to support F.1 (Sense Environment) are inexpensive and low impact to the spacecraft. They can be placed in multiple locations around the spacecraft. Their placement on multiple sides of the spacecraft structure will provide a general understanding of the radiation and plasma environments as the vehicle travels its orbit around the Earth. These sensors are small enough that they can be placed on or near critical spacecraft components, such as the payload or star trackers, or any component particularly sensitive to the spacecraft environment. The system designer should use these sensors in much the same way they already use thermistors to monitor the temperature of thermally sensitive components. These low-impact sensors, as defined in Chapter V, have a low power requirement, which does not impact the general sizing requirement of spacecraft batteries or modifications to the standard spacecraft bus power distribution unit. The micro dosimeter described in Chapter V can accept a wide range of standard voltage inputs from “13V to 40V” (Teledyne Microelectronic Technologies 2015, 1). Additionally, the micro dosimeter output is a “simple linear analog output [that] connect to standard spacecraft housekeeping systems” (Teledyne Microelectronic Technologies 2015, 1). For these reasons, simple physical modifications must be considered when incorporating targeted sensors. Power and data wiring harnesses must be installed to support the additional sensors, which is a relatively very low impact modification. The wires must be integrated in the standard power supply distribution units and the sensor output integrated into the standard spacecraft data bus.

To perform functions F.2 (Capture sensor output) through F.5 (Store telemetry data) requires no modification with this proposed architecture. The standard C&DH, TT&C, Ground Segment and Data Repository mechanisms are already in place for all current and proposed national security satellites, and the targeted sensor telemetry can be incorporated with the rest of the vehicle's telemetry with no modification. The mechanism that supports F.6 (Display stored telemetry data for operator) may require slight modification. The graphical user interface (GUI) would require software changes to display this specific telemetry that would not otherwise be displayed. This data would likely be monitored in the background on a GUI display accessible by the user but not found on the primary display where other more mission critical data is actively monitored. The software may also be designed to have certain limits put in place, where if the environment exceeds certain levels, a warning or alarm may be displayed if conditions for the space vehicle are approaching unsafe levels. This configuration is typical for standard spacecraft monitoring, allowing operators to focus on mission needs but respond to possible anomalies quickly. These low-impact modifications to the mechanisms of the spacecraft and the user interface are all that is required to satisfy the first spacecraft level problem, and achieve targeted spacecraft weather data to assist in anomaly resolution, threat determination, and proactively protect the spacecraft from local environment effects. Additional, relatively minor modifications must be made to the mechanism supporting the F.7 function (perform data fusion for multiple spacecraft).

Data fusion centers, the mechanism that supports F.7 for comprehensive space weather data, already exist at the AFWA and NOAA. The challenge would be scaling up the components required to transfer the individual spacecraft telemetry to the fusion center and sizing the components at the fusion center to process the additional data. Scaling up the processing capability at the fusion center is not a challenging problem; however, a small investment in the computing infrastructure and software is likely required to incorporate the increased amount of space weather data. Some consideration may need to be made for national technical means (NTM) satellites operated by the NRO and other national security satellites operated by the United States where the specific orbit of the spacecraft may be classified or otherwise sensitive. The orbits of these NTM satellites is classified and transmitting their real-time location and space environment conditions to a non-classified system, operated by NOAA, would be prohibited. The Joint Interagency Combined Space Operations Center (JICSpOC) or other data consolidation centers where NTM data can be processed and stored could report their fused data with general observations, in much the same way that comprehensive sensors do today, without having to compromise specific NTM operating orbits. In this way, the NTM could still contribute to the real-time understanding of the space environment. Additionally, they could provide specific data to the government space weather modeling teams to improve spacecraft models to realize the benefits outlined in Chapter V. With these modifications to the physical architecture in space and ground elements, the national level problems defined previously could be solved.

3. Recommendations for Integration

To meet the very low cost and "do-no-harm" requirement, it is recommended that the low impact targeted space environment sensors be designed into the system during the preliminary design phase, prior to the preliminary design review (PDR) and the milestone C decision (Figure 31). During this period, the technology development of the primary mission is still being finalized. The end of this phase is still considered a preliminary design, meaning changes are expected; however, if system designers plan to incorporate targeted sensors during this phase, the cost impacts can be minimal. Systems engineers can plan for the minimal SWAP impacts far ahead of the finalized design and the potential cost and schedule impacts of designing these sensors into the system is very low.

A low risk alternative would be to incorporate these sensors into the system design no later than the critical design review (CDR). At this point, the spacecraft integration process of procuring material and manipulating it for integrations has not yet begun. Plenty of time remains to procure and install the sensor hardware if the design properly incorporated the sensors and was approved at the CDR. These sensors do not have long procurement cycles, also known as long lead parts. If the interfaces are well defined and harness routing has been mapped, no additional costs should be incurred for the design except for the relatively insignificant cost of the sensor hardware. This pre-CDR approach is only less desirable than the pre-PDR because an additional unplanned, but still low, systems engineering cost impact to incorporate the sensors into the final design of the system is probably likely. Integrating sensors into the design during the build and operations phase would pose a higher cost risk for design modifications and potential negative work to readjust harnesses and install unplanned hardware. In addition, the integration of unplanned hardware post-CDR without a significant risk reduction activity could lead to unintended consequences that impact the primary mission and break the do-no-harm requirement. This scenario could be avoided with a risk reduction activity that evaluates all interfaces and potential system impacts, but which would drive up costs and break the low-cost requirement.

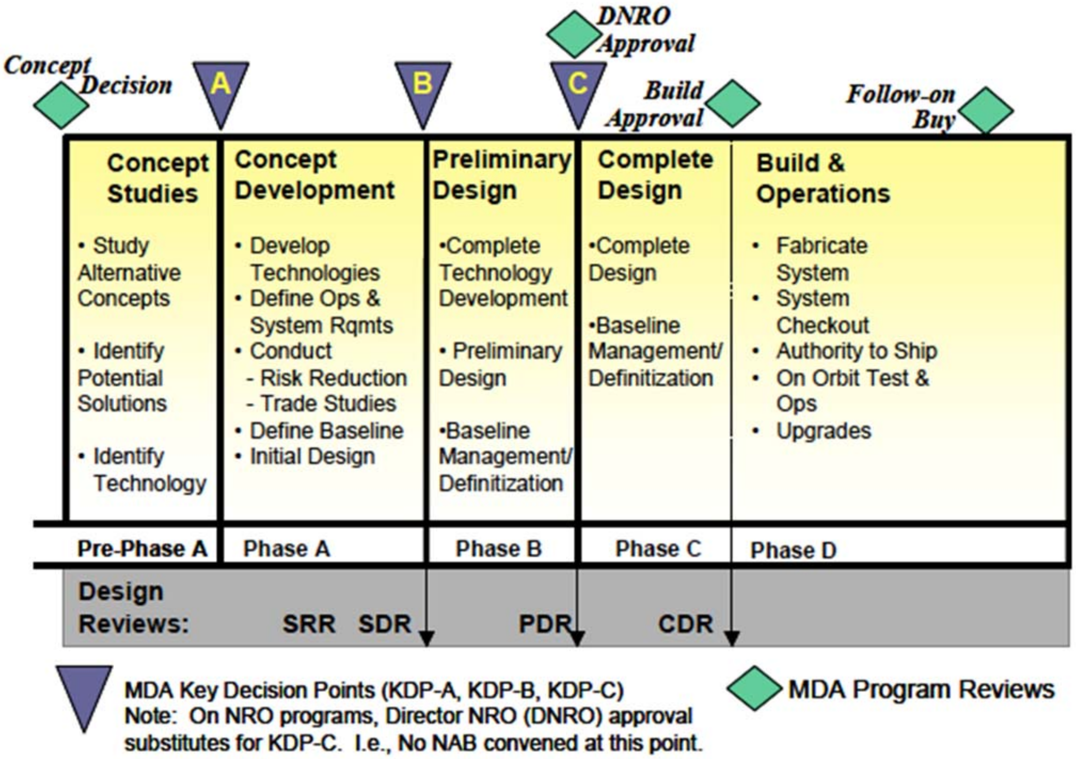

Figure 31. Space Acquisition Process Overview. Source: The Aerospace Corporation (2005, 20).

Physical build and integration of these sensors, and the required wiring and harnessing, is no more challenging than the incorporation of other low impact sensors on the spacecraft, such as thermistors. If the system interfaces with the spacecraft telemetry have been designed into the system prior to the CDR, then the sensors would be about as challenging to install as thermistors. Thermistors on most spacecraft are found in abundance across all payloads and subsystems; they track the temperature on multiple components, including but certainly not limited to batteries, actuators, and traveling wave tube amplifiers on communications systems. If these space environment sensors are designed into the system prior to the CDR, they should be no more complicated than other simple sensors used for telemetry on the vehicle.

4. Validation and Verification

To meet the stakeholder’s needs, several levels of verification are required at the unit, sub-system, and space vehicle level. Integration is “putting parts together in a particular order and fashion to demonstrate the requisite system functionalities” (Langford 2012, 269). Testing is an important component of integration that demonstrates the functionality of these sensors. The space environment sensors will be tested first at the unit level and can be tested at the space vehicle level as well.

To meet the low cost and do-no-harm requirements, the space environment sensors should first be verified at the unit level. Testing each individual unit is expensive, and “lot testing” is recommended for this type of sensor. Thus, one in every X sensors is tested to ensure mission reliability for the entire group of produced sensors. This quality assurance approach allows for continued inexpensive manufacturing of the sensors while still garnering insight into the reliability of each unit.

After these sensors are delivered and integrated into the spacecraft, the spacecraft typically undergoes several stages of testing. Initial functional and performance testing is completed at ambient temperatures and pressures to establish baseline values. At this stage, targeted space weather sensors could be tested with minimal impact to the entire test schedule. Both the spacecraft charging sensor and the micro dosimeter previously introduced have self-test capabilities to ensure functionality at the spacecraft level. For example, the micro dosimeter "incorporates a test function to allow electrical testing of the hybrid without the need for a radiation source" (Teledyne Microelectronic Technologies 2015). Exposing the spacecraft to a charged particle or radiation environment during testing can introduce a risk to both the spacecraft and those building the vehicle. A simple self-test is adequate to check the sensor's functionality although it does not provide performance data.

The performance of each sensor will be established once the spacecraft is launched and placed by the launch vehicle in its expected orbit. At this stage, the spacecraft operators will monitor spacecraft charging potential and radiation dose, and make appropriate preventive and reactive vehicle commands to prevent spacecraft damage just as they would with other spacecraft sensors.

C. OPPORTUNITIES FOR INTEGRATING TARGETED SENSORS ON THE SPACECRAFT

This chapter previously introduced a no/low risk approach to integrating space weather sensors onto national security spacecraft. The conservative approach is to design new spacecraft with the intention of integrating these sensors from the beginning. The sensors recommended in this paper have very low resource requirements, so an opportunity may arise to incorporate them after the initial design phase with some additional risk to the rest of the system. These risks are evaluated in this thesis as low and may be recommended for consideration from the spacecraft program offices.

The least risky approach for incorporating these sensors is to have the requirement clearly established prior to starting spacecraft design, milestone C, as depicted in the standard spacecraft development plan, Figure 30. If these sensors were incorporated early in the design, then the government and contractor team can ensure no harm is done to the rest of the vehicle, and the likelihood and consequence of negative impacts associated with sensor integration is very low.

a. Pre-Milestone C

The lowest risk approach for sensor integration is to incorporate these sensors during the concept development phase, phase A, of the space acquisition process, Figure

30. During this phase, the team is developing key technologies, defining operations and systems requirements, conducting risk reduction activities and trade studies, defining the baseline, and starting the initial design. The system requirements review and system design review during this phase helps set the baseline, but it is not uncommon to have requirements and designs change considerably during phase B prior to the preliminary design review/milestone C. Incorporating low-impact space weather sensors after milestone C is still low risk but would require more systems engineering effort to incorporate the sensor into the build.

b. Phase C

During phase C, the design is completed; engineering and requirements are locked-down and managed using a configuration control process. At this time, the program office would put the new requirement for space weather sensors through an engineering review board to assess impacts to the system and risk to the system and program execution. Both technical challenges and funding constraints are identified. Depending on the vehicle design, sensor integration risk could vary widely between national space systems. If the spacecraft ADCNS and TT&C systems are configured to allow for additional ingestion of unplanned sensor data, then the impact of adding additional space weather sensors may be a minimal impact.

c. Phase D

Integrating a space weather sensor in phase D is the highest risk for the program. At this stage of development, the design is complete, hardware is being built, and vehicle integration has begun. An opportunity may still exist to incorporate the new space weather sensors. The vehicle electronics must be able to accept telemetry from a new source without modification or a source of telemetry not associated with the vehicle’s fault architecture, such as a redundant thermistor, may need to be sacrificed. The space low-impact space weather sensors introduced in this thesis have the potential to be integrated in place of other spacecraft telemetry sources that use simple linear analog outputs with minor modification.

VII. CONCLUSION AND RECOMMENDATIONS

This paper covered the types of space vehicles currently deployed by the United States' national security space community. Then, the spacecraft subsystems were introduced as a foundation for understanding how space weather and its effects can impact individual systems. The space environment and its effects can be characterized in five domains: vacuum, neutral, plasma, radiation, and orbital debris. Two of these domains pose significant threats to national security spacecraft, the plasma, and radiation environments, and can be characterized and monitored near real-time by inexpensive and low-impact sensors incorporated into each national security satellite. These environments both threaten spacecraft with immediate impacts and delayed degraded effects.

The current comprehensive space weather architecture is inadequate to meet the emerging needs of national space systems. Only targeted space weather sensors can provide temporal and local space weather situational awareness for specific national security spacecraft that improves an operator's ability to respond to spacecraft anomalies and potential adversarial impacts. The amalgamation of the data from these targeted space weather sensors will also help to improve space weather models, improving the design of all future spacecraft helping to reduce engineering design margin, and drive down costs of future vehicles. Sensors proliferated among multiple spacecraft in varying orbits will also provide a resilient space weather architecture that is not reliant upon only a few very expensive monolithic comprehensive space weather satellites.

National security space stakeholders perceive their needs for space situational awareness differently. The stakeholders defined in Table 7 can perceive their needs independently and relative to their expected benefit. Space system operators are primarily concerned with spacecraft currently on orbit and would benefit from targeted space sensors incorporated onto those spacecraft to help resolve anomalies and differentiate between general space weather effects and adversarial threats. The community interested in space weather forecasting and space weather model development benefits from the combined data set provided by the proliferated space weather sensors on all national security satellites. These interests are common but the stakeholders are not unified in presenting a common argument to national security space leadership for incorporating inexpensive low-impact space weather sensors on all national security space satellites because of their perceived benefit is independent and their chain of command is disaggregated.

Although an established need for targeted space weather sensors on national security satellites exists, it is not a formal requirement for all systems. The lack of a formal requirement for national security space systems to host space weather sensors is the most significant obstacle that prevents the government SPO from integrating these sensors on their satellites. While program management offices may acknowledge many of the benefits of localized space weather, the lack of firm requirements typically leads to funding not being allocated specifically for this capability. This thesis recommends that leaders of national security space, at both Air Force Space Command and the NRO, mandate that all future national security spacecraft incorporate targeted space weather sensors for the purposes of characterizing the local environment. The targeted space weather sensor data would not only help in adjudicating possible threats for each individual spacecraft but also lead to a better understanding of orbital regimes that ultimately lead to better space weather models and lower spacecraft cost.

A. RESPONSE TO RESEARCH QUESTIONS

Responses to both the primary research questions and the secondary research questions are presented as follows. The benefits of integrating targeted space weather sensors on all national security spacecraft are the focus of the primary research questions, while the secondary research questions present a general understanding of space weather and its effects on national security spacecraft.

1. Primary Research Questions

The primary research questions of this thesis address the benefits of integrating targeted space weather sensors on all national security spacecraft. These benefits are realized immediately by the spacecraft operators, as well as by space weather forecasters and space weather model developers after the amalgamation of this space weather sensor data is compiled and analyzed over time. The primary research questions also address the technical and acquisition challenges of incorporating these sensors on all national security spacecraft, as well as how the community can overcome these challenges.

- What Are the Expected Benefits of Increased Space Weather Situational Awareness Local to the Spacecraft?

As discussed in Chapter V, the immediate and direct benefit of targeted space weather sensors is to assist operators with the rapid adjudication of on-orbit anomalies, reduce uncertainty, and allow corrective resources to be allocated appropriately to direct effects; be that space weather influenced or otherwise. Targeted space weather sensors would improve an operator's ability to respond to on-orbit anomalies with an increased awareness of temporal and local radiation and vehicle charging conditions to support the operator by potentially eliminating space weather effects as a contributing factor to the anomalous event. Additionally, while the space domain continues to develop increasingly into a contested environment where the potential for adversarial impacts to national security spacecraft are substantially increasing, an awareness of local spacecraft environments can help operators assess and respond to anomalous conditions.

In addition to the immediate improvement to anomaly resolution, the information provided by targeted space weather sensors can "directly provide data for new specification models, which, in turn reduce cost and risk on future missions" (Mazur et al. 2010, 17). This data can be used to increase the accuracy of space weather models used during the development of spacecraft systems. Ultimately, the amount of protection for spacecraft charging and single event upset designed into these systems could be reduced, allowing spacecraft designers to decrease the amount of component level and subsystem level testing. This decrease would directly contribute to reduced total system integration costs.

- If the National Space Community Desires Those Benefits, What Are the Dimensions of an Acquisitions Strategy, Both Programmatic and Technical, That Must be Addressed?

Covered in Chapter V, it is perceived that integration of these sensors would impact individual programs cost and schedule. For this reason, it is unlikely that any individual SPO would incorporate low impact space weather sensors on its vehicles unless a higher-level requirement was driven from the Space and Missile Systems Center of Air Force Space Command or from the leadership at the NRO. If the national security space community decided that the benefits of targeted space weather sensors were desirable, then a policy directive would be required for all spacecraft to incorporate these sensors, and it would be expected for each SPO to submit waivers required to justify their exclusion.

A comparable precedent for this kind of policy directive exists. In the mid-2000s, the DOD directed all national security spacecraft to incorporate GPS receivers to improve space situational awareness during launch and spacecraft operations. Program offices whose spacecraft did not have this capability incorporated into their baseline requirements had to request waivers to this requirement or make changes to the system that had cost or schedule impacts. Those systems early in their design life could incorporate those new GPS sensors with little to no impact to the programs cost or schedule. This approach is similar to that recommended by this thesis.

If the national security space community determines that the benefits of integrating targeted space weather sensors on all national security space systems outweighs the minor impacts, then the leadership within the DOD and intelligence community (IC) must direct those requirement updates in the same way they directed GPS receiver integration.

2. Secondary Research Questions

Answering these secondary research questions allows the reader to have a general understanding of space weather, its effects on national security spacecraft, and to appreciate how incorporating inexpensive low-cost space weather sensors on all national security space systems would benefit both the immediate operators of that system and the entire enterprise at large.

- What Is Space Weather and How Does It Affect Space Systems?

For near Earth operating satellites, where those supporting the national security space enterprise reside, the space environment is primarily impacted by the interaction between the Earth’s geomagnetic field and the Sun. Chapter III went into detail on where national security space systems operate and how the interaction between the Sun and the

Earth's magnetic field manipulates the space environment in those regions and how that environment can ultimately affect the spacecraft.

- What Are the Current Operational Space Weather Monitoring Capabilities?

Chapter IV discusses DOD and NOAA operational architectures of both on-orbit and ground-based space weather sensors and the space weather operation centers that consolidate gathered space weather information to provide an understanding of current space weather conditions, as well as attempt to forecast space weather events and issue alerts, watches, and warnings to stakeholders.

For the DOD, the responsibility for monitoring and communicating current and expected space weather conditions falls to the 2nd Weather Squadron, under the 2nd Weather Group, part of the 557th Weather Wing stationed at Offutt Air Force Base, the home of U.S. Strategic Air Command. The Air Force maintains its own set of comprehensive space weather sensors, and some targeted, to provide national security stakeholders with relevant space weather data.

The SWPC, part of NOAA under the DOC, based in Boulder, Colorado, is the civilian hub for space weather data collection, product development, and information dissemination. The SWPC teams with the U.S. Air Force to provide current comprehensive space weather conditions and forecasts.

- What Technology Exists Today or in the Near Future That Could Provide Real-time Local Space Environment Data for Individual Spacecraft?

Two types of low impact space environment sensors exist today that meet the low-impact definition presented in this thesis and are ready for integration onto today's national security space systems. Multiple vendors, with the support from DOD and the IC, can provide these sensors as COTS parts ready for immediate integration. This thesis discusses individual sensors that have been introduced to monitor both the plasma and spacecraft charging potential environment, and the radiation environments.

- How Can Localized Sensors Contribute to a Comprehensive Understanding of Space Weather Conditions and Forecasting?

Targeted space weather sensors primarily benefit localized space weather situational awareness around the host vehicle. They assist in space vehicle anomaly resolution and potential adjudication of adversarial threats. If all national security spacecraft incorporate these inexpensive and low-cost space weather sensors, the community has an opportunity to use this proliferated data set to improve space weather models, assisting both space weather forecasting and establishing engineering thresholds for spacecraft design. These incorporated sensors will allow for an unprecedented availability of observed space weather data from multiple orbits, considerably improving the understanding of space weather and actual space environment effects.

B. RECOMMENDATIONS AND FUTURE WORK

Space vehicle design, development, manufacturing, integration, and testing can take many years. It is recommended in this paper for the national security space enterprise to establish a requirement for all national security space systems to integrate inexpensive and low-impact space weather sensors. These sensors could significantly contribute to the health, safety, and operational availability of each individual satellite, as well as build a more comprehensive understanding of the space environment in all national security space areas of operation. Today, the national security space enterprise can no longer view space as an uncontested operational environment. The space environment is a relatively new domain of warfare that requires significant investment to ensure the United States maintains domain superiority in this region. The very low-impact sensors and low-risk integration plan supported in this thesis should allow the SPO to incorporate these sensors with little cost or schedule impact to current and future space vehicles.

It has become apparent through this research that national security space systems would benefit from an investment in commercially hosted sensors, as well as developing a standard interface on all national security space satellites for integration of secondary low-impact sensors. The same low-impact sensors introduced in this thesis could be integrated into commercial spacecraft that operate in similar orbital regimes as U.S. national security spacecraft. As discussed earlier, space weather and its environmental effects can be local and independent to each spacecraft; however, commercially hosted sensors may help bridge a gap between comprehensive sensors and targeted sensors. These sensors would contribute to aggregated targeted and comprehensive space weather data to improve space weather models, and ultimately, spacecraft design and space weather forecasting to assist in protecting current on-orbit systems. The Appendix provided in this thesis discusses the approach taken by the Iridium satellite commercial communications company that developed satellite systems where low-impact sensors could be incorporated with a simple SWAP analysis. U.S. national security spacecraft could benefit from implementing a common standard for low-impact auxiliary payload integration. This approach has the potential not only for building a more resilient and responsive space weather architecture but also can be utilized for multiple space missions, such as communications and remote sensing.

In addition to both nationally and commercially hosted sensors, the community may consider investing in space weather sensors hosted on small cube satellites, or “cube sats.” These satellites are very small compared to most national security satellites and have relatively little resource requirements compared to traditional spacecraft. These cube satellites can also be launched relatively cheaply, several at a time, along with a larger primary payload. Space weather sensors could be integrated into these small satellites and placed in proximity to national security satellites to provide the local targeted space weather data for those satellites currently in operations, as well as an alternative to integrating space weather sensors in national security satellites currently in development.

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APPENDIX. RESPONSIVE ENVIRONMENTAL ASSESSMENT COMMERCIALLY HOSTED DEMONSTRATION TALKING PAPER

This appendix discusses the approach taken by the Iridium satellite commercial communications company that developed satellite systems where low-impact sensors could be incorporated with a simple SWAP analysis (Space and Missile Systems Center 2014, 1–5).

Responsive Environmental Assessment Commercially Hosted
Talking Paper
19 February 2014

1.0 RESPONSIVE ENVIRONMENTAL ASSESSMENT COMMERCIALLY HOSTED (REACH) DEMONSTRATION TALKING PAPER

REACH is the first Low Earth Orbit Air Force hosted payload demonstration. It will provide extensive space radiation data for spacecraft anomaly resolution and the identification of innate versus hostile acts in a resilient and affordable manner.

REACH provides an unprecedented opportunity to demonstrate the ability to deploy responsive, affordable, and disaggregated space systems

- Data significantly enhances anomaly resolution for DoD & other Gov't/Civil agencies
- Six radiation sensing payloads
- Uses commercial hosting opportunity to significantly reduce cost
- 25 months from concept to launch
- Total demonstration cost of $7.336M

1.1 Program History

In August 2011, SMC/CC directed the newly formed SMC/XR Hosted Payload Office (HPO) to investigate payload options to leverage excess Size, Weight and Power (SWaP) of 50 Kg/50 Watts on the Iridium NEXT constellation, slated to launch from 2015-2017. After careful mission analysis, SMC/XR determined that the most prudent scenario was for Iridium NEXT to select a commercial customer and for the Government not to invest in the hosting opportunity. Subsequently, in June 2012, Iridium created Aireon, a subsidiary of Iridium Communications Inc., which will leverage the commercial communication system to provide a global pole-to-pole aircraft tracking and surveillance capability. The Automatic Dependent Surveillance-Broadcast (ADS-B) system, built by Harris Corporation, was the payload selected to utilize the 50Kg/50W of SWaP.

In the summer of 2012, Harris recognized that they would have 1Kg/1W of SWaP on ADS-B for a hosted-hosted payload. HPO performed an analysis of options and determined that there was a space environmental radiation monitoring sensor that could exploit the available SWaP. In late 2012 a preliminary feasibility assessment was conducted by Aerospace and Johns Hopkins University/Applied Physics Laboratory. Initial results concluded that an Aerospace designed REACH dosimeter pod could be integrated within the Harris ADS-B hosted payload as shown in Figure 1. In late 2013, SMC/CC directed HPO and the Operationally Responsive Space (ORS) office to pursue REACH as a demonstration of rapid, responsive, low-cost commercial hosting for disaggregated space architectures.

Figure 1. REACH is an affordable, responsive, and resilient hosted payload being fielded by SMC's Hosted Payload Office

1.2 Key Accomplishments

HPO conducted a preliminary design review (PDR) on 18 January 2013 and determined that the ADS-B could adequately host REACH. Subsequently, the REACH team successfully held a Critical Design Review (CDR) on 22 May 2013 during which it was determined that REACH satisfied the non-operational “Do No Harm” requirements established by Harris and Iridium.

After CDR, The Aerospace Corporation began fabricating and testing the initial lot of hardware deliverables for REACH. An extensive qualification test program included 3 axes random vibration to 46 Grms, shock testing up to 2,000 G’s, thermal cycling and thermal vacuum from -59C to +71C, and proton beam calibration at Lawrence Berkeley Lab. The first Government deliverables to Harris were a mass model for shock and vibe testing and an Engineering Development Unit (EDU) for initial compatibility testing with the ADS-B qualification unit. For the demonstration, a total of six flight units will be integrated and flown on six separate spacecraft in three distinct planes. HPO delivered the mass model on schedule to Harris on 9 October 2013 followed by EDU delivery on 20 November 2013. Final delivery of flight hardware was completed on 12 February 2014.

The REACH demonstration leverages a fleeting opportunity on Iridium NEXT using its commercial communication architecture to provide unprecedented coverage and refresh rate. A single dosimeter on a single vehicle over a one day period, as shown in Figure 2, provides a very limited amount of environmental characterization data, severely limiting a satellite operator’s ability to quickly resolve onboard anomalies. A fully deployed constellation of REACH pods on every Iridium NEXT satellite would provide global coverage in all six planes with a one second refresh rate. This capability used Technology Readiness Level (TRL) 9 components developed and tested by Aerospace in only one year. The first launch of REACH pods will occur on a Dnepr rocket in February 2015, illustrating the ability to field space systems in only 25 months from PDR to launch.

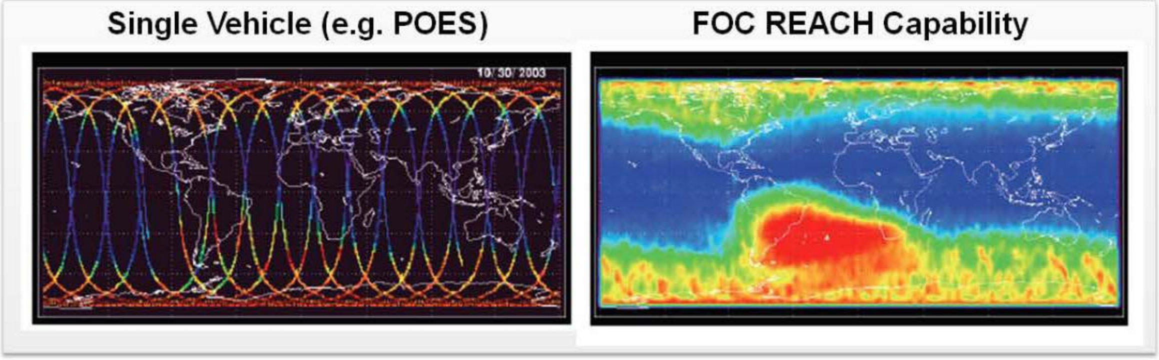

Figure 2. REACH provides significant improvement over existing capabilities for a fraction of the cost

1.3 Program Structure and Current Status

The project, originally known as the Hosted Environmental Assessment of LEO Radiation (HEALER) began as an SMC/WM funded risk reduction effort for future Weather System Follow-on (WSF) architectures to provide Space Based Environmental Monitoring (SBEM). As originally structured, the project would host a dosimeter pod on each of the 72 (66 + 6 on-orbit spares) Iridium NEXT spacecraft. The project transitioned to focus on demonstrating rapid, responsive, low cost capabilities. The REACH project is segmented into five distinct phases as described below and shown in Figure 3.

- ✓ Phase 1: HPO worked with JHU/APL and Harris through an existing SMC/XR contract vehicle, to execute a detailed feasibility study for hosting a micro-dosimeter payload on ADS-B. Completed on 18 January 2013.
- ✓ Phase 2: Matured a micro-dosimeter design to support ADS-B CDR in May 2013. Demonstrated that the REACH design satisfied ADS-B and Iridium NEXT non-operational "Do No Harm" requirements. Completed on 22 May 2013.
- Phase 3: Integrate six pods for launch. Complete remaining qualification testing and satisfy operational "Do No Harm" requirements and receive final hosting commitment. Supports the delivery of one mass model, one EDU and six flight units, constructed by Aerospace. Develop flight software and finalize ground architecture. ECD is September 2014.
- Phase 4: Finalize REACH demonstration hosting fees and on-orbit operations of 12 months. Procurement and integration of remaining hardware for full REACH constellation of 72 pods, if funded. ECD is dependent on funding.
- Phase 5: Launch and on-orbit ops for full constellation

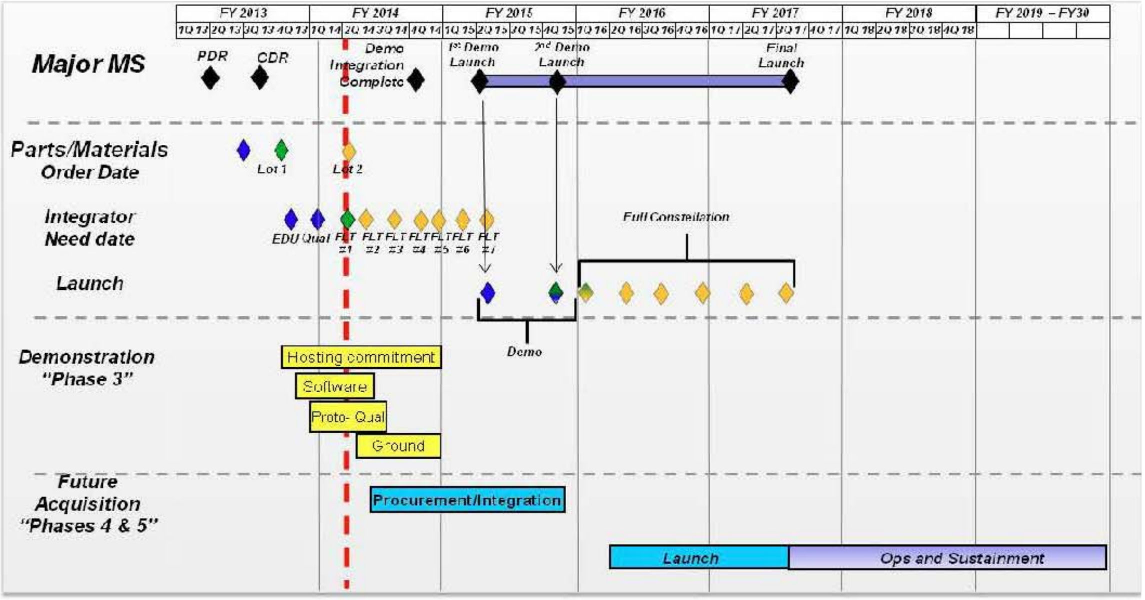

Figure 3. The REACH demonstration will launch only 25 months after PDR

Phase 3 is proceeding on schedule and will result in six REACH pods on-orbit.

With Phases 1 and 2 complete, the HPO is currently conducting an Engineering Change Proposal (ECP) for Phase 3 to incorporate the full scope of work required to satisfy the remaining operational “Do No Harm” requirements established by ADS-B and Iridium NEXT. The ECP includes acceptance testing, flight software development, and ground architecture design and development. Award of the Phase 3 ECP is expected in mid-March 2014. More than 90% of the funding required to field the REACH demonstration has been provided by various stakeholders as shown in Figure 4.

Currently, the REACH demonstration is limited to six on-orbit pods. However, as shown previously in Figure 2, the true value offered by REACH is realized through the fielding of a full constellation. The current demonstration made all non-recurring engineering (NRE) investments, making the incremental cost for a full 66 pod constellation relatively small.

The HPO estimates the incremental cost for each future pod is only $60K in direct labor materials and $60K in hosting fees. Although the demonstration is only planned for one year, the pods have a 15-year design life. A 15-year lifecycle for a constellation of 72 REACH pods, which is primarily comprised of O&M costs, is estimated at $30M above the demonstration cost. Fielding a comparable system as a standalone capability would cost well over $100M and take much longer to deploy.

1.4 Benefits of REACH Demonstration and Full Constellation

The US National Space Policy dated June 28, 2010 states, “The SecDef and the DNI shall… Improve, develop, and demonstrate, in cooperation with relevant departments and agencies and commercial and foreign entities, the ability to rapidly detect, warn, characterize, and attribute natural and man-made disturbances to space systems of U.S. interest”. REACH dosimeter data is key to distinguishing between hostile and natural disturbances quickly and accurately. Satellite operations are potentially impacted by space weather hazards such as Single Event Effects (SEE), radiation dose effects, and deep dielectric (“internal”) charging. With its global coverage and one second refresh rate, REACH would provide satellite operators the ability to rapidly distinguish between environmentally induced anomalies and hostile actions.

Phase	FY13	FY14	FY15	Total
Phase 1&2	**$3.000M**			**$3.000M**
Phase 3	**$1.010M**	**$2.726M**		**$3.736M**
Phase 4			**$.600M**	**$.600M**
Total	**$4.010M**	**$2.726M**	**$.600M**	**$7.336M**
Funded	**$4.010M**	**$2.726M**	**$0**	**$6.736M**
Shortfall	**$0**	**$0**	**$.600M**	**$.600M**

Figure 4. The REACH demonstration rapidly fields capability for only an additional $.600M

In addition to its application as an SBEM tool, REACH will provide numerous benefits to the space enterprise. In addition to the Air Force, NOAA, NRO, NASA and the National Science Foundation (NSF), have expressed a high interest in receiving the data. Additionally, completion of a responsive commercially hosted dosimeter demonstration will be a pathfinder for the new Hosted Payload Solutions (HoPS) IDIQ contract. It will be SMC's first hosted, disaggregated system architecture and the first Air Force commercially hosted LEO payload. The NRE completed as part of the REACH demonstration will serve as a prototype for commercial ground integration and data distribution. The data will provide operational value applicable across the entire space enterprise. Figure 5 provides a summary of how REACH aligns with US space policy and vision.

Defending on-orbit space systems from natural and hostile acts is critical to the US and its allies to ensure persistent access to key warfighting capabilities. REACH provides a unique, fleeting opportunity to deliver a low cost, significant capability to enable global access, persistence, and awareness.

Features of REACH	Alignment with Space Enterprise Goals
• Six pod demonstration with the ability to fly up to 72 pods in six different planes	• Resilient: The ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary actions.
• Less than 1 second refresh rate using existing commercial infrastructure and automated data analysis with existing statistical models	• Improves situational awareness • Move toward less complex, more affordable, more resilient systems and system architectures • Maximize inherent synergies found in common architectures and data standards • Automate systems and processes • Increase partnerships across the space enterprise
• Leverage existing commercial hosting opportunity with Iridium NEXT	• Reduces costs and schedule compared with fielding standalone solution • Increase partnerships across the space enterprise • Posture for use of commercial systems
• 25 Months from PDR to launch	• Responsive to requirements
• Demonstration cost of only $7.336M - $120K per pod for additional capability	• Affordable: The procurement of systems to meet sufficient mission requirements while considering both life-cycle costs and projected budgets.
• Uses TRL 9 components	• Move toward less complex, more affordable, more resilient systems and system architectures
• Data made available to all stakeholders including non-DoD agencies such as NASA and NOAA	• Increase partnerships across the space enterprise

Figure 5. REACH offers significant benefits to the Government in terms of cost and capability

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