SolarMax

Final Report

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SSP 2013
The SSP 2013 Program of the International Space University was held at the ISU Central Campus in Illkirch-Graffenstaden, France.

Cover Art: An arc-shaped solar flare erupting from the Sun; the Earth is visible between the arc and the Sun’s photosphere. At the top of the page, text reads “SOLARMAX A Space Weather Survival Guide.” Text in the lower left-hand corner reads “Final Report.” There is an ISU logo in the lower right-hand corner.

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The SolarMax team would like to acknowledge Johns Hopkins University Applied Physics Laboratory for supporting this project.

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In addition, SolarMax would like to acknowledge the help and support of Ruth McAvinia, Christopher Johnson, and Carol Carnett for their tireless work in editing our report.
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ABSTRACT

The Sun is the most important driver of life on Earth. It is also the most important factor in space weather phenomena throughout the Solar System. Sunspot number observations reveal an 11-year cycle of activity, caused by changes in the Sun’s magnetic field. During this cycle, the Sun goes from a relative quiet period, known as solar minimum, to a more active phase, known as solar maximum. Around solar maximum, events like solar flares and coronal mass ejections are more frequent than during the minimum.

Protected by the Earth’s magnetic field, space weather events are normally not harmful to life, however from time to time solar flares and coronal mass ejections can wreak havoc with modern human infrastructure, both in space and on the ground. Satellites, telecommunication systems, and electricity grids are most vulnerable, and their malfunctions can affect multiple other infrastructures. This poses a threat to society, against which we should protect ourselves.

This Team Project Report aims to provide a survey of the threat posed by solar weather, evaluate the potential risks to civilization, and finally suggest means of counteracting these hazards. We will show that a great many technologies and techniques for risk mitigation to protect our terrestrial and space-based infrastructure already exist or are currently in development, but that the greatest obstacle to implementing them is that there is a lack of knowledge of the risks of space weather outside of the scientific community. Towards this end, we will propose a number of public relations campaigns targeting various sectors, including government, military, business and the general public.
FACULTY PREFACE

A core component of the International Space University Space Studies Program each year is a team project, tackling a topical issue under the tutelage of space experts from across the world. One of the three team projects at SSP 2013 was entitled Spacecraft protection and solar maximum, abbreviated to SolarMax.

The Sun was worshipped in primeval times as the source of all power on Earth. We have only recently started to understand how thoroughly it influences life, from local weather systems and climate change to geomagnetic storms and radiation flux. Given the sudden and global adoption of electronics, from mobile phones and satellites to long distance power transmission and car fuel management systems, and the susceptibility of these systems to errant solar weather events, we are more dependent than ever on our Sun’s stability. Recent data has suggested that perhaps that dependence is a risk we cannot justify.

In only nine weeks, the 36 participants from vastly different cultural and disciplinary backgrounds melded into a united team, formulated a strong management structure, studied ground-breaking heliophysics with world experts, identified gaps in our knowledge of the Sun-Earth relationship and suggested a number of measures to mitigate the damaging effects of solar weather.

Along the way they also had a great time. Dubbed TP SocialMax by the other teams, SolarMax formed lasting friendships while producing a very polished, comprehensive product, as summarized in this report, the accompanying executive summary and the formal presentation at the end of the program.

It has been an honor to observe and coach this group of tireless, talented and dedicated people.

S. Pete Worden, Chair

Rogan Shimmin, Emerging Chair

Dave Haslam, Teaching Associate
TEAM PREFACE

"Space weather destroys stuff": A powerful statement, yet poorly understood in society. Only recently have researchers begun to reveal some of the forces that underlie the Sun’s behavior. And what they are finding is both spectacular and frightening. We have learned that the Sun is not always our best friend. Study of the 1859 Carrington event has shown that large explosions on the solar surface can have devastating effects on life on Earth. It is now clear that if such an event were to happen again today, it would destroy vulnerable electronics, many of our satellites and large parts of our power distribution networks.

The SolarMax project team spent a lot of time working with the world’s best experts in the fields of heliophysics and space weather observation. Without exception these experts are concerned about the risks of space weather to society. Impressed by these largely unknown risks, the team formulated the objective to investigate the current level of knowledge, further assess the risks of space weather for society. The next step was then to come up with solutions to how we can address the dual factors of addressing these risks and to raise awareness with the key stakeholders, so as to create a sense of urgency in order to lead the stakeholders to take action.

This report should be viewed as a first step towards safer futures. After finishing the report and the accompanying executive summary, our team members will reach out to the space weather stakeholders and together define measures to detect, deflect, mitigate, respond and possibly recover. We wish our work to be an eye opener and discussion starter. We also wish our work to be an inspiration, providing tangible products to raise awareness and realistic ideas for managing space weather risks. We will ensure that this document doesn’t remain hidden behind the walls of the great International Space University, but will find its way out into the world, to be read by those that make a difference and ultimately help us protect our planet.

The SolarMax team wishes to express its sincere gratitude to all at ISU who helped us do a lot of work in so little time. We would like to thank our chairs Dr. Simon Pete Worden and Dr. Rogan Shimmin of NASA Ames, as well as our tireless and always optimistic Teaching Associate David Haslam. Together with the rest of the ISU staff they gave us access to the best space weather experts in the world and provided a platform for the team to shine!

Team SolarMax,
August 20th, 2013.
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<th>Advanced Compositional Explorer</th>
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<tr>
<td>ACE</td>
<td>United States Air Force Weather Agency</td>
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<tr>
<td>ATM</td>
<td>Automatic Teller Machine</td>
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<td>AU</td>
<td>Astronomical Unit</td>
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<td>C</td>
<td>Command and Data Handling System</td>
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<td>CME</td>
<td>Coronal Mass Ejection</td>
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<td>COWS</td>
<td>Cell on Wheels</td>
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<td>CSA</td>
<td>Canadian Space Agency</td>
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<td>D</td>
<td>Direct Current</td>
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<td>Deoxyribonucleic Acid</td>
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<td>Galactic Cosmic Ray</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>Geostationary Orbit</td>
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<td>Geomagnetically Induced Current</td>
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<td>Global Positioning System</td>
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<td>Highly Elliptical Orbit</td>
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<td>High Frequency</td>
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<td>HOCOMOCOO</td>
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<td>HZE</td>
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<td>LF/HC</td>
<td>Low Frequency/High Consequence</td>
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<td>M</td>
<td>Magnetometer</td>
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<td>Description</td>
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<td>MEO</td>
<td>Medium Earth Orbit</td>
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<td>MESSENGER</td>
<td>Mercury Surface, Space Environment, Geochemistry, and Ranging</td>
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<td>Near Earth Object</td>
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<td>National Oceanic and Atmospheric Administration</td>
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<td>PSS</td>
<td>Particle Spectrometer System</td>
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<td>PUS</td>
<td>Public Understanding of Science</td>
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<td>PWPI</td>
<td>Plasma Wave and Properties Instrument</td>
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<td>RAD</td>
<td>Radiation Assessment Detector</td>
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<td>REPT</td>
<td>Relativistic Electron Proton Telescopes</td>
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<td>SDO</td>
<td>Solar Dynamics Observatory</td>
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<td>SEB</td>
<td>Single Event Burn-Out</td>
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<td>Solar Radio Burst</td>
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<td>Space Studies Program</td>
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<td>STEREO</td>
<td>Solar Terrestrial Relations Observatory</td>
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<td>SWPC</td>
<td>NOAA Space Weather Prediction Center</td>
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<td>TID</td>
<td>Total Ionizing Dose</td>
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<td>TP</td>
<td>Team Project</td>
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<td>UN</td>
<td>United Nations</td>
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<tr>
<td>UNCO PUOS</td>
<td>United Nations Committee on the Peaceful Uses of Outer Space</td>
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<tr>
<td>WAAS</td>
<td>Wide Area Augmentation System</td>
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<td>Y2K</td>
<td>The Year 2000 CE</td>
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1 INTRODUCTION

A coronal mass ejection explodes from the surface of the Sun. Solar matter is thrown into space, accelerated by an intense magnetic field and is propelled towards Earth. Particles interact with the Earth’s magnetic field, causing a geomagnetic storm and knocking several satellites out of operation. The magnetic field variations caused by the interactions of particles with the Earth's magnetic field induce currents in power lines and undersea cables, overloading transformers and disrupting large areas of the power grid. High frequency communications are affected, causing polar flights to be rerouted and critical navigation devices to be unable to acquire a GPS signal for several hours. This would be the resulting scenario if a solar weather event on the scale of the 1859 Carrington event were to occur today.

The Carrington event refers to a massive solar storm that hit Earth in 1859. The storm was so powerful that the currents induced in telegraph lines were reported to have blown switchboards, throwing some operators across the room. Red auroras were observed at latitudes far lower than normally seen; another sign of a powerful geomagnetic event. Carrington-level events are rare and given their scale, difficult to prepare for. Smaller solar weather events occur with increasing frequency towards the end of the 11-year solar cycle, with the peak in events around the peak in the Sunspot cycle, referred to as “solar maximum.” Although the scenario described above presents a worrying vision, the threat is not absolute and we can take concrete steps to protect the planet from the effects of solar weather.

All industries, governments, militaries, and peoples worldwide should prepare for the challenges that solar weather presents. Some industries have already shown a high level of commitment to addressing these issues. For other industries, the lack of recognition of solar weather as a threat is not just a direct risk to their own operations, but also a risk to any dependent activities as well.

This report outlines the nature of the threat posed by giving a background on solar weather and correlating this with a risk assessment of the current terrestrial and space infrastructure. It then attempts to quantify the effects that both a major and lower intensity solar storm would have on the Earth. From this perspective, this report is one of the first to offer such a broad perspective on all areas of solar weather.

This report then goes further by providing specific examples of how solar weather-related problems can be addressed in the power transmission industry and on interplanetary exploration missions. In addition, it proposes a new solar observation mission to improve our understanding of the scale and timing of the Sun’s weather events, and highlights a method for gleaning new information about our Sun’s activity at this point in its lifecycle by using existing data on solar-type stars from the Kepler mission.

Finally, methods of addressing solar weather are of little value if the information is not distributed, or if there is no will to implement them. As part of this report, TP SolarMax has crafted an awareness campaign targeted at governments and policy makers, industry and the general public giving them the information they need in order to respond effectively.
The challenges of dealing with solar weather are broad but manageable. Focusing on potential solutions and getting this information in the hands of the decision makers—whether power distribution executives, the heads of major satellite operators, the heads of space agencies, politicians, or the general public—is an effective way to manage threats of solar weather.

### 1.1 Departmental breakdown

Within this project, all seven departments of the ISU Space Studies Program are covered. The main contributions to each department will be summarized briefly in order to demonstrate the multidisciplinary nature of the project.

The **space sciences** department is key to this team project, as the knowledge of solar phenomena – or rather lack thereof – is what drives the mission proposals as well as the awareness campaigns. The link to this department is clearly visible in the background chapter, where the physics of space weather is described. An important part of this work is to point out the various solar weather knowledge gaps.

Since solar storms have the potential to wipe out satellites, **space applications** are also central to our project. Losing satellites has many cascading effects in terms of telecommunications, Earth monitoring operations, and space weather observation missions.

The **space engineering** department is also clearly present throughout our report, especially in the chapters where we determine the various failure modes of spacecraft and power grids due to solar storms. Engineering is also central in establishing recommendations for spacecraft hardening or shielding in particular, and in the various mission proposals.

**Human performance in space** is important to our work in terms of understanding the radiation that astronauts are exposed to. This includes understanding both the increase in radiation dose after a solar storm, as well as protecting astronauts during manned deep space missions.

The cost estimations and subsequent risk analysis form the basis of our work on **business and management**. Time was also spent on analyzing the various types of industries and their vulnerabilities to solar storm damage. This work was central to the awareness campaign targeted at those industries. Last but not least, in the first few weeks much effort was put into organizing the team and designating designing its management structure. Splitting up our work into smaller work packages allowed us to work more efficiently.

**Space policy, economics, and law** aspects are mainly discussed in the final chapters of the report. A logical subsequent step to identifying the various impacts that solar storms can have on technology and society is to make policy makers aware of these impacts. This will enable the implementation of the various recommendations.
Finally, **Space humanities** aspects are covered throughout the entire report. In particular the impact of a solar storm on society is a recurring theme. These impacts are on a more personal level, and therefore provide an incentive for policy makers and industries to explore mitigation options. As the message is more personal, it should be tuned to different cultural backgrounds and propagated through various media.
2 BACKGROUND

Most solar events do not reach our planet or are not strong enough to damage human infrastructure or life itself; however, in some rare instances this is not the case.

In this chapter, we will examine the nature of the threat posed by space weather. We will first provide a broad overview of the science involved, including descriptions of open questions in the field. We will then provide a survey of the threat that such space weather poses to our technological infrastructure—both in space and on the ground.

2.1 Scientific Background

2.1.1 Heliophysics

The Sun is the driver of all space weather in the Solar System. If we are to fully understand the potential threat that space weather poses, we must start with an overview of heliophysics.

The Sun has many different layers that define its structure as shown in Figure 2-1, including the core, the radiative zone, the convective zone, the photosphere, the chromosphere, and the corona (Zirker, 2002). In the core, the density is as high as $150 \text{ g/cm}^3$ and the temperature is over 15 million K—hot enough to fuse hydrogen. At the other extreme, near the base of the corona, the density drops to mere $1 \times 10^{-7} \text{ g/cm}^3$ (Gough, 1987). Moving away from the heat-producing core, the temperature drops to about 6000 K at the photosphere, the surface of The Sun. The temperature then rises again to more than 2 million K in the corona, which is the furthest layer from the core, a phenomenon that scientists have not yet been able to satisfactorily explain.

![Figure 2-1: Schematic view of the structure of the Sun (SOHO)](image-url)
All matter in The Sun is in the form of “plasma”—gas that has been ionized by high temperatures. This makes it possible for The Sun to rotate faster at its equator (about 25 days per rotation) than it does at higher latitudes (about 35 days near its poles). This effect is known as “differential rotation.” Plasma is made up of charged particles, so moving plasma generates a magnetic field through a dynamo effect, although it is still difficult to measure this magnetic field in detail (Zwaan, 1990). One can imagine this magnetic field as consisting of a series of invisible lines, running between two poles. Charged particles in the Sun’s corona move along these field lines, forming the solar wind (Meyer-Vernet, 2007).

Within The Sun’s convective layer, strong magnetic fields are carried through cylindrical channels known as “magnetic flux tubes.” Sunspots occur when these tubes get twisted by differential rotation and intersect with the photosphere. Charged particles caught in this magnetic field have difficulty moving from one field line to another, so convection—and therefore heat circulation—is inhibited, resulting in The Sunspot being both colder and darker than the surrounding area. Sunspots have magnetic fields with strengths around 2000-4000 Gauss (much stronger than that of The Sun itself) and occur in pairs, with each spot serving as one pole of a magnet. Sunspots usually last for a few days, with particularly large sunspots lasting up to several weeks. Because of their powerful magnetic fields, sunspots are associated with solar flares and coronal mass ejections or “CMEs” (Solanki, 2009). Sunspots are therefore an important visual indicator for the relative activity of space weather. While sunspots are among the best-known solar phenomena, they are still not completely understood. In particular, it is not clear how The Sun’s magnetic field forms into flux tubes (Charbonneau, 2010). There is also a lack of detailed modeling of sunspot formation and evolution (Rempel and Schlichenmaier, 2011).

Over time, the solar magnetic field becomes extremely wound-up and twisted by differential rotation. When this happens, magnetic field lines running between different sets of poles can meet-up and merge with one another, in a process known as “reconnection.” Eventually, so many reconnection events take place that the magnetic field breaks down altogether, only to re-emerge later with its polarity reversed. This happens once every eleven years and is known as the “sunspot cycle”. During this cycle, sunspot activity alternates between maxima—when sunspots occur most frequently—and minima, when sunspots may hardly occur at all. As a new cycle begins, sunspots first appear in bands on either hemisphere at around 30 degrees latitude as shown in Figure 2-2. Gradually the bands of activity thicken, and their center lines slowly migrate towards the equator but never quite reach it (Rempel, 2011). The question of why this cycle occurs approximately every 11 years remains a mystery, as analytical models suggests that this period should be shorter (Aschwanden, 2008). Scientists also do not understand why the rise to solar maximum occurs much faster than the decline to solar minimum, why sunspot activity emerges at low latitudes and then drifts towards the equator (Hathaway, 2010) or what causes the regeneration of the solar magnetic field (Charbonneau, 2010). Science has also yet to explain the occasional observed periods of prolonged solar inactivity—the most recent being the Maunder Minimum, which lasted from the mid-seventeenth to early-eighteenth centuries.
Magnetic fields in the Sun’s corona also contain large amounts of energy. When field lines reconnect, some of this energy gets released in the form of a huge explosion known as a “solar flare,” consisting of gamma rays, x-rays, protons, and electrons (Hathaway, 2012). In terms of sheer power, not even solar flares can hold a candle to “coronal mass ejections” (CMEs), which are the single most energetic events in the Solar System. CMEs occur when huge bubbles of plasma and magnetic field lines are ejected from the Sun over the course of several hours. While they are frequently associated with solar flares, CMEs have also been known to happen on their own (Hathaway, 2012). Solar flares appear to be yet another consequence of the Sun’s magnetic field: when plasma is held down by magnetic field lines, it builds up in potential energy; if these magnetic field lines recombine, the plasma may be allowed to escape (Chen, 2011). Both solar flares and CMEs can cause serious problems for Humanity if they happen to be pointed towards Earth (Cane, Richardson, and St. Cyr, 2000).

While scientists generally agree that all solar events are driven by the Sun’s magnetic field, this field itself is not actually very well understood. For example, the mechanism for magnetic field reconnection is unclear, as there is not enough illumination or spatial resolution in our observations to know the field configuration before reconnection takes place. We can only infer it from topological constraints and observations of the field after the explosion has already happened. It is also not quite clear how massive particles are accelerated by the energy released in recombination. While there are many theoretical models available, observational evidence supports does not support any of them over the others (Aschwanden, 2008). Scientists also do not know whether recombination is actually necessary for a CME to take place (Chen, 2011); and the ultimate fate of The Sun’s magnetic field remains an open question: in approximately five billion years, The Sun will swell into an enormous star known as a “red giant.” The differential rotation rates in the solar zones are a result of different temperatures, densities and composition, so one can reasonably expect that the magnetic field will change during the lifetime of The Sun (Heger, 2005), although it is not know exactly how.

### 2.1.2 Space Weather and Interactions with the Earth

Like the Sun, the Earth also has magnetic field, which is thought to originate from the Earth’s molten iron core. The core is in constant motion and produces a magnetic field through a process called magnetic induction (NRC, 2012). The magnetic field provides vital protection for maintaining the Earth’s atmosphere, deflecting solar wind and other space weather events which would otherwise lead to the loss of large amounts of the atmosphere and harmful effects on the Earth’s climate (ESA, 2013).
It takes about two to three days for CMEs to reach the magnetosphere of the Earth, where they may trigger spectacular and potentially destructive “geomagnetic storms.” CMEs can happen at any time over the solar cycle, but tend to happen more often during solar maximum. At solar maximum, the number of major CMEs observed at The Sun is about three per day (Cane, Richardson, and St. Cyr, 2000), but some weaker CMEs are also observed using space-based instruments (Gopalswamy, 2011). The number of shockwaves detected near the Earth, however, is about 0.3 per day, meaning that only one tenth of CMEs reach us (Webb and Howard, 1994). The CMEs interact with the Earth’s magnetosphere through magneto-hydrodynamic interactions as shown in Figure 2-3. These interactions are known as “geomagnetic storms.”

![Interaction between the magnetic fields of The Sun and the Earth resulting from a halo CME reaching Earth (NASA)](image)

Although CMEs dictate a large part of the ionization characteristics of Earth’s atmosphere and day-to-day operations of satellites and space exploration missions, there is considerable uncertainty in understanding their behavior (Schwenn, 2006). It is not yet possible to predict the eruption of CMEs, the path that a CME is expected to take, or the time at which it will reach the Earth far enough in advance to implement precautions.

The Sun’s interactions with the Earth’s magnetosphere create both the “Van Allen belts” and “induced ring currents.” These environments are hazardous to spacecraft, and they are important to our understanding of the origin and location of intense particle radiation in our solar system.

The Van Allen belts are the two (or more) layers of plasma (ionized gases/charged particles) that surround the Earth and are held in place by its magnetic field. The belts extend from approximately 1,000 km to 60,000 km above the surface of the planet. The belts contain charged particles thought to come mainly from the solar wind, with the level of radiation varying across each belt. The belts typically consist of an inner radiation belt and an outer radiation belt, centered along the Earth’s magnetic equator in the magnetosphere. The inner radiation belt consists mainly of energetic electrons and is the most intense, stretching from approximately 1,000 km to 6,000 km above the Earth. The outer radiation belt consists of both protons and electrons and ranges from 15,000 km to 25,000 km above
the Earth (Ecoffet, 2013). In 2013, a temporary third radiation belt was observed for four weeks by NASA’s Van Allen Probes, before a solar shockwave destroyed the belt (Baker et al, 2013). Scientists are still determining the mechanics of how the Van Allen Belts operate. Most recently the Van Allen Probes used Relativistic Electron Proton Telescopes (REPT) to learn how particles in the belts are accelerated to ultra-high energies (Reeves et al, 2013). Other questions—such as how particles can sometimes escape, how the belts sometimes disappear and reform during geomagnetic storms, and what caused the temporary appearance of the third belt—remain open.

The ring current is a donut-shaped region of charged particles in Earth’s equatorial plane, mainly consisting of hydrogen, oxygen, and helium ions. The current is trapped in the Earth’s magnetosphere at altitudes between 10,000 km and 60,000 km and is responsible for shielding the planet’s lower latitudes from electric fields induced in the magnetosphere. The ring current is continuously regenerated by the Earth’s ionosphere and the solar wind, which the ions lost via charge exchange decay, wave-particle interactions, and electromagnetic collision with thermal plasma as shown in Figure 2-4.

The waxing and waning of the ring current is a crucial element of the planet’s space weather; this phenomenon is capable of inducing magnetic fluctuations on the ground as well as transmitting disruptive surface charges onto spacecraft and orbiting satellites (Egeland, 2012). Satellites in low, medium, and geostationary orbits around the Earth are susceptible to damage from these ring current fluctuations.

There are still several gaps in our knowledge of the ring current. For example, the question of the source of the protons in the ring current is still unanswered. Specifically, further investigation is required to determine if these protons originate in the ionosphere or the solar wind. A more complete model of the interaction between the Earth’s magnetosphere and the solar wind is needed to better understand particle transportation and acceleration in the ring current (Daglis, 1999).
During geomagnetic storms, electric currents in the atmosphere and magnetic field undergo large variations due to fluctuations in the solar wind intensity as shown in Figure 2-5. These variations cause Ground Induced Currents (GICs) in conductors operating on the surface of the Earth, such as powerlines and buried pipelines.

Solar events are not the only factor contributing to space weather as Galactic Cosmic Rays (GCRs) also have a role to play. The GCRs are highly energized particles (mainly protons and atomic nuclei) which originate from outside of the Solar System or even from outside the Galaxy. Their sources and the mechanisms under which they are accelerated are deeply mysterious (Biermann, Gaisser and Stanev, 1994), but our current understanding is that they originate primarily from the supernovae of massive stars and from active galactic nuclei (Ackermann et al., 2013). Ney (1959) hypothesized that GCRs influence the Earth's cloud coverage and atmospheric conditions, but work still needs to be done to quantify this relationship (Dickinson, 1975).

If cosmic rays come into contact with electronic integrated circuits they can cause computational errors and result in corrupted data. Such events could result in anything from inconvenience to the damage of sensitive systems such as the navigation computer on board an aircraft (Atwell, Koontz and Normand, 2013); fortunately such events are infrequent.

The GCRs are tangentially related to the solar cycle in that our everyday exposure to GCRs depends upon the strength of the solar magnetic field (Heber & Burger, 1999). The GCR energy range quadruples between solar minimum and solar maximum; however no satisfactory models exist for predicting statistical time variations in GCR flux on Earth as a function of the solar cycles (Nemiroff, 1994).

2.2 Resources at Risk

Space weather can have a damaging effect on resources in space and on Earth. To analyze vulnerability to space weather, the different resources were classified into two main categories – space resources and terrestrial resources, each in turn split into sub-categories.
2.2.1 Space Resources

Humanity relies heavily on satellites orbiting the Earth for day-to-day activities and processes. Human inhabited spacecraft with international crews orbit the Earth. Important space science missions function throughout the Solar System. Space weather has the potential to cause chaos indirectly on Earth through direct effects on these spacecraft.

The hostile manifestations of space weather can be categorized into geomagnetic storms, GCRs, large variations in x-ray flux, extreme ultraviolet flux (EUV) in solar flares, and solar energetic particles (SEP) (Hochedez, 2005). High-energy particles, including electrons, protons, and heavy ions can inflict devastating effects on spacecraft (Mikaelian, 2001; Garrett and Whittlesey, 2012).

First, charging can occur. Trapped charged particles cause charging on or below the surface of the spacecraft. The particle depth depends on particle energy, density, and atomic mass. Surface charging involves electrons in the range of 10-50 keV, whereas internal, or “deep dielectric”- charging, involves electron energies above 2 MeV (Allen, 2002). Discharge of the built up current can degrade outer surfaces and cause single event effects (SEEs) when spacecraft limits are reached. SEEs are catastrophic events, caused by the passing of single, energetic particles through sensitive regions in electronic circuits. In extreme cases, SEEs can cause spacecraft system malfunction, and even whole spacecraft loss (Xapsos, 2013).

Different types of SEEs include:
- latch-up (SEL), a type of short circuit
- gate rupture (SEGR), where an insulating layer is damaged and the circuit gate loses the ability to regulate current
- burn-out (SEB), where a short circuit is made between the source and the drain

Errors can also result from bit flips or single event upsets (SEU), where the state of a single bit of data is changed from 0 to 1, or vice versa. Bit flips (also known as soft errors) are errors in data or memory and can be rectified by rebooting. They can cause unintended logic changes, command errors, spurious signals, and phantom commands (NASA, 2011). When a single event upset hit satellite NOAA-10 on March 13, 1989, the effect was excessive rotational rates. This caused the roll/yaw coil to use backup mode, a lucky avoidance of a more serious consequence (Bedingfield and Leach, 1996).

Radiation effects can also cause errors relating to total ionizing dose (TID) and displacement damage (DD). Over long exposure periods to radiation, TID and DD affect electronic component and semiconductor properties, resulting in performance degradation and device failure (Xapsos, 2013). Afflicted devices experience threshold shifts, increased leakage and power consumption, and timing changes (Holbert, 2007). Radiation effects cause compromised performance in solar arrays, sensor resolution, and structural components.

Spacecraft drag can also be affected by space weather. During geomagnetic Sun storms the Earth’s atmosphere heats-up and expands, so Low-Earth Orbit (LEO) spacecraft may experience increased drag over the solar cycle. Increased drag can cause spacecraft to decay out of orbit.
Evidence shows that HZE (high charge and energy nuclei) produce both quantitative and qualitative differences in biological effects compared to terrestrial radiation (Cucinotta et al., 2012). GCR, in particular, may exceed radiation risk limits by 10% on a long duration mission (>180 days) (Cucinotta et al., 2006). In addition, SEP events can have serious effects on the health of human explorers, depending on factors such as the total absorbed dose and rate, which in turn depend both on physiological factors and on the characteristics of the event (energy spectra, intensity, duration). Acute effects from exposure to SEPs range from dizziness, nausea, and headaches, to radiation sickness and death in acute cases (McComas et al., 2008).

2.2.2 Spacecraft Classification

SolarMax considered two main categories of spacecraft to help with analysis:

- Satellites, probes, and robotic missions
- Crewed missions (where human health must be protected)

Energy levels and densities of the charged particles trapped in the Earth’s radiation belts depend on the geomagnetic field characteristics (Mikaelian, 2001). These geomagnetic field characteristics change with orbit type. Therefore, SolarMax assigned sub-categories based on orbit type:

Low Earth Orbit: Spacecraft are prone to charging, especially in the inner electron belt. The protection of the magnetosphere reduces SPE and GCR for low inclination orbits. The photoelectron effect is negligible, but drag is a concern.

Polar Earth Orbits (LEO with high inclinations): Spacecraft pass through the precipitation of particles towards the Earth’s poles. These particles enhance charging and reduce the protection of the geomagnetic field against GCR and SPE.

Medium Earth Orbit (MEO): Spacecraft are in the high-energy proton radiation belt, increasing the risk for SEE.

Geosynchronous Earth Orbit (GEO): Spacecraft are subject to internal and surface charging, due to the outer electron belt. Spacecraft face EUV, GCR, and SPE radiation because of the limitation in the geomagnetic protection.

Highly Elliptical Orbits (HEO): Spacecraft in this area experience effects from all these environments.

The Union of Concerned Scientists’ satellite database (2013) was used to document the distribution of satellites within the chosen categories. To include recent launches, SolarMax added launches up to July 31 2013 to the database. The distribution of currently active satellite is as follows: 49% are in LEO, 40% in GEO, 7% in MEO, and 4% in HEO, as depicted in Figure 2-6.
A satellite’s purpose drives its orbit location (Figure 2-7). As a result:

- In LEO, 37% are for communications (at low inclination) and 26% are for remote sensing (in polar inclinations). Noise or electrostatic discharge in the major subsystems is a concern. Polar remote sensing satellites would also face significant SEU/SEL/SEB events. Increased drag would lead to overconsumption of propellant, reducing their in-orbit life.
- In MEO, 94% are for navigation systems (NAVSTAR GPS, Galileo, Beidou/COMPASS). Risk of charging is medium, but SEE can significantly affect the positioning service.
In GEO, 89% are for communications. A major event in the magnetosphere could provoke failures in power, attitude control, and communications electronics (SEU and SEL at best, burn-out through arc discharges or SEB at worst)

### 2.2.3 Mitigations

Mitigation strategies exist for spacecraft, and generally involve the use of shielding. Added shielding can run-up against financial and mass constraints, so detailed computer simulations need to be undertaken to determine precisely how much shielding is required. These simulations rely on databases containing information from the Geostationary Operational Environmental Satellites and ground instruments (Garrett and Whittlesley, 2012). Worst-case scenario simulations cover a 99.9% event (a single day in over 36 months). For instance, with the current version of the Space Environment and Effects Tool (SEET) in the Systems Tool Kit (STK), it is possible to consider electron fluxes with energies of up to seven MeV (NASA-AE8 model), and proton fluxes with energies up to 400 MeV (NASA-AP8 model) for trapped particles (STK, 2013).

Shielding can protect electronic components as well as Human Beings, however current shielding materials are only marginally effective for protecting humans against GCR cancer risks. This is due to the penetrating nature of GCR and the secondary radiation produced. SolarMAX recommends further materials research and testing to develop effective radiation mitigation shielding.

Future human radiation mitigation strategies include autonomous delivery of radiation countermeasures. Countermeasure medicine could be autonomously delivered using carbon nanotube technology. This technology could protect astronauts from solar particle events or other forms of space radiation through the release of biological radiation countermeasures (Loftus et al., 2011).

A spacecraft charging effects protection plan is one method to protect spacecraft from charging. This plan involves an in-depth analysis of the natural space plasma to which the spacecraft will be exposed. NASA has developed design guidelines with the purpose of reducing or eliminating the effects of spacecraft charging. They perform computer analyses to model charging level of the spacecraft and determine how effects of spacecraft charging might interfere with mission goals and objectives (NASA, 1994a). A schematic of this plan is shown in Figure 2-8.
There are many areas where these guidelines and design practices are followed (NASA, 2011). By avoiding certain orbits, spacecraft can avoid being subject to hazardous environments. Total Ionizing Dose effects are decreased by the use of radiation hardened or shielded devices. Electric or magnetic fields can actively shield spacecraft, and bulk material can passively shield spacecraft, to prevent particle penetration. Latch-up short-circuit protection, using insulation or chip shut-down procedures, prevents bit flips and high current from causing lasting damage. Logic voting compares signals from multiple components doing the same task. If a component is damaged, its output will be different from that of a healthy one, and so the signal from the majority healthy components is used. Finally, grounding and electrical harness design configurations are used to prevent arcing, where current passes between components like lightning.

Radiation-induced effects are systematically pointed out as a consequence of the natural space environment (NASA, 1994b; ECSS 2008a); however, SolarMax found design guidelines limited to spacecraft charging only (NASA, 1984, 1994a, 2007a, 2007b; ECSS, 2008b). Since off-the-shelf electronic systems are increasingly used for spacecraft and are not necessarily shielded enough against SEE, particular mitigation strategies are needed. SolarMax recommends that spacecraft standards for resistance to high-energy particle radiation should be established. These standards would be similar to those for spacecraft charging, and eventually translated into design guidelines for practical use by engineers.

Operational procedures are also used to prevent damage to spacecraft. Charge rates can be reduced if high solar activity is expected, or during a satellite’s passage through the radiation belts, by powering down unnecessary components, sensitive instruments, and attitude control mechanisms. This also saves radiation-sensitive equipment from higher noise level or failure, and prevents attitude disturbances if anomalies occur (SPACECAST, 2013). In addition, operation centers postpone uplink and downlink time to maintain

**Figure 2-8**: Spacecraft Charging Effects Protection Plan (NASA, 1994a).
communication (SPACECAST, 2013). Complementing this, orbit determination and analysis performed on the ground enables satellite tracking during this period, especially during atmospheric expansion and increased drag (SPACECAST, 2013). Critical operation measures can be taken in orbit to safeguard against solar activity.

Aside from damage prevention, the ability to repair spacecraft is crucial to maintain space assets. For benign to intermediate SEE events, systems can be restarted as a commonly used solution. As systems experience greater damage, rerouting information through redundant systems becomes viable. Spacecraft are in development to provide on-orbit repair to bring spacecraft back to operation, such as in NASA's Robotic Repair Mission (NASA, 2010). Satellite constellations can help mitigate the loss of a satellite using extra, redundant satellites. Although spacecraft reparability is limited, some missions and multi-satellite systems can take advantage of system adjustments to maintain functionality.

2.2.4 The impact of space resource failure

Global communications are affected when satellites are disrupted. News and television broadcasting, radio services, mobile telecommunications, internet services, automated teller machines (ATMs), credit card services, and critical public and military communications would be impacted by communication satellite losses (Marusek, 2007). Even minor communication disruptions cause timing de-synchronization, which leads to data transfer losses (Harding, 2001). If a big solar storm occurred, a lack of communications would hamper a coordinated disaster response. Banking and financial services would be made hard or impossible, causing both short and even long term economic slowdown depending on the length of the system outage.

Incapacitated navigation satellites would bring chaos to worldwide transport systems, particularly in aviation. Aviation relies on navigation systems to optimize flight paths, to land safely in poor visibility, and to provide air traffic management. Disruption of this system adds fuel and time costs to aviation operations and subsequently to consumers. Increased costs, extended flight duration, and flight delays follow. If navigation errors were experienced in flight, the impact of space weather could cost lives due to missed landings or even mid-air collisions.

Maritime vessels rely on navigation to prevent collisions, to provide positioning during distress, to avoid hostile or protected waters, and to aid in port docking (Harding, 2001). Satellite navigation systems serve to protect ships and crews from natural hazards. Maritime navigation systems provide clear and concrete boundaries to naturally or legally protected waters. Furthermore, docking and port navigation management aids in the quick and seamless transport of goods. The effects of a reduction in efficiency include port congestion, delayed products to consumers, and a drop in economic efficiency.

Farmers use GPS devices for seeding, watering, and fertilizing crops. The precision offered by navigation devices prevents overuse of resources, by saving 15-25% in unplowed land, 20-30% in work time, and €100-300 per hectare in costs (Auernhammer, 2001). In addition, commercial and government road operations rely on navigation systems. The commercial sector reduces costs by optimizing the transport of goods and monitoring the drivers' hours and travel patterns (Harding, 2001).
Rail transportation providers use satellite navigation capabilities to monitor schedule, deliver goods, and rail condition (Harding, 2001). Rail operators must implement manual monitoring and tracking instrumentation if navigation satellites are lost. Satellite navigation system failures affect the global economy in several industries, and inefficiencies lead to increased cost.

Severe damage to manned space stations could affect the future of human space exploration. First, extreme space weather jeopardizes astronaut safety due to potentially lethal radiation exposure. The radiation levels would compromise human health, causing ethical concerns regarding manned missions. A solar storm in 1990 subjected Mir cosmonauts to a year’s worth of radiation within a few days (Odenwald, 1999). After a large event, it may not be justifiable to endanger lives just to save scientific experiments. Second, costly repair efforts would result from extensive damage.

## 2.3 Earth Resources

Resources on the Earth can feel direct effects from extreme space weather as well as indirect effects caused by spacecraft damage. Systems on Earth can be crippled by extreme solar storms, including large scale power and communications losses, transportation breakdown, and lack of basic services and emergency disaster response. SolarMax has analyzed a number of important infrastructures. These are power grids, oil and gas pipelines, aviation, rail, space operations, telecommunications and climate. Further, SolarMax considered the psychological and physiological impact on humans.

### 2.3.1 Power Grids

Kappenman (2003) states that during a solar geomagnetic storm, ground induced currents (GIC) “are generally on the order of 10’s to 100’s” and that “GIC levels of only 1 to 10 amperes” can initiate damage. These currents flow everywhere in the grid and can add unexpected inductive load, which can saturate or overheat transformers. Damaged or broken transformers can result in major power failures (Marusek, 2007). Damaged transformers need to be replaced to restore normal operation, which could take from 40 days to one year if a new custom design transformer needs to be built (Kappenman, 2003).

Power outages and damage occurred in the Hydro-Quebec grid in 1989. Severe space weather produced GIC, which caused a 10 gW loss of capacity and destruction of two transformers (Pugh 2011). This event was estimated to be around 10 times weaker than the Carrington event. There are conflicting studies assessing the impact of a Carrington class geomagnetic storm on the Grid today. Some suggest that a one in a hundred years geomagnetic storm would lead to large scale blackouts lasting for several months (Kappenman 2010), while Pugh (2011) finds this scenario unlikely. However, the loss of 14 transformers during the Halloween Solar Storms in 2003 in South Africa (Hapgood and Thomson, 2010) shows that when the grid is unprepared, severe local damage is possible; even during smaller storms and at lower latitudes.
Electrical power grid technology and structure varies greatly among different national and international grids, therefore, the susceptibility to GIC produced by space weather also varies greatly. Large interconnected grids at high magnetic latitudes, for example in North America and Europe, are at greatest risk (A. Viljanen, Personal communication, July 26, 2013).

The susceptibility to GIC depends largely on the technology used. One example is the comparison of Finnish and Swedish power grids. Both grids experience similar severe space weather conditions and are built on a high resistivity type of soil. Still, the power grid of Finland has not experienced major problems caused by GIC. The Swedish grid, however, has technical differences and has experienced some cases of disruptions caused by GIC (A. Viljanen, Personal communication, July 26, 2013).

### 2.3.2 Oil and Gas Pipelines

Some of the longest oil and gas pipelines pass through high-latitude locations and are more affected by ground induced currents than those at lower latitudes. Pipelines in these areas, like Alaska and Finland, have well-documented effects caused by GIC. These GICs can induce electric currents of up to 1000 amps (Hapgood and Thomson, 2010). More research is needed into GIC at lower latitudes. A study on Australian pipelines suggested that space weather can still affect pipelines at mid-to-low latitudes (Marshall et al., 2010).

Pipelines are protected from corrosion by using cathodic protection, where the pipeline is held at a negative potential compared to the ground. This protection minimizes corrosion from exposure to moist air or the ground. The currents induced by GIC reduce the performance of the cathodic protection, causing corrosion and reducing the lifetime of the pipeline, though there is no critical risk of catastrophic pipeline failures from space weather (Riswadkar and Dobbins, 2010).

Solutions to GIC issues are well known in the engineering community: change the corroded pipe, increase insulation and grounding of pipeline; enhance protection by sacrificial anodes and monitor corrosion process of different sections to plan the repair before a leak occurred (Zurich Financial Services Group, 2010-2011).

### 2.3.3 Aviation

Communications are essential for aircraft, as they must stay in contact with ground stations at all times during flight (ICAO 2005). When flying over oceans and polar-regions, this communication is maintained using high frequency radio which is used because communications satellites are not accessible in latitudes above about 82 degrees. Solar flares can cause blackouts lasting hours, while severe geomagnetic storms can cause blackouts that last days. In autumn 2003, geomagnetic storms caused disruption every day from 19 October to 5 November (Hapgood and Thomson, 2010). If HF communications are disrupted, aircrews can use alternate communications such as SATCOM or inter-aircraft very high frequency radio.
Lower level space weather events can often change reflection frequencies and locations for HF radio. Modern radio systems such as the HF Data Link have the ability to modify frequency and ground station link, a capability which allowed 97% of HF Data Link communications to be relayed during the October-November 2003 disruption (Goodman et al. 2006).

Other systems are affected by space weather, including navigation systems. During the severe space weather events of October-November 2003, the Federal Aviation Administration’s (FAA) GPS-based Wide Area Augmentation System (WAAS) was affected. The system failed for 30 hours (National Academy of Sciences 2008) and during this event the FAA vertical error limit of 50m, which affects landing approach path accuracy, was exceeded (Hapgood and Thomson, 2010).

Aircraft crews and passengers are also at risk from solar radiation, even during normal flight. High-energy cosmic ray and solar particles generate secondary particles that reach maximum flux at around 18 km altitude. Dyer, et al. (2007) calculated that in February 1956, solar activity increased radiation levels at high latitudes by 300 times. This could have caused some aircrews to exceed current annual occupational flight limits in just one flight (Dyer, et al., 2007). During the major space weather events that occurred in October 2003, all routes above 35 degrees north or south latitude were deemed by a formal FAA advisory bulletin to be subject to excessive radiation doses (Hapgood, 2010).

2.3.4 Rail

Railway operators are using more electric trains and fewer diesel ones than before. Electric trains are at risk from the effects of GIC. During the severe magnetic storms of March 1989 and events between 2000 and 2005, there were anomalies in the operation of signaling, centralization, and blockage in high-latitude areas (58°-64°N) of Russia (Eroshenko et al. 2010).

Space weather effects have been shown to drive additional currents in electronic rail signaling (Hapgood and Thomson, 2010). This is a hazard, as trains may be misdirected by faulty signals. Overload of current can damage signaling equipment and make it unusable (Marusek, 2007). It is important that rail operators in all areas, and not just high latitudes, are made aware of potential space weather effects. Railway engineers may then better understand and monitor malfunctions in signaling systems.

Repairing small equipment is relatively easy, but losses—both of money and of lives—can be greater should collisions occur. Estimation of reparability then becomes almost impossible, however incidents can be avoided by hardening equipment, making systems redundant, and monitoring systems (Zurich Financial Services Group, 2010-2011).
Future rail systems, such as the European Train Control System (coordinated by the European Rail Agency) are moving towards mobile communications technology, which makes railway operations more likely to be affected by space weather. Radio burst interference caused by high energy waves emitted during geomagnetic storms, is of particular concern. Interference could cause huge disruptions to a future rail system using mobile communications technology (Hapgood and Thomson, 2010), so these systems should be designed with space weather mitigation in mind.

2.3.5 Space Operations

Space weather data is required for a variety of space operations activities. Customers require space weather data for go/no-go launch criteria, on-orbit operations planning, and anomaly investigation (National Academy of Sciences 2008). Launch delays caused by solar storms are accepted because vehicles are not designed to operate in such severe conditions. To maintain launch system integrity, accurate predictions of space weather conditions are required for the hours immediately following launch. Improvements are necessary in the prediction of major solar events to better support space operations planning.

2.3.6 Telecommunications

Telecommunications can be disrupted by space weather both directly and indirectly. Radio bursts and GIC in ground communication lines are examples of direct space weather effects. Failures of satellite navigation services can also affect mobile networks, which often rely on timing information from these satellites (Hapgood and Thomson, 2010).

Availability of electrical power causes indirect effects. Mobile phone cell towers need to have electricity for operation, as do the mobile phones themselves. The use of Cells on Wheels is one possible mitigation strategy. Cells on Wheels are movable cell sites that generate their own electricity. Hardening of cell phone sites with back-up electricity generators is another potential strategy.

Another impact from space weather is solar radio bursts, which can increase the noise in mobile phone network system from 1dB to 10 dB without loss of connection. More severe solar radio bursts can cause temporary loss of service (Royal Academy of Engineering, 2013; Tulunay and Bradley, 2004).

Space weather events can also have an effect on long distance telephone systems. Telephone systems based on copper wire can be disrupted, as happened in the US during a severe magnetic storm in August 1972 (Hapgood and Thomson, 2010). In addition, telephone calls that are relayed through satellites can be disrupted, as was the case in Canada and the US in the 1990s (Hapgood and Thomson, 2010).
High frequency (HF) communications are often disturbed by geomagnetic storms caused by solar flares and coronal mass ejections. X-rays produced in these events cause the density of the lower layers of the ionosphere to increase, affecting the ability of these communications signals to propagate. In addition, the channeling of highly energetic solar particles to polar regions by the Earth’s magnetic fields can cause similar disturbances in these regions. Disturbances in this case can last from days to weeks (Omatola and Okeme, 2012).

Several methods can be used to mitigate the effects of space weather on HF communications. An obvious method is to use alternative means of communications where available while waiting for the interference to subside. Second, many modern HF radios are frequency agile and can move to a frequency that is experiencing a lower level of interference. Third, the development of new software or hardware filters may enable HF radios to operate with a greater tolerance to interference (Royal Academy of Engineering, 2013; Tulunay and Bradley, 2004).

2.3.7 Climate

There are still gaps in our understanding of terrestrial climate change. However, certain statistical correlations suggest the need for additional studies. For example, the current solar cycle appears to be quieter than any of the previous cycles during the last 100 years. It is possible that this might mark the start of a longer and less active period, similar to the Maunder Minimum.

A cold period, commonly referred to as “the Little Ice Age,” coincided with the Maunder Minimum. Figure 2-9 shows how Northern Hemisphere temperature anomalies have varied along with solar irradiance since 1600. Using observed temperature data from the Maunder Minimum period, it is estimated that reduction in solar activity contributed to 40% of overall cooling during this period (Rind, 2004). Further, data shows that solar forcing is attributable to approximately half of the surface temperature warming since 1860, and a third of the warming since 1970 (Lean, 2012). Due to the climate system response to solar irradiance shown by these results, continued monitoring is necessary in order to properly measure solar forcing of the climate in the future, and its contribution to global warming.

![Figure 2-9: Decade-averaged values of reconstructed solar total irradiance and northern hemisphere temperature anomalies from 1610 to the present (Lean, 2012).](image)

In addition to sunspots and solar irradiance, there are other space weather effects that may be related to climate fluctuation (Friis-Christensen, 2001; Rycroft, 2000):
- UV flux is doubled in solar maximum, increasing temperature in the stratosphere when compared with solar minimum
- Solar wind, characterized by the global magnetic index, has increased by 130% in the last century. The index used is the AA index, a measure of the disturbance level in the magnetic field of the Earth based on measurements from two stations, as summarized on the INGV website (2013)
- Formation of low clouds caused by variations in GCR particle flux
- GCR effects on absorbed sunlight and resultant mean temperature increase of the planet
- Energetic protons produce clouds, and holes in the arctic ozone layer, which contribute to the greenhouse effect

2.3.8 Physiological and psychological impacts on society

Physiological and psychological effects due to solar weather may range from inconveniences and discomfort to injuries or even fatalities (Baker, et al., 2008) (Hapgood, 2010). For example, people may become stranded away from shelter due to failures in transportation systems. This problem may be compounded by the fact that most communication methods require electricity and may not work. Mobile phone batteries would run out and many people would have no means of charging them. Stranded people may not be able to contact family members or emergency services if needed.

Potable water may become scarce within a few days, due to the failure of water pumps. This could become a major problem quickly, as humans are not able to live for more than approximately three days without drinking water (Zawalsky, 2007). Likewise, sanitation problems could develop, as power is needed to pump waste water and sewage away from homes and businesses. In addition, perishable food will run out within a few days due to lack of refrigeration and low inventories in stores. Many major cities rely on just-in-time delivery, and only keep enough food in stores to supply local populations for one to three days (EMP Commission, 2008).

Purchasing supplies may be difficult, as electronic payment methods and bank machines will not work in the event of a power outage. Even gas stoves that require electricity to pressurize the gas supply will be inoperable. Propane tanks for barbecues and other cooking equipment require electricity for refilling and will only provide a short-term solution.

The sick and elderly will be at risk if reliant on electronically operated medical devices at home. Although hospitals will likely have back-up power, this will only last for a finite amount of time. Perishable medicines and medical supplies (e.g., insulin) may spoil from a lack of refrigeration, and the inability to produce more without electricity.

In addition to societal effects of failed infrastructure, there may be direct effects of increased radiation to the human body, and psychological effects of disaster response. Increased radiation will likely affect people travelling on aircraft in the immediate aftermath of severe space weather (Hapgood, 2010). Major disasters can cause psychological distress and mental illness. In the case of Hurricane Katrina, there was a documented increase in cases of mental illness, as defined by the Diagnostic and Statistical Manual of Mental Disorders, following the disaster (Kessler et al., 2006).
The potential problems associated with a severe space weather event could be serious and it is important to make the public aware of potential risk; however, this awareness should not induce panic, as in the case of the “Y2K” bug at the turn of the Millennium (Quiggin, 2005). Regardless, social consequences may be reduced through educating the public and policy makers on possible impacts, with an emphasis on emergency preparedness. Emergency preparedness plans will need to consider varying effects depending on the time of day, time of week, and time of year of the space weather event. For example, during the 1989 power grid failure in Quebec, Canada, the power grid failed within 92 seconds and led to five million people being without power for up to nine hours, during cold weather (Hapgood, 2010). In addition, dense urban populations will feel the effects most dramatically, and will need to be most thoroughly prepared (Hapgood, 2010). Finally, as systems become increasingly complex and interdependent, social and economic impacts from space weather will likely increase (Baker et al., 2008).

2.4 Conclusion

Scientists agree that space weather is driven by the Sun’s magnetic field more than by any other factor, but our current understanding of this magnetic field—and how it interacts with that of the Earth—is inadequate. Closing these knowledge gaps is of paramount importance, since space weather can be severely detrimental to Human infrastructure.

In the next chapter, we will assess the risk of severe solar storms, and consider the potential impact in economic terms.
3 RISKS AND COSTS

In this chapter, we examine the threat of space weather through an economic lens. We first analyze the risks involved with space weather, and then consider the potential financial costs to the world economy based on historical data. We conclude by performing a cost-benefit analysis, and suggesting some possible cost-mitigation strategies.

3.1 Risk

Multiple industries rely on risk analysis to make substantial financial investments, guide their long term planning, and project the successes and failures of their endeavors. Space agencies and space-related companies integrate risk analysis and mitigation techniques into the engineering and launch activities at a fundamental level. When it comes to the actual estimation of risk associated with an event, a mix of art, science, experience, and intuition are required. The amount of energy and time spent analyzing risk depend on the potential severity of the event. When loss of life or large sums of money are at risk, stakeholders normally demand a more structured and comprehensive analysis. Finally, regardless of the results of the analysis, it is still incumbent on the leadership structures of the affected organizations to make critical decisions and implement mitigation techniques.

3.2 Modeling

A subset of risk analysis, particularly associated with insurance, falls into the category of ‘catastrophe modeling.’ Catastrophe modeling has particular significance to space weather phenomena because of the unpredictable nature of solar flares, solar proton events (SPEs), and coronal mass ejections (CME). Catastrophe models rely on statistical analysis as part of the actuarial science; however other components of engineering, meteorology, and seismology have also been included. Actuaries have traditionally marginalized or omitted considerations of space weather from natural catastrophe models, because of the paucity of reliable space weather data. Consequently, the costs underwritten by insurance companies have not been passed downstream to space and terrestrial companies that are potentially affected by these events. This oversight has caused the development of a “risk gap” associated with space weather events.

Over the past few years, the world’s best solar physicists have begun to ring alarms on the potential for our Sun to cause widespread damage to terrestrial and orbital assets, particularly if a CME on like the 1859 Carrington event were to occur. While it is currently impossible to predict exactly if and when an extreme solar event will occur, scientists, engineers, insurance industry professionals, actuaries, authorities, and politicians have begun to recognize the threat.
Last year, Jeffrey Love published “Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms” (Love, 2012) in the Geophysical Research Letters journal. In this article, Love and his team used statistical techniques to estimate the most likely long-term occurrence rates and probabilities of various natural disasters, including severe magnetic storms.

In their analysis, Love and his team considered three magnetic “super-storms” that had taken place in the previous 153 years—the Carrington Event of 1859 and other, smaller storms in 1921 and 1989 (another magnetic storm in 1909 was ignored for lack of reliable data). Following Tsoubouchi and Omura (2007), Love modeled the occurrence of large magnetic storms as a “time-random process with inter-event wait times that are long compared to the solar cycle (Love, 2012).” This statement effectively suggests that severe solar events are infrequent on a human timescale (every hundreds of years), and that we have little ability to predict them.

Love’s conclusions on probabilities can be found in Table 3-1.

Love also acknowledges the work of Daniel M. Baker’s team (Baker, 2008), which estimated that a severe geomagnetic storm scenario would cost the global economy $1-2 trillion during the first year alone, with recovery times between four and ten years, and concludes that the probability of another Carrington event happening in the next ten years is 6.3%. Love himself, however, is quick to caution that this value has “limited accuracy (Love, 2012),” because of the inadequate data available for properly characterizing historical events.
3.2.1 Risk Analysis and Conclusions

Using the work of Love et al. (2012) and Baker (2008), it is clear that a Carrington-level event is a true Low Frequency/High Consequence (LF/HC) event.

![Risk Analysis Matrix](image)

**Figure 3-1:** A risk-analysis matrix, comparing severity of impact to likelihood of occurrence. Green, yellow and red represent items of low, moderate and high risk, respectively. Space weather events fall in the yellow area.

Using data from the NOAA Space Weather Prediction Center, the trillion-dollar cost-estimate, and a simple risk assessment matrix (Figure 3-1), we characterize the prospect of a Carrington-level event occurring today as a Medium Risk Event. Multiple industries should consider this risk while crafting their detection, defense, mitigation, response, and recovery strategies. Finally, while Carrington-level events are truly low frequency, there is a range of less catastrophic but higher probability space weather events; taking potential impact and relative probability into account, we find that these are also Medium Risk Events during each and every solar maximum. We recommend that stakeholders take moderate measures while developing their strategies.

3.2.2 Risk to Future Missions

We have compiled a world-wide launch manifest for the next year to support our analysis of risk to future missions. Rather than discussing risks to each individual launch, the team has characterized the risk for classes and families of satellites that have aspects of their planned orbital mechanics, planned payloads and missions, or design and hardness engineering considerations that make them more vulnerable to space weather events. The types of missions that can be affected are geolocation, communications, satellite operations, space tracking, navigation, remote sensing, and others. Because of the low frequency nature of space weather events, radiation hardness requirements often fall prey to financial or mass budget constraints.

The following are main factors that increase the susceptibility of spacecraft to space weather:

- Orbital mechanics: Orbits which fly closer to The Sun or which travel through weaker parts of Earth’s magnetosphere will suffer greater effects from space weather than those in low inclination, LEO orbits (i.e. the BepiColombo mission to
Mercury). High-inclination orbits over the Earth’s poles are also at greater risk.

- Mission/Payload Considerations: Communications or broadcast payloads that operate in spectra affected by the ionosphere are more affected by space weather. For example, Galileo satellites use transponder frequencies that are subject to ionospheric interference.
- Design/Hardness/Redundancy/Resilience weaknesses: Because financial and mass budgets for nanosats tend to be constrained, those designs with reduced emphasis on radiation hardness are more susceptible to space weather. An example of this is the O3B family of satellites, which (like most nanosats and cubesats) sacrifice hardening in favor of overall affordability.

Figure 3-2 shows an approximation of launch manifests for the next few years. Since military and intelligence-related launches are not published, there are several programs that are not available, and which may suffer from a lack of access to space weather education campaigns.

Launch Manifests

![Pie chart showing launch percentages by year]

Figure 3-2: Percentage of launches to take place by year

Launches after 2013 will be outside of this cycle’s solar maximum; hence, there is less of an immediate threat to those with a mission duration lower than ten years. Missions launching in the 2020-2025 window, however, should give serious consideration to space weather as they will be in operation during solar maximum.
3.3 Historical Cost Analysis

In studying the costs that severe space weather have had to the economy, we found it useful to consider terrestrial and space-based resources separately.

3.3.1 Terrestrial Resources

When space weather harms terrestrial infrastructure, it costs the economy in three major ways (NAP, 2008):

- There is the direct cost of the failed resource. For example, a large transformer in a power station might cost as much as US$10M to replace (Marusek, 2007).
- You must consider the dependency of other resources, and society itself, on the failed device. This includes, for example, the cost of rerouting flights from polar orbits due to excessive radiation.
- Several resources may be interdependent, so that the loss of one can harm the others (Figure 3-3).

![Figure 3-3: The interdependencies of various infrastructures](image)
While the direct impact is easily calculated and computed, the interdependencies vary heavily with the scenario being considered, and so they cannot be accurately predicted or even definitively calculated after an event has occurred. Due to this difficulty, we get a rough estimate for the costs of a major solar event by examining the economic impacts of similar historical events. We did not limit the study to only solar radiation event, but also included events triggered by other causes that might have a similar impact, such as hurricanes. The different events are summarized in the following list:

- The 2003 blackout in eastern North America was caused by space weather and lasted for 32 hours, affecting some 60 million people. The estimated cost of this blackout is US$4-19b, with the most common estimate is US$10b (Murtagh, 2008; Forbes & St. Cyr, 2012).
- The 1989 Quebec blackout was also caused by a space weather event which overloaded the power grid in a matter of 90 seconds, costing US$13m (Pugh 2011) in direct damage with as much as US$2B (Riswadkar and Dobbins, 2010) lost to the economy altogether.
- A typical geomagnetic storm can cost around US$400m in direct losses (Murtagh, 2008), while total losses to the GDP can soar as high as US$3-6b. For an individual industrial consumer, the cost of a blackout can be as high as around US$1,000/kWh (Siemens, 2011).
- The airline industry is estimated to suffer a loss of US$100-150k per each diverted polar flight to lower latitude routes, not including the increased health risk of those flights (Murtagh, 2008). Assuming around 5000 thousands polar flights per year [S3], the net loss of one day of space weather to the airline industry can be between US $1.5M and US $2.3M.
- Losing the ability to navigate with satellites can cause US$50-1000k per day for each company that relies on navigation (Murtagh, 2008). The accumulated effect for all the companies combined can be very big and have a serious effect on the economy. The median damage of an Atlantic hurricane is US $1.8B (NRC, 2008) but this also accounts for physical damage that is not part of a solar storm. We assume that the non-physical damage that is caused by a hurricane is less than half of the total damage, probably in the US $0.5-1.0B range.

The damage will also be compounded by the economic situation: severe damage to one or more companies will affect other companies, and lead to decreases in stock value. Although further study is needed to properly assess the economic effect of space weather, the true cost may never be known. Nevertheless, by investigating the damage per day, it may be possible to learn more about the speed at which the situation could deteriorate.

### 3.3.2 Space Resources

In this section, we address the economics of the failure of space resources caused by increased solar activity. This is important in order to obtain a general idea of the full impact of geomagnetic storms of various magnitudes. We will compare the impact of spacecraft damage caused by a small geomagnetic storm with that caused by a larger storm. A first indication of the costs involved with complete or partial spacecraft failure due to small geomagnetic storms can be obtained by looking at data from two telecommunication satellites – Galaxy 15 and Anik E2.
In April 2010, a solar storm damaged the communication systems of Orbital Sciences Corporation’s Galaxy 15 satellite (Hapgood and Thomson, 2010), to the point that it became an unresponsive “zombie satellite”, autonomously continuing its operations. In total, approximately US $8M was spent, US $1M on remedial actions and US $7M on payments that would have been made as a result of Galaxy 15’s in-orbit performance. It was estimated that the storm had reduced the satellite’s lifetime from 10-15 years down to 4 years. Given the fact that a communications satellite typically costs US $250M, the total loss was predicted to be around US $100M (Hapgood and Thomson, 2010). Several months later, Galaxy 15’s battery drained completely, the satellite rebooted, and eventually communications were restored (Chow, 2010). Similarly, in January of 1994, Telesat lost Anik E2; a US $290M satellite. The recovery effort cost approximately US $50M, which excluded the cost of lost services during the 6-month recovery effort. Fortunately, the satellite was successfully restored to its operational status (Baker, 2008).

These two cases appear to be representative for the damage done by such storms (de Selding, 2010). One could therefore conclude that the cost of relatively minor damage done to space resources is to the order of $50 million. The higher value of the two cases was chosen because the cost of the recovery efforts described above is likely conservative.

A second cost estimation can be made for larger geomagnetic storms, such as the “Halloween” storm in October 2003. Hapgood and Thomson (2010) indicate that this space weather event caused approximately 30 satellite anomalies. One of these anomalies resulted in complete failure of one of JAXA’s Earth observation satellites, ADEOS-II (also known as Midori-II) (Kramer, 2002), which cost approximately US$640m (Evans et al., 2004). Assuming that the other 29 spacecraft anomalies required some form of recovery effort similar to the two cases presented previously, costs would have amounted to a total around US$1.5b. If we include the cost of ADEOS-II, the total damage done to space resources by the October 2003 storm would be approximately US$2b. This also appears to be a conservative figure, and according to Hapgood and Thomson (2010), a Carrington-like event would result in a total revenue loss of about US $30B just for the satellite operators.

As with terrestrial infrastructure there are also indirect costs to consider such as:
- The lost revenue from users during periods of reduced operations
- Financial compensation for not being able to provide particular services
- A decrease in purchasing power parity caused partially by defective cash machines, or the percentage of satellites damaged with respect to the total number of satellites owned by an organization.

The international telecommunications industry is worth approximately US$225b (Marusek, 2007). Because of its financial worth, businesses will likely have greater incentives to ensure that their satellites remain operational, than similar satellites used for scientific research. However, many services depend on the telecommunications industry, which also means that recovery or replacement efforts are required within a short period of time to minimize the financial losses.
Another problem to consider is the possible failure of human-carrying spacecraft (such as the ISS). Potential recovery efforts would cost more due to the reduced time budget for recovery and strict requirements for maintaining the safety of all astronauts. Indirect costs in such a situation include decreased incentives to send more astronauts into space and less public support for manned space travel.

### 3.3.3 Cost-Benefit Analysis

Using a risk assessment for SPEs (NOAA, 2013), SolarMax developed a cost benefit analysis. Based on severity levels of an event, we multiplied the cost of recovery by the likelihood of such an event occurring, and divided by the cost of prevention. Using this method, we made an estimate of the effectiveness of preparing for six different severity categories of solar event (Figure 3-4). The analysis shows that, given that Carrington-level events are so rare, the majority of investment should go towards preparing for relatively minor solar storms. Investment into any of the six categories will have benefits across the board, but clarifying the level of the effectiveness of investment across the board will allow for optimization, maximizing effectiveness of resource allocation.

![Figure 3-4: Cost Benefit Analysis suggesting distribution of resources for addressing negative effects of SPEs](image-url)
3.3.4 Cost-Effective Mitigation Strategies

Both multi-industry and industry-specific mitigation strategies for space weather exist, but because of the high costs associated with some strategies, and the relatively low probabilities of severe solar events, industries, governments, and other organizations tend to ignore the steps associated with these strategies. There have been several improvements on this front as the public’s awareness of space weather has grown. For example, since the 1989 solar event, Hydro Quebec has installed transmission-line series capacitors at a cost of more than US$1.2b, and has improved its various operational mitigation strategies. (Zurich, 2010)

Unfortunately, most utility companies do not have replacement transformers readily available, which can cost more than US$10m per unit and take more than a year to manufacture (United States Department of Energy, 2013). As part of the analysis and cataloging of these strategies, the team split them into multi-industry strategies, regional and level of development-based strategies, and specific industry strategies, which are discussed in chapter 5.

3.4 Conclusion

While Carrington-level solar storms have the potential to cause trillions of dollars in damage to our infrastructure, they are very rare. Our cost benefit analysis shows that it is more effective to invest money in guarding against smaller ‘minor’ to ‘strong’ level events. In the next chapter, we will suggest a variety of technological measures which can be taken against the problems of space weather.
4 TECHNOLOGICAL SOLUTIONS

SolarMax developed three technological solutions to the threat faced from solar weather, based on our research. Each solution focuses on a different problem that was identified. First, we propose a robust smart power grid that would protect our vulnerable electrical system. Second, we proposed a small satellite mission that aims to close gaps in knowledge of how spacecraft are affected by solar radiation. Finally, we propose a methodology for radiation exposure mitigation for both manned and unmanned spacecraft, based on material redistribution.

4.1 Robust Smart Power Grid – An International Terrestrial Solution

We have shown that the Sun, through the solar wind and space weather, can directly affect the lives of people on Earth in a number of different ways: by impacting the performance of electrical power grids, decreasing telecommunications systems bandwidth, damaging railroad switching equipment, accelerating corrosion processes in oil pipelines, and direct physical and psychological effects on humans. These phenomena are more frequent during solar maximum and their effects are especially apparent at higher latitudes. More research is needed to determine whether there are similar effects at lower latitudes (Babayev, 2007). GICs cause disruption to the terrestrial power transmission grid and of the many consequences of space weather they cause the most immediate effect on the population.

4.1.1 What is the problem?

In power grids, HVAC (High Voltage Alternating Current) transformers can experience catastrophic failure when subjected to ground induced currents. Power transmission lines act like antennas, fully absorbing and propagating the GICs. The excess of unregulated currents caused by GICs have the power to melt the copper windings of the electrically stressed transformers. These transformers are necessary for power distribution and have very long commissioning and repair schedules, and their failure poses a significant risk to societal functions.

4.1.2 Potential Regions of Impact

Power grids in Northern Hemisphere countries seem to be particularly at risk of disruption by GICs and we have chosen to study the following six countries: Canada, China, Germany, Ireland, Russia, and the United States of America. Our study is quite general so it can be adapted for the Southern Hemisphere. Although countries in the Southern Hemisphere are at low risk for GICs, there is historical evidence that GICs have occurred there (Marshall, 2011)
Table 4-1 shows a general cross-section of power transmission industry across our selection. This, in conjunction with Figure 4-1, provides us with GIC risk estimate for the selected countries.

**Table 4-1: National power grid overview**

<table>
<thead>
<tr>
<th>Country</th>
<th>Public owners</th>
<th>Private providers</th>
<th>Grid length</th>
<th>GICs soil risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>8</td>
<td>~55</td>
<td>160 000km</td>
<td>High - Low</td>
</tr>
<tr>
<td>China</td>
<td>5</td>
<td>0</td>
<td>900 000km</td>
<td>Medium-Low</td>
</tr>
<tr>
<td>Germany</td>
<td>1</td>
<td>4</td>
<td>1.8 million km</td>
<td>Medium</td>
</tr>
<tr>
<td>Ireland</td>
<td>1</td>
<td>5</td>
<td>6500km</td>
<td>High</td>
</tr>
<tr>
<td>USA</td>
<td>6</td>
<td>240</td>
<td>724 204.8km</td>
<td>High-Low</td>
</tr>
<tr>
<td>Russia</td>
<td>1</td>
<td>0</td>
<td>124 000km</td>
<td>Medium-Low</td>
</tr>
</tbody>
</table>

*Figure 4-1: Where GICs risk is high according to soil conductivity: a) North America, b) Asia, C) Europe and D) Ireland.*

SolarMax concludes that every country considered has some risk of problems due to GICs.
4.1.3 Power grid definition

A smart grid, as defined by the Global Smart Grid Federation, is an electricity network that can intelligently integrate the actions of all users connected to it to efficiently deliver sustainable, economic, and secure electricity to customers. Figure 4-2 shows a typical smart grid topology.

![Figure 4-2: Smart Power Grid](image)

For the implementation of a smart power grid, processors need to be built in each switch, circuit breaker, transformer, and component of the power distribution network. This allows communication to occur between different sections of the power grid from the central power plant to the residential smart meter – a digital meter capturing, processing, displaying and communicating data energy usage in real time. In addition to making the network more fault tolerant, these smart meters enable the customers to monitor their power consumption and therefore become more interactive in the system (Amin, 2013).

4.1.4 Our Proposal

As the power industry changes from the current power grid to a smart grid, there exists an opportunity to incorporate appropriate robust measures to mitigate the harmful effects of space weather on power distribution infrastructure (Amin, 2013). We propose the adoption of robust smart power grid topology to minimize and correct the effects of space weather. Such a robust smart grid will mitigate GICs using the same information and communication technology that allows regular smart grids to monitor, modulate, and optimize their performance (Amin, 2013). This idea is based on three core measures:

- Real-time monitoring and reaction to GICs,
- Anticipation of future events,
- Instantaneous identification and isolation of hardware failures.
Robust smart grids are further differentiated from general smart grids, in that they automatically incorporate preemptive actions based on space weather forecasting. Furthermore, a robust smart grid acts by continually tuning itself to an optimum state, detecting disturbances in the network and taking appropriate measures to mitigate their effects. This then allows the system to deal with potential hazards such as GICs in an automated manner. Thus if one part of the grid infrastructure should fail during a severe geomagnetic storm, it would be immediately isolated from the network in order to protect critical equipment and prevent cascading failures – the subsequent failure of interconnected nodes.

4.1.5 Solution Comparison

In addition to a new robust smart grid topology, alternative proposed solutions to the harmful effects of GICs include transformer redesigns, redundant transformers, fault current limiting superconductor cables, and capacitor grounding techniques. However, all of these solutions have an associated high overhead and implementation cost without significant improvement on the existing services; thus, they are not likely to be an economically viable strategy for the mitigation of space weather effects. Robust smart grids protect the overall health of the grid during geomagnetic storms, while also providing reliable, safe, and efficient power transmission.

4.1.6 Implementation of a Robust Smart Grid

A robust smart grid uses the same technology used to implement smart grids: interconnected nodes communicating their status back to a central command node, to reduce the harmful effect of GICs on the network. Implementation of the two systems, robust smart grids and smart grids, will require the same investment. The application of a robust smart grid would also directly incorporate space weather forecasting within automated processes that monitor disturbances and reduce current in susceptible lines. Additional measures would also be taken to create margins of safety or tolerance to severe space weather. Finally, procedures specifically tailored for solar storm and GIC mitigation are also incorporated into robust smart grids. The community will also have to weigh the benefits and costs of smart grids in general.

4.1.7 Benefits of Using Smart Grids

A power grid with monitoring, reaction, anticipation, and isolation features will be capable of limiting failures due to GICs across the network. Furthermore, such a smart power grid will facilitate a seamless and transparent upgrade to a DC power grid. A DC power grid permits better control of GICs due to their DC current-like nature (Molinski, 2000). This, in turn, will cater for integration of a space power grid as proposed by Komerath (2009). The author describes a joint India/USA collaboration for a constellation of low/mid Earth orbit satellites transmitting beamed power to 100 terrestrial power plants.
Smart grids have been shown to reduce carbon emissions into the environment, thereby increasing the generation, transmission, and consumption efficiency of the system, consequently lowering the associated costs (NETL, 2010). This solution offers a higher degree of security, reducing the probability and impact of damage due to space weather or hostile attack. Furthermore, the use of a smart grid suggests that the number of grid-related accidents would be reduced.

Robust smart grid technology will anticipate GICs by using forecasting information from different sources, such as NOAA and ACE (a solar wind-monitoring satellite), and then be able to prepare the grid for GICs instead of reacting (Kappenman, 2009). This preemptive action will decrease both the chances and the extent of a power loss.

4.1.8 Societal Issues

Levitt (2011) suggests that the related issues of smart grid adoption are non-trivial and worthy of consideration. He suggests that there are a number of privacy, safety, health, and liability issues associated with the implementation of a smart grid that should be considered. In brief, residential smart meters are transceivers, and pose a potential security risk for unauthorized access. Privacy issues are also a concern here. Finally, a distributed smart grid would provide a more tempting target for hackers and other nefarious access.

Although the ability to predict extreme solar weather should help mitigate against these events, there are two concerns. If, due to incorrect predictions, actions taken are too radical, for example unnecessary power shut-offs, the public may stop believing in the technology. This could evolve into a movement to stop the funding of smart grid technology. It is also important to be transparent with the public about such a system; however, it should be done in a way that avoids panic.

4.1.9 Health Issues

From an environmental standpoint, Levitt (2011) claims that the implementation of a smart power grid system would involve polluting the environment with “electro smog.” In addition, studies have shown that human exposure to radio frequencies hold a higher risk of cancer, infertility, heart arrhythmias, miscarriages, and sleeplessness. Moreover, while the Federal Communications Commission (FCC) regulates the effects of such radio frequencies on humans, there is no such regulation for migratory wildlife that may be impacted.

4.1.10 Drivers for Smart Grid Development

The development of a smart grid is a lengthy process that requires dedicated capital over several years and the concerted effort of energy producers, engineers, policy makers, regulatory agencies, and local officials. A variety of drivers exist for the development of smart grids in countries around the globe, shown in Figure 4-3.
The risk from global space weather events (such as GICs) can be added to this list for all developed countries, especially those in the highest latitudes, including whole regions of the United States and China. As policy makers become more aware of the risks, consequences, and costs associated with space weather events, the power industry can also expect increased pressure to adopt adequate measures for uninterrupted service, even in the face of severe space weather events such as GICs. In Europe this could be particularly difficult as countries will have to agree on a defined framework for full-scale deployment (World Energy Council, 2011).

4.1.11 Financial Considerations for Smart Grids

In 2011, the Electric Power Research Institute estimated that if the U.S. were to continue its smart grid implementation plan through 2030 the total investment required would be between US$338-476B (Table 4-2) (EPRI, 2011).

Table 4-2: Estimated costs and benefits from EPRI analysis April 2011 (EPRI, 2011).

<table>
<thead>
<tr>
<th></th>
<th>20-Year Total (Billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Investment Required</td>
<td>338 – 476</td>
</tr>
<tr>
<td>Net Benefit</td>
<td>1,294 – 2,028</td>
</tr>
<tr>
<td>Benefit-to-Cost Ratio</td>
<td>2.8 – 6.0</td>
</tr>
</tbody>
</table>

This cost of smart grid implementation pales in comparison to the impact of a major solar event occurring today. In a 2013 report from Atmospheric and Environmental Research, Inc. (AER), the total economic cost for such a scenario is estimated to be US$0.6-2.6T (Lloyd’s, 2013).
Table 4-3 shows the approximate investment (in billions of USD) per year over 20 years required to implement a smart grid. These numbers are interpolated from the estimation provided by (EPRI, 2011) and (Lloyd’s, 2013) in conjunction with their individual Gross Domestic Product (GDP) (International Monetary Fund, 2013).

<table>
<thead>
<tr>
<th>Country</th>
<th>Country GDP</th>
<th>Major solar event minimal cost</th>
<th>High Investment Smart Grid (per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>1736.87</td>
<td>69.52</td>
<td>2.78</td>
</tr>
<tr>
<td>China</td>
<td>7203.78</td>
<td>288.32</td>
<td>11.54</td>
</tr>
<tr>
<td>Germany</td>
<td>3604.06</td>
<td>144.25</td>
<td>5.77</td>
</tr>
<tr>
<td>Ireland</td>
<td>221.02</td>
<td>8.85</td>
<td>0.35</td>
</tr>
<tr>
<td>USA</td>
<td>14991.30</td>
<td>600.00</td>
<td>23.80</td>
</tr>
<tr>
<td>Russia</td>
<td>1857.77</td>
<td>74.35</td>
<td>2.98</td>
</tr>
</tbody>
</table>

A robust smart grid requires the upgrade of technology at every stage in a power transmission network. As we have seen, this can be an expensive proposition, but the power industry can also take advantage of increasing government and industrial awareness to apply for public, private, or regulatory funding for the incremental upgrade of the power distribution infrastructure, as shown in Figure 4-4.

A robust smart grid has clear benefits for energy producers and customers as it increases both efficiency and survivability.

4.1.12 Current Smart Grid Development

Smart grid technology is still in its infancy. At present, the industry consists of a large number of constituent contributors including many start-up technology companies and service providers. In their review, McHale et al. (2013) lists several instances of physical smart grid implementations worldwide.
According to McHale, et al. (2013), Asia is at the forefront of smart grid development. This is primarily due to the lack of existing large scale terrestrial power transmission networks on the continent. In North America, trial smart grid networks already exist in parts of Virginia, Florida, Texas, New Mexico, and California in the USA. Smart grid implementation is slower, however, as the existing power grid inhibits adoption of this new technology.

In Europe, smart grid adoption is also underway, but there is still a large investment required to change from a centralized to a pseudo-decentralized infrastructure. The adoption of micro grids into the power system would facilitate this by allowing better integration of renewable energy, supporting the balance between supply and demand. From a commercial standpoint, smart grids will require a distributed plan to finance the required smart grid development and implementation. Possible sources of this funding include public funding, external grants, private funding, and regulatory incentives, as shown in Figure 4-4.

4.1.13 Conclusion
Smart grids are a natural progression from the currently outdated and overloaded power transmission networks. Robust smart grids will allow the mitigation of space weather effects such as GICs by utilizing real-time monitoring, reaction, event anticipation, and instantaneous isolation of faults. Public and private support is required for robust smart grid adoption or upgrades in order to realize these advantages.

4.2 Heliocentric Orbit COntinuous MOnitoring COnstellation “HOCOMOCO”

To provide new understanding of the solar wind to protect vulnerable space and Earth based assets.

4.2.1 Mission Objectives
To resolve knowledge gaps in heliophysics related to this as identified in Section 2.1, a heliocentric solar observation constellation is proposed, the Heliospheric Orbit Continuous Monitoring Constellation (HOCOMOCO).

HOCOMOCO is a constellation of small satellites (~50 kg each) designed to monitor, predict, and protect against severe solar events. To complete the mission objectives, the constellation must be operational for at least 11 years to record data during the entire solar max-min cycle. The main goals are to:

- Continuously monitor the solar wind and map the Sun's magnetic field to determine the trajectories of energetic particles relative to the Earth
- Help to identify how and where satellite failure modes occur
There has been a lot of effort spent on heliophysics research, but not enough information on the effects of the Sun on spacecraft exists. To obtain this data, we propose to insert a constellation of satellites in multiple elliptical solar orbits at different inclinations around the Sun. On board, scientific instruments should measure magnetic field strength and orientation, particle energies, particle composition, plasma properties, and subsystem component degradation and failure.

Through the operation of this constellation, solar activity on the Sun’s surface can be compared to magnetic field orientation and may provide forecasting of a solar event’s effect on Earth. Solar physicists would be able to update and refine the magnetic field models that are used to understand the solar cycle with the data collected from this mission. Ultimately, space-based and terrestrial infrastructure operators would be able to take the necessary precautions to safeguard against an impending solar storm, CME, or flare. In addition, we will study the vulnerability of spacecraft components to radiation exposure. This information will help improve component design and decrease sensitivity to these phenomena in future military, commercial, and civil space assets.

The mission strives for accurate and valuable solar scientific data with a constellation of probes, while keeping the probe payload and system design as simple as possible. The limited number of scientific objectives allows the use of a small satellite bus, which is suitable for constellation missions. Although the use of a small satellite bus imposes stringent constraints for power, mass, and telemetry budgets, these are achievable for the chosen platform.

4.2.2 Orbital Parameters

The USA, Europe, and Russia have sent many scientific missions in the past few years to gather scientific data from the Sun (Wilkinson, 2012). In the mid-1970s, for example, NASA launched HELIOS-A and HELIOS-B into two different elliptical heliocentric orbits that came close to the Sun (Bell, 2013). The vehicles had opposing spin directions and were designed to accurately measure the solar magnetic field. Details are shown in Table 4-4 and Figure 4-5 (Papitashvili, 2013; Braeunig and Wennmacher, 2011)

<table>
<thead>
<tr>
<th>Helios</th>
<th>Launch date</th>
<th>Last Data</th>
<th>Perihelion</th>
<th>Aphelion</th>
<th>Period</th>
<th>Inclination</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10 Dec 74</td>
<td>18 Feb 85</td>
<td>0.31 AU</td>
<td>0.99 AU</td>
<td>190.15</td>
<td>0.02 deg</td>
<td>0.5218</td>
</tr>
<tr>
<td>B</td>
<td>15 Jan 76</td>
<td>23 Dec 79</td>
<td>0.29 AU</td>
<td>0.98 AU</td>
<td>185.6</td>
<td>0 deg</td>
<td>0.5456</td>
</tr>
</tbody>
</table>
Figure 4-5: Trajectories of the two HELIOS space probes (HEASARC, 2013)
4.2.3 Constellation Design

These orbits provide proof of concept and SolarMax proposes to adopt similar orbital parameters for the proposed mission as shown Figure 4-6.

Perihelion, the point on the orbit closest to the Sun, will be 0.3 AU. Aphelion, the point on the orbit furthest from the Sun, will be 1 AU. In contrast to the HELIOS missions, however, we will launch sixteen probes into heliocentric orbit. This allows for high spatial resolution of magnetic field measurements. Eight of the 16 orbits will be inclined to 2.5 degrees in relation to the ecliptic plane. This shallow angle provides enhanced three-dimensional data without the difficult and lengthy gravitational assists that are necessary to achieve highly inclined solar orbits.
4.2.4 Launch and Deployment

The small spacecraft bus enables two launch options: either carried as a “parasitic payload”, or through the use of a dedicated launch vehicle. The idea of 16 “parasite load” launches within a short time was discarded due to the restrictions in launch platforms and their availability. Additionally, technical complications would result from the safety and interface requirements that the small spacecraft are required to comply with when launched next to more expensive payloads. Thus, a dedicated vehicle will launch multiple probes simultaneously into a parking orbit. Only two to four launches are necessary to deploy the entire constellation. The details of the distribution of the satellites within the launcher payload bay, the temporal separation of each launch, and the physical separation of the satellites once in the parking orbit are yet to be defined.

To insert into the final orbit, probes will be launched from Earth to a LEO parking orbit at or above 350 km to mitigate drag. Launching between the autumnal and vernal equinox and varying the launch angle based on the time of year will enable proper orientation of the probes in the ecliptic. System functionality and spin direction will be established in LEO. From there, in the course of one year, each probe will independently escape Earth’s gravity and be inserted into the proposed heliocentric orbit using the hyperbolic excess speed (Curtis, 2009). At this stage, those spacecraft requiring inclination change will perform a combined inclination change and injection burn. As an alternative, a direct injection orbit towards the Sun is still being considered at this phase of the mission design. A probe will be inserted into heliocentric orbit every 22.8 days to evenly distribute the spacecraft in the constellation. Up to now, no records are available on controlled formation flying of small satellites for inner Solar System exploration and further orbit optimization needs to be performed.

4.2.5 Payload and Experimental Subsystems

Rather than focusing on the detailed spacecraft design, this proposal will focus on the payload. The proposed payloads will study and monitor the most fundamental properties of space weather. Simultaneous magnetic field and plasma properties observations are needed in order to understand solar wind, interplanetary magnetic fields and space weather. The following instruments are proposed for the HOCOMOCO probes:

- Magnetometers
- Particle Spectrometer System
- Plasma Wave and Properties Instrument

The purpose of the magnetometers is to determine the direction and the magnitude of the magnetic field in interplanetary space. The magnetometers must accurately measure the changing magnetic field of the solar wind, in spite of the possible disturbing effects of the spacecraft. The information provided by the magnetometers will help to explain the interplanetary magnetic field and to distinguish plasma accelerations due to magnetic effects from thermal effects, for example.
The Particle Spectrometer System is used to determine the types and energies of individual particles in the solar wind. It will categorize incoming charged particles into electrons, protons, and heavier ions. It will need a high dynamic range to measure energies from slow electrons to fast ions. The measured energies can be used to derive the speed of the solar wind and the heavier ions give us hints on solar wind connections to the surface material of the Sun. (Roberts and Gosling, 1997).

The Plasma Wave and Properties Instrument is used to discover more information on the properties of the plasma as a whole. The instrument will study metric to kilometric plasma waves. These waves provide information on solar type II radio bursts (Gopalswamy et al, 2005), which are associated with energetic white light CMEs, and type IV radio bursts, which are related to material ejected by CMEs (Kaiser, 2003). The instrument also measures type III radio bursts, which are associated with solar flares (Hucke et al, 1992). In addition, the Plasma Wave and Properties Instrument will measure the basic properties of the local plasma, temperature and density, as well as the spacecraft potential.

HOCOMOCO will identify component failures during the mission in an effort to affect future spacecraft command and data handling systems. Both monitor component health and to reduce radiation risk, it is proposed to use redundant command and data handling systems. The system includes three computers, with one running at a time. The operational computer’s health is monitored continuously, and should failure occur, a second computer will automatically assume operation of the satellite. The redundant software generates scheduled resets and periodically scans through the command and data handling system memory, fixing errors. In addition to the control and data handling system, the software monitors the solar panels’ efficiency and degradation. The above events will be reported through telemetry data to provide better understanding on radiation failure mechanisms and protection.

4.2.6 Mission and Spacecraft Systems Key Drivers

The following key drivers were identified as critical points to consider for successful mission design:

- Protection against thermal loads produced by proximity to the Sun
- Protection against radiation loads due to interplanetary space and proximity to the Sun
- Telecommunication with a constellation of spacecraft operating near the Sun

4.2.7 Thermal loads

A major challenge will be the immense variation of thermal flux during the orbit. At perihelion (0.3 AU) the flux is about 16300 W/m², while at aphelion the flux is about 1,400 W/m² (Wertz and Larson, 1999). The spacecraft’s systems must remain operational within the flux and temperature range, so a combination of active and passive thermal control techniques is required.

Passive methods include thermal control coatings and multilayer insulation, in order to minimize absorbed solar energy, prevent excessive heat loss and excessive heating from environment. Active methods utilize heat pipes and refrigerators, to remove large quantities of heat from the satellite body. At perihelion, for example, the temperature is
very high, so the refrigerator requires a special high-efficiency design to convert power to sufficient cooling capacity for all the components of the spacecraft. On this point, future designers should consider the feasibility of using advanced superconducting technology. At aphelion, heat pipes and heaters will be used to keep the batteries, fuel tanks, and sensitive instruments of the spacecraft within a reasonable temperature range. The thermal sub-system will function in a way similar to an Earth-orbiting spacecraft thermal sub-system (Wertz and Larson, 1999).

### 4.2.8 Radiation Loads

The perihelion proximity to the Sun introduces ionizing radiation risks to each spacecraft in the constellation. Ignoring the effects of high doses of solar radiation will lead to a shortened mission lifetime. In addition to the triple-voting computers mentioned above, meticulous radiation testing, spot-shielding of the most vulnerable components with aluminum or tantalum, and avoiding single points of failure in the overall design may be used to mitigate radiation effects. Further details on the damaging effects of radiation on spacecraft and mitigation strategies to prevent malfunctions are discussed in Section 2.2.

Due to the relatively small number of earlier spacecraft sent towards the Sun, only limited data is available on the levels and effects of ionizing radiation close to the Sun. Thus, the HOCOMOCO mission will contribute significantly to our knowledge of spacecraft radiation exposure between the Sun and Earth, and its effects on the spacecraft systems.

### 4.2.9 Telecommunication

HOCOMOCO has significant communication challenges due to interference and blockage by the Sun, power, and size constraints. The Sun produces large quantities of natural radio emissions, which present one of the biggest engineering challenges. Since the HOCOMOCO probes will approach the Sun as close as 0.3 AU, solar radio emissions introduce noise into the transmitted signals. Furthermore, the orbits of the constellation sometimes place the spacecraft behind the Sun. Without a direct line-of-sight to the Earth, communications are not possible without being relayed by other satellites in the constellation. Case studies are necessary to determine the optimal communication technique including possible data relaying architectures, to transmit data from these satellites to Earth. The small satellite platform poses another issue for telecommunications - the available power for communication and the size of the communication equipment (e.g., antennas) is strictly constrained. Deployable solar panels and communication antennas may be a solution to these challenges. In addition, contact with the constellation needs to be maintained almost constantly as it is necessary to provide real-time measurements and space weather forecasting. As a whole, the spacecraft will “cooperate” to fulfill the mission purposes; thus, studies on a robust control loop are envisaged (Breger, 2004).

### 4.2.10 Cost

A cost estimate has been calculated by incorporating a variety of analog missions. Small satellite Earth missions and services have prices ranging from US$15-60M (Sweeting, 2012). Due to the few instruments required for the proposed mission, the expected cost of each HOCOMOCO probe will be on the lower end of this range. This cost will be further reduced through serial production techniques. Next, two solar observing mission costs were
compared: Helios-A and IMAGE in heliocentric and geocentric orbits respectively. Helios-A had a total mission cost of US$260M (Davis, n.d.), whereas, IMAGE accumulated expenditures reached US$81.9M (Gibson et al, 1999). This suggests a heliocentric mission costs about three times as much as a geocentric one. Combining this information, the estimated cost associated with HOCOMOCO is around US$500M.

The information obtained from this mission would benefit a number of organizations, for the reasons outlined in Section 5.3. For this reason, we propose a joint venture funded primarily by NASA and ESA, with additional financial support from an industry partner such as Intelsat.

4.2.11 Alternative Methods for Understanding the Likelihood of Severe Solar Events

We can gain indirect information on the likelihood of severe solar events on our Sun through observing similar events in other similar stars using the data collected by the Kepler mission. This mission was designed to use hypersensitive optics to detect exoplanets transiting across distant stars. As luck would have it, this same optical equipment can also detect increases in star brightness associated with solar flares.

If we can calculate the magnitude and frequency of solar flares in these distant stars, it may be possible to extrapolate those findings and improve our ability to predict severe solar events at this point in the Sun’s lifecycle.

From direct observations, a typical solar flare from our Sun releases $10^{21}$ kJ of magnetic energy (Harrison, 1995), and it is estimated that the most disruptive solar flare observed by humankind (the Carrington event in 1859) was caused by a $10^{22}$ kJ solar flare.

Preliminary analysis of the data from the Kepler mission found that for solar-type (slowly rotating, G-type main sequence, 5,100-6,000 K) stars, superflares that released $10^{24}$ kJ of magnetic energy were produced by a given star once every ~350 years, $10^{25}$ kJ superflares were produced once every ~800 years, and the largest superflares ($10^{26}$ kJ) were produced once every ~3500 years. Superflare production tended to be lower in warmer (5,600-6,000 K vs. 5,100-5,600 K) stars, and thus may decrease over the lifecycle of a solar-type star as its temperature rises (Maehara, 2012).

Unfortunately, this analysis is only based on the observation of 14 superflares from 14,000 solar-type stars over 120 days. The Kepler mission has observed 172,264 solar-type stars in a period of 223 days (Maehara, 2012), and so there is a large capacity to improve these estimates.

Analysis of these events is straightforward, but time-consuming. Candidate stars are identified by consulting the Kepler Input Catalog (Brown, 2011), then the duration and shape of light curves, and presence of nearby stars and nature of the pixel-level data is verified by independent observers. This independent analysis is important for separating solar flares from other phenomena, like fluctuations from orbital motion in binary star systems or from stellar pulsation.
The maximum energy released by a superflare does not seem to be related to the rotation rate of a given star (as assessed by periodic variations in luminosity). This suggests that the maximum buildup of magnetic field energy near sunspots may not be related to rotation rate. This has interesting implications for Earth as it suggests that superflares can also be produced by slowly-rotating stars like the Sun. Superflare frequency, however, does seem to be related to the rotation rate of a star. It is possible that more “tangles” in the magnetic field are produced at higher rotation speeds, resulting in increased solar flare production.

It is significant for humankind that these events occur every few hundred years. A period of 3,500 years is only a snapshot in geologic timescales – it is only one thousandth of the age of the Sun. The reduced flare frequency in warmer stars should not be overstated, as it risks fostering a false sense of security. Humankind should consider superflare events as inevitable, as they occur frequently in terms of the lifecycle of our Sun. These predictions have been made using only a fraction of the data available to us from the Kepler mission and further analysis must be undertaken to determine the true likelihood and strength of severe events in solar-type stars.

4.2.12 Future implications

Although some details are still to be fully explored, we consider this mission to be feasible and necessary to understand the Sun’s magnetic field. Future designers should develop the physical spacecraft, and network architecture; however, at this stage it can be defended against other planned scientific missions such as Solar Probe Plus or Solar Orbiter. Data produced by the HOCOMOCO mission can be used in conjunction with that from other missions (e.g. ACE, MESSENGER, STEREO, WIND, the Van Allen Probes, and SDO) to increase the overall understanding of our Sun.

4.3 Radiation Mitigation Case Study: Inspiration Mars

4.3.1 Introduction

We propose a method for mitigation of radiation exposure through characterizing the directionality of a radiation profile signature and redistribution of the interior architecture of a spacecraft. We demonstrate this on a habitat module with the 2018 Inspiration Mars fly-by trajectory of Mars. Our first iteration of this methodology reduced estimated radiation dosage by 37.4%. We also discuss the importance of acute and chronic radiation dosages, and present a risk assessment of a solar particle event directed at the Inspiration Mars mission. We also investigated ergonomic constraints in design for astronauts. Finally, we examined the implications of the success or failure of the manned Inspiration Mars fly-by mission to government, space agencies, and private industry around the world.

4.3.2 Overview

Like venturing over the ocean or into the sky, extending humanity’s reach into the darkness of space is fraught with difficulties. Solar radiation and galactic cosmic ray exposure are major concerns for the lifespan both of spacecraft hardware and of astronauts (Schwenn, 2006), in terms of long-term attritional degradation and catastrophic radiation events. We depend increasingly on satellites for navigation, weather forecasting, observation, disaster
management, and a myriad of other functions that facilitate our daily lives. Given this, it is surprising that we have only identified in the last ten years how vulnerable our entire space infrastructure is to the local space weather environment as shown in image 3.3.

The focus of this sub-chapter is to suggest a methodology that mitigates the radiation exposure of vulnerable assets within a spacecraft in space, whether delicate instruments or astronauts. The methodology focuses on redistribution of the existing interior bulk architecture in the hopes of extending the functional life of a spacecraft, and increasing the career life-span of astronauts through reduced radiation exposure as shown in Appendix 6. Increasing the working life span of spacecraft could result in fewer craft being launched, and reducing congestion and the quantity of debris orbiting the Earth. Increasing the career life span of astronauts could reduce total astronaut training costs, as fewer astronauts would need training. Incorporating this methodology at the beginning of the spacecraft design process should reduce radiation exposure while incurring minimal cost.

Such a methodology for radiation mitigation could be used in parallel with other radiation-reducing technologies. Through mitigation with existing architecture, the additional mass and power consumption associated with purpose-built technologies could be reduced, consequently reducing total mission cost and insurance.

Though applicable to any spacecraft architecture, this methodology is demonstrated through a case study, the Inspiration Mars mission trajectory (Figure 4-7) a 501-day manned Mars fly-by mission set for 2018 (Tito, 2013), but with the NASA Design Reference Mission habitat module (Figure 4-8) (Drake, 2009). The objective of this case study is to provide proof of concept that redistribution of the existing interior bulk can reduce radiation exposure of astronauts without significantly impeding on the ergonomics of the living space.

The general methodology involves:

- characterization of the spacecraft in terms of structural layout
- mapping of mass distribution between averaged astronaut location and the spacecraft exterior wall, $0^\circ-360^\circ$
- characterization of solar / GCR radiation exposure through mission profile, $0^\circ-360^\circ$
- coupling of radiation data to mitigation through existing distributed mass, $0^\circ-360^\circ$
- generation of design variables / constraints associated with structural layout design
- optimization of mass distribution for radiation mitigation for vulnerable assets

For the reasons outlined, this methodology would be of interest to any organization launching space vehicles - manned or unmanned - in particular governmental space agencies and the private industrial space sector. Not only would the implementation of such a methodology in the design process reduce various costs associated with the entire space architecture of an organization, but it would help meet current and future regulations associated with debris mitigation, radiation exposure, and liability (United Nations).
4.3.3 Implications for Success or Failure of Inspiration Mars Mission

The success of the Apollo program 50 years ago had wide-ranging implications on Earth. Inspiration Mars, due to launch in 2018, will also have a wide range of effects on Earth. These effects will be very different should the mission be a success, or a failure.

If the outcome is a success, this will imply consequences from different point of views. Governments may see funding pressures reduced if a private company achieves this goal, as others may imitate it in the space sector. A success, however, may also cause governments to feel pressure to invest more in human spaceflight. The technologies, methodologies, and data generated could accelerate development of a manned mission to the surface of Mars. Private industry could expand their influences and increase their profit by accessing the technologies developed.

If such a mission were to fail, the consequences for the three main sectors would be catastrophic. Governments may gain a bad reputation in relation to the technology of the country, implying economic losses which could lead to serious consequences in different fields. It may be also be harder to obtain the necessary funds to perform crewed missions. Furthermore, the relationship between private industry and space agencies could be damaged. For private industry, a failure could raise the question of whether private enterprises can really perform space missions independently. Private industry may be dissuaded from attempting such grand challenges. History, however, shows that the failures of private groups to attain their goals, reaching the North Pole, summiting Everest, have inspired more to try.
4.3.4 Interplanetary Radiation Environment

As noted in Chapter 2.3, crews and spacecraft beyond Earth’s magnetosphere experience radiation risks from solar energetic particles and galactic cosmic rays.

Typically, GCR fluxes are isotropic and represent the highest fraction of radiation received by the crew members during a mission. Because they are made of very energetic particles, the current techniques (passive or active) cannot completely mitigate these radiation sources (Figure 4-9). To date, counter-measures (medication) seem to be the best option to reduce the impact of these radiation sources on the human body together with passive shielding techniques to reduce the average levels inside the spacecraft. Further active technologies for radiation mitigation to be used in conjunction with the method described here are suggested (Appendix 1) as is the implementation of synthetic biology in Appendix 2.

Alternatively, solar proton emissions represent a lower fraction of the absorbed radiation but can represent a potential threat in the case of an intense single solar event (a solar flare during a mission could reach a lethal level). These proton emissions must therefore be shielded against, and their lower energy levels make this task easier than for GCRs. Since these protons are coming from the Sun, the emission flux is essentially lateral. It is not necessary to shield everywhere on the spacecraft to mitigate this radiation. Thus, the net radiation flux impinging on the spacecraft during a solar event is directional, and a tailored shielding methodology should take this anisotropy into account (Figure 4-10).

4.3.5 Human Factor Ergonomics in Spacecraft Design Process

Human factors focus on the interface between people and the system. The human factors interaction model provides a reference point of items to be aware of while designing, operating, and maintaining systems. Detailed checklists should be generated and customized for the particular system under development. The model illustrates a typical information flow between the human and machine components of a system.
While human factor principles are often researched and understood at a generic level, their application is only appropriate when tailored to the design phase (appendix 1.1.12). Human factors analysis methods are used to analyze systems, provide data about human performance, make predictions about human-system performance, and evaluate if the human-machine system performance meets design criteria. Ergonomic constraints for astronauts were taken into account in the redesign of the habitat module (NASA, 2010).

4.3.6 Method for Radiation Mitigation by Redistribution of Interior Architecture

The habitat module considered for the Mars Inspiration Fly-By Mission has been designed without consideration for radiation mitigation through bulk material within the interior architecture. Using an averaged location on each floor, based on estimates of how astronauts would spend their time day to day, a total averaged location on each floor was determined (Appendix 3). From these averaged locations, the habitat module is segmented into slices. These slices have an associated amount of material (polyethylene, aluminum, and water) between the averaged location and the exterior of the habitat module. Each material has a particular profile for which it mitigates radiation. The sequence of material distribution, the thickness of material, and these unique mitigation profiles were used in determining the amount of radiation an astronaut would receive over the entire mission from each unique segment.

We decided to include the need for mitigation of a major solar event, on top of mitigating the expected solar radiation and galactic cosmic rays throughout the mission. The most significant features of the original interior architecture (Appendix 5) changed for the redistributed architecture (Appendix 6), was moving the food and water storage tanks from above and below the two floors, to the walls. This was done to shield against directional radiation dosage from a large solar event and galactic cosmic rays. Considering the estimated movement habits of the crew (80%: second floor, 20%: first floor), it was decided to place both food and water storage tanks on the second floor to maximize shielding effectiveness. Full three-dimensional illustrations are viewable (appendix 7-8).

As a result of the first iteration of this redistribution design and optimization cycle, the shielding on the first floor increased in mitigation effectiveness by reducing total dosage from 32.5% of unshielded dosage to 26.7%, and for the second floor from 26.2% to 14.2%. With astronaut movements accounted for, through simple ergonomically constrained redistribution of the internal architecture, the total dosage is reduced from 27.5% to 16.7%.

Illustration of the results are condensed (Figure 4-11 to Figure 4-14) with a display of material thickness distribution from the perspective of the averaged astronaut location through their entire $0^\circ$-$360^\circ$ field of view. Overlaying this material distribution is a comparison between the unshielded radiation and the mitigated radiation dosage through each degree of view from the averaged astronaut location.
Figure 4-11: Lower Floor of original HAB: mitigated to 32.5% of exposed radiation dosage

Figure 4-12: Upper Floor of original HAB: mitigated to 26.2% of exposed radiation dosage

Figure 4-13: Lower Floor of modified HAB: mitigated to 26.7% of exposed radiation dosage

Figure 4-14: Upper Floor of modified HAB: mitigated to 14.2% of exposed radiation dosage
4.3.7 Cancer Risks associated with Mars Fly-by Radiation Levels

The measure of the energy transferred to a medium per unit mass by ionizing radiation is referred to as the absorbed dose (measured in units of radiation absorbed dose). However different types of radiation deposit energy in different ways. To have a consistent measurement of radiation impact on living organisms an equivalent biological dose is used, the Sievert (Sv), where 1 Sv = 1 J/Kg.

Cosmic rays, depending on type, have the potential to significantly impair the health of astronauts. High energy particles penetrate the human body and cause direct damage to DNA. This can lead to cancers and other diseases, making understanding the effects of space radiation on the human body vital for planning interplanetary missions.

Human space flight has so far been almost entirely in Low Earth Orbit (LEO). Data on the effect of cosmic rays on astronauts beyond this are limited. The Radiation Assessment Detector (RAD) mounted on the NASA Curiosity rover measured radiation levels on a trip to Mars to gather more data. Even during solar minimum, it revealed that the dose an astronaut would receive would be $0.66 \pm 0.12$ Sv, equivalent to a whole-body CT scan every 5 days (Zeitlin, 2013).

The annual radiation limit for highly exposed nuclear workers is set at 0.05 Sv/year, or 2.5 Sv for lifetime exposure, corresponding to a 5% risk of contracting a fatal cancer (NASA Space Radiation Program Element, 2009). NASA’s maximum exposure limit for its astronauts over their career is not to exceed 1 Sv or 3% of the risk of contracting a fatal cancer at a 95% confidence level (Cucinotta et al, 2010). The radiation exposure an astronaut would be subjected to on a Mars mission “is right at the edge of what is considered acceptable in terms of career exposure limits defined by NASA and other space agencies” (Phelan, 2013).

![Figure 4-15: Radiation exposures for a set of events (Fumihiko, 2002).](image)
The health risk of radiation exposure depends on the dosage level and the timescale over which it is received (Figure 4-15). A large dose delivered in a short period of time (minutes to hours) does greater damage than the same dose delivered over a long time (years). Exposure to intense doses of ionizing radiation within a short timescale can lead to radiation poisoning, with symptoms developing within hours (known as acute radiation syndrome) and even to death. Delayed effects, from both acute and chronic exposure, which may appear after many years, include tissue damage, cataracts, cancer, and development of abnormalities in children, discussed in Appendix 4. Considering the scarcity of information regarding the biological effects of GCRs, the uncertainty in radiation exposure must be taken into account.

4.3.8 Risk Assessment for Prompt Radiation Dosages from Major Solar Events

Though solar flares are difficult to forecast, high energy protons take at least two hours to reach the orbit of Earth from the time they are visually detected. Astronauts then have some lead time in which to prepare themselves. A massive solar flare on January 20, 2005 released the highest concentration of protons ever directly detected, which gave astronauts only 15 minutes to find shelter (Netting, 2005).

The dose of radiation a completely unshielded astronaut can receive from a solar flare is on the order of 1 Sv over the course of several hours (enough to cause radiation sickness). Fortunately, most solar protons can be stopped by relatively modest amounts of spacecraft shielding. Taking for example the three largest solar flares observed, February 1956, November 1960, and August 1972, the radiation dose an astronaut would encounter on board a spacecraft would average 0.38 Sv (assuming a spacecraft hull thickness of 5 grams per square cm of mass). However, if the spacecraft had a storm shelter with 35 grams per square cm of shielding, the dose would be reduced to about 0.08 Sv (Zubrin, 1996).

It was determined that during solar minimum, and assuming no major solar flares occur, the amount of radiation the crew would be exposed to during their mission would be 2.06 Sv using the original spacecraft internal layout. However, with a reconfiguration of the internal structure the radiation exposure can be reduced by 37.4% to 1.29 Sv. If a major solar event were to occur during the journey the astronauts would be exposed to 3.17 Sv, assuming the original spacecraft design. However this can be mitigated by 40.4% to 1.89 Sv if our structure reconfiguration recommendation was employed.

4.3.9 Conclusions and Further Work

The methodology described for tailoring the distribution of an existing interior architecture of a spacecraft to extend operational life of the spacecraft itself or astronauts on it, when demonstrated on the Mars Inspiration case study, has shown a reduction of dosage by 37.4%. The total radiation dosage estimated for the fly-by mission correlates well with previous work. Used in parallel with other future technologies for active radiation mitigation (Appendix 1.3.9), incorporating this methodology into the spacecraft design process could significantly reduce total mission and insurance costs.

Gaps in knowledge that have been exposed through this case study that are recommended to be addressed:
- radiation effects on core biological processes with an emphasis on further genetic research on carcinogenesis and degenerative diseases
- empirical data on the delayed long term risks of radiation exposure
- empirical data on solar / GCR radiation level variation through the solar system
5 SPACE WEATHER AWARENESS

5.1 Introduction

Dr. Alan Title is one principle investigator for NASA’s Solar Dynamics Observatory (SDO) and his biggest fear is not a modern day Carrington event. His biggest fear is the growing divide between the world’s solar science community and the rest of the world. When one of the foremost solar scientists on the planet made this statement in front of the SolarMax team, it created a reaction: this campaign. Dr. Title has seen the growing gap in awareness between the global science community, the key decision makers, and the general public. In 2012, the European Commission Joint Research Center published below graph (Figure 5-1) on space weather awareness, which supports Dr. Title’s thoughts.

Team SolarMax dedicated our project to closing this awareness gap. Using the marketing principles of price, product, place, and promotion, the team devised a threefold campaign aimed at the following groups:

- Policy Makers, Regulatory Agencies, Military
- Industry (Space industry, insurance, electricity, medical, etc.)
- General Public

We also created a set of actual marketing tools designed to serve as the basis for a true awareness campaign, which are to be used as follow-up to the SSP program. We follow Dr. Title’s sage advice and begin to close the gap on this critical topic.

Figure 5-1: Space weather awareness levels (European Commission Joint Research Council, 2012)
5.2 Policy makers and military awareness campaign

5.2.1 Introduction

Policy makers, regulatory agencies, and military organizations are a critical target in our awareness campaign. Because policy makers control appropriations and set priorities for industry, the general public, and all of government, it is imperative they are included. Regulatory agencies establish safety standards and provide frameworks for industry and society. Military organizations are concerned primarily with national security matters. Space, as the ultimate military high ground, has become a national security matter. Moreover, because the space weather threat poses the largest threat to critical infrastructure, all of these groups should consider it a national security threat. Framing the threat of space weather in this way should get it the attention it deserves. Additionally, government policy makers should consider themselves at risk as well. According to the US Department of Homeland Security, the domain of government services may be one of the primary casualties during a severe solar event, as depicted in the Figure 5-2.

![Figure 5-2: A web of interdependencies makes the modern economy especially sensitive to solar storms (US Department of Homeland Security, 2009)](image_url)

5.2.2 Special interests

Realizing that policy makers and regulatory agencies, especially in the developed world, are inundated by special interests, it is important to think about how to make an impact on these groups. The threat of space weather has to be delivered in such a way as to convey the seriousness of the threat of space weather and at the same time be financially and politically palatable. The realities of today’s political landscapes can marginalize an issue if it doesn’t have support from lobbies and other influencers. Moreover, short campaign cycles for elected officials tend to shorten the institutional memories for some special interests, and politicians are often concerned about acceptance by their respective electorates. For this reason, the policy maker portion of the awareness campaign must be planned and
executed in close concert with the industrial and public awareness campaign. Only in this way can a unified message reach its intended audience with enough momentum to clearly make a difference.

### 5.2.3 Legal rationale to inform public of hazards

An important rationale for governments to include space weather risks in their national disaster preparedness policies can be found in the Outer Space Treaty. Article IX of the treaty says that “States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extra-terrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.”. Articles I and XI mention the importance of “international cooperation”, while article V states that “States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.” (UN, 1967). These articles imply that states should cooperate in studying space-related adverse changes in the environment of the Earth and warn citizens and each other of dangers that these studies may reveal.

### 5.2.4 Relationship to national security

Many nations depend on space for national security purposes. Whether relying on navigation satellites for precision guiding weapons, situational awareness, or leveraging space as a reconnaissance platform, the military has a long history of relying on space to gather advantage. Some say that militaries have become too reliant on these systems, and command and control of critical systems is at risk (Krepon et al., 2007). Because of this, military and civilian command and control structures are at risk, and this point should be emphasized with military leaders and civilian policy makers. While the military have known of this threat since they started using space, more can be done. A second way space weather threatens national security is through its threat to critical infrastructure. This document lays out clear threats to that infrastructure in multiple chapters. If policy makers and agencies whom regulate this infrastructure truly deem it critical, the message we send about threats to it will be heard. Most governments have plans to protect their terrestrial and space-based critical infrastructure, however many do not consider the threat of space weather, instead focusing on other natural and manmade disasters. The aim of our awareness campaign is to begin to close this gap, so that planners and policy makers around the globe will consider space weather risks when performing their national security planning.

### 5.2.5 Channels and policy brokers

An ISU Master’s Program Team Project proposed an International Space Weather Organization to monitor and communicate space weather hazards (Abrahami et al., 2006). Unrelated, in 2007, the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) added a new item to its standing agenda, entitled “International Space Weather Initiative” (ISWI). The objective of this initiative is to coordinate global monitoring of space and ground weather assets, combine global forecast abilities and increase global
awareness, develop procedures for damage control, and to build up mutual assistance systems in case of a major event. Other possible channels for influencing policy makers include the Secure World Foundation, the US National Oceanic and Atmospheric Administration (NOAA) and specialist space weather institutes, often as part of space agencies. These organizations bridge the gap between solar science and policy makers, and are often referred to as policy brokers.

The people of the SolarMax team can help increase awareness by distributing the Executive Summary to relevant channels in our network. These channels include:

- At national level: Members of national parliaments, disaster management organizations, space weather related organizations (like the French Parliamentary Group for Space), NOAA, and lobbyists.
- At European level: The European Space Agency Space Situational Awareness group, EUMETSAT, and the Space Policy Unit of the European Commission.
- At international level: Secure World Foundation and the United Nations (UNCOPUOS and ISWI)

5.2.6 Conclusion and recommendations

While some policy makers are aware of the threat of space weather, many are still oblivious. Some interest groups and non-profits, such as the Secure World Foundation and ISWI have begun a concerted effort to educate key members of the international policy making and military community in an effort to spread the message about the importance of space weather risks. More help is needed in order to build on this momentum, before a major event occurs. Regardless of the recipient, this segment of the awareness campaign holds the keys to driving national and international policies on the space weather hazard.
Based on these conclusions, we recommend several low-cost high value steps that can be implemented to continue to make key policy makers, regulatory agencies, and the military more aware of space weather hazards.

- Advocate for national security documents to recognize the threat of space weather through their inclusion in key national strategic security plans.
- Consider the threat of long term outages, based on the effects of a large solar event.
- Engage critical infrastructure-related lobbies to send a unified message to policy makers.
- Work with the military space community to build an effective message to deliver to the non-military space community and leadership such that a cogent message from military commands can be delivered to civilian policy makers.
- Show policy makers that incorporating resilience into new and refurbishment construction has big effects for only marginal extra expenditure.
- Work with non-profit space advocacy groups to elevate space weather on their lobbying agendas with policy makers.
- Work with non-profit space advocacy groups to identify key policy makers in each country to deliver a tailored message to them.
- Leverage national and international conferences, and strategic office calls to deliver tailored messages to individuals and groups who have the power to alter appropriates and set policy.
- Characterize the threats to critical national security command and control infrastructure, so policy makers know to apply the appropriate priority to the problem.

5.3 Industry awareness campaign

5.3.1 Introduction

Industry knows how to handle changes in a profitable manner. The same is true for industries potentially affected by space weather. For many years, the power generation and distribution, and satellite manufacturer/operator industries have closely monitored space weather with an eye toward protecting their assets. However, a span of other affected sectors is not at this awareness level.

Our goal is to create a set of analyses and recommendations which can be applied across a spectrum of organizations in an effort to increase awareness. Team SolarMax has created an industry “briefing book,” which is a library of presentations, tailored to individual sectors we view as vulnerable to the effects of space weather. The briefing book is designed so that a team of one or two members of team SolarMax can use it to brief any industry at any given time. (Figure 5-3)
The team has identified the primary factors for communicating with industry stakeholders as conferences, tradeshows, and office calls. In the appendix we have included a list of upcoming events where the team can make an impact. The briefings contain the slideshow for the audience and enough background information for the speaker to make them an expert. The briefings are tailored to different industries, but also to different geographies. Both the level of understanding of space weather and the communication standards differ in different parts of the world.

Regardless of the target audience or geography, the team’s motto is: “Detect, defend, mitigate, respond and recover” (Figure 5-4).

**Detect, Defend, Mitigate, Respond, Recover**

**Figure 5-4:** Space weather response strategy

### 5.3.2 Interdependency of industry systems

After the industrial revolution, the space race, and the internet revolution, the world has effectively enmeshed communications, electronics, transportation, and many other critical infrastructures. It is easy to see why many speculate a Carrington-like event today would have far more grave consequences than in the past.

While the space and power industries have surely taken steps forward to protect their own equities, they are also aware that multiple systems have become heavily dependent on them (Baker et al., 2008). Almost every major system has dependence to either the space or power generation and distribution systems of the developed world. Because of this, it is even more critical that the awareness campaign target multiple and diverse industries. Only in this way can concerted mitigation strategies be implemented to create a higher baseline of infrastructure resilience.

### 5.3.3 Developed versus the developing world

Team SolarMax quickly realized a universal campaign would not work. Specifically, the Chinese and Indian members of the team indicated that the rural areas of their countries are of less risk than those in the urban cores. The team thinks that the proliferation of technology into rural areas for communications, agriculture, and health is happening at a
fast rate. The gap in technology dependence is quickly fading, increasing vulnerability to space weather events.

The indirect impacts of a solar event will affect the developing world. Access to fuel, transportation, and healthcare are examples of these effects. We concluded that factors such as distance from farm to table, access to fresh water, and other basic survival considerations are important for these regions.

For these reasons, the team designed a special industry briefing category for the developing world. The multi-industry briefing takes into account some of the resilience that already exists in developing world infrastructure, and takes advantage of the lower level of interconnectivities.

5.3.4 Dependency creep and risk gap

Dependency creep is the phenomenon wherein a system becomes increasingly dependent on another related or previously unrelated system. An example of dependency creep is the television industry. In the early days, the television industry relied on a broadcast signal that was received by antenna, cable, and later internet. Because of this phenomenon, almost all modern transportation, communications, and services industries have some creeping dependency on the power generation industry.

The risk gap manifested primarily during our insurance and reinsurance industry analysis, and represents the difference between actual and perceived risk which a company may experience. In other words, because a reinsurance company’s disaster risk modeling software does not take into account the hazards of space weather, their risk load is actually higher than they perceive it. Many of the studied industries have a risk gap, based on the potential hazard of space weather.

5.3.5 Incentives for awareness

Most industries are under a lot of financial and regulatory pressure. Any recommendations for change need to be delivered with one of two strategies. There needs to be a clear incentive for a company to unburden some of its risk. There are several industries that naturally offer these incentives. For example, the oil and gas industry typically has a strong lobby with policymakers and leaders.

Although, the oil and gas industry has traditionally ignored some of the risks associated with space weather, it has not engaged with discussions about policy concerning space weather. This is a lost opportunity and a prime example of leveraging industry to create larger policy and regulatory changes. Similarly, because several critical industries have become over-dependent on the power generation and distribution industry, some might argue that industry is carrying too much of the world’s risk load. Certainly, the CEOs and shareholders of those companies would enjoy any policy, operation, or procedure which would reduce that load, and therefore the business risk associated with the endeavor.
5.3.6 Findings

Industry stakeholders will like a highly incentivized and tailored message, delivered in a forum designed to garner the most exposure, and backed with substantial research and support. They will also welcome government support and regulatory guidelines, as many feel they are carrying an unfair share of the risk load. Based on this, team SolarMax created a library of portable briefings, to engage various industry decision makers. These briefings are an important product of this project and will be made available through a special website.

5.3.7 Multi-industry steps

Team SolarMax identifies multiple strategies which apply across multiple industries. These are the multi-industry steps, which often have a mutually reinforcing effect on each other:

- Create awareness in customers, clients, and leaders
- Prioritize resilience into the design phase of all engineering projects
- Work to identify and prevent dependency creep
- Design and maintain performance surplus in systems to allow future loading and surges
- Educate regulators and policy makers to potential disasters and risk loading
- Educate industry incentivizers like financial, medical, and energy lobbies
- Design to remove or control interdependency for downstream assets, clients, and partners alike
- Gather/Interpret current and future data
- Advocate data sharing between industry, science, and the general public
- Help educate the general public

5.3.8 Industry Snapshots

Targeting the Insurance and Reinsurance industry is the key to our strategy. The entire insurance industry is underpinned by financial and statistical models used in their everyday activities, but as we explained in Chapter 4, these models do not usually take space weather into account. Insurance is one of the few true motivators of multiple other industries; if we can educate the insurance industry on solar hazards, the true value of the risk can be shifted downstream to the clients who are directly affected by space weather.

Similarly, the financial sector has invested heavily in vulnerable industries and stands to lose a great deal of money in the event of a severe geomagnetic storm. The finance industry itself is also heavily dependent on electricity and telecommunications. Generally, the finance industry reacts quickly to new scientific information. It can offer important incentives for change to its corporate customers.

Once we have brought the Insurance and financial industries on-side, it will be much easier to motivate other sectors to adopt our industry-specific recommendations as summarized below.
Satellite Manufacturers

NASA reports suggest that many satellites have already been lost to space weather. (Bedingfield et al., 1996). A well-known example of this is the Anik E2 satellite, as described in section 4.3.2. The satellite builders industry is one of the industry leaders in mitigation efforts. We recommend the following steps for the satellite manufacturing sector:

- Educate business and programmatic staffs on the business risks to the company that space weather poses
- Educate technical staff to implement resilience, redundancy, and hardness into the design work, and maintain the principles through the building phase, even in the face of mass and financial pressures
- Work with insurance companies and clients to ensure the risk load is understood and spread evenly among these stakeholders
- Satellite risks are shared by manufacturers and operators. Any campaign targeted at these sectors should emphasize this relationship, to affect decision makers (Figure 5-5)

Satellite operators

Satellite operators have long been aware of space weather threats. They often have procedures in place to react to potentially adverse space weather. During space weather events, satellite operators have critical decisions to make regarding safety shut downs.

Satellite operators typically consider their equipment to be part of the critical infrastructure (Baker et al., 2008). Similar to the power industry, resource constraints drive hard decisions, and LF/HC events are tough to factor into long term planning. Team SolarMAX has the following recommendations considering all those factors:

- Educate customers, and the satellite manufacturers on expectations regarding space weather.
- Educate staff on the threats so as to better quantify the business decisions regarding safing and downtime procedures.
- Educate policy makers and regulatory agencies on the risk load associated with space weather, and seek to share that load, as a true critical infrastructure industry.
Power generation and distribution
Energy companies are aware of potential for massive ground induced current-related outages and permanent infrastructure. They have installed sensors to be able to predict problems and implemented procedures to mitigate disaster. While many improvements have been made, large scale power distribution network consolidations have increased the risks of space weather related outages (Baker, 2008). To complete the robust smart grid proposal (section 5.2), we recommend:

- Building resilience into power distribution systems. Customers should be assisted in identifying and mitigating dependency on the power distribution infrastructure
- Reach out to the solar science community and assist in identifying gaps in our ability to predict and mitigate the effects of space weather

Transportation
While the transportation sector has contingencies for short term outages, few have invested in long-term disaster planning. According to Conrad (2001), most global food crises involved breakdown of regional distribution systems. All components of the transportation networks are critical. We recommend that:

- Customers should be made aware of their dependence on transport
- Strategic industrial reserves of fuel and spare parts to decrease outage vulnerability should be carefully considered

Aviation
The aviation industry is well aware of space weather risks. This experience makes them an important partner in our outreach to other critical industries. They can help put space weather situational awareness on the lobbying agenda for the industry as a whole, and educate staff, employees, the public, and policy makers. The aviation industry should encourage international data sharing to improve the ability to analyze and predict space weather to prevent operational losses.

Meteorology
The meteorology industry is a key facilitator in our space weather awareness campaign. We recommend that they act as an industry and public educator. It can engage the general public through forecasts and additional solar physics and space weather events. Meteorologists should have close relations with the solar science community and demand better quality data for improved modeling.

Healthcare
The medical and healthcare industries are of critical importance during crises. They should clearly understand space weather threats. In addition to their role in disaster management, they are themselves very dependent on electricity and transport, although they have implemented measures to protect critical internal systems in case of power outages and transport failures. We recommend continued development of resilient systems, guaranteeing independent continued operation of healthcare services in case of major outages caused by solar events.
5.3.9 India, China, and the developing world

Implications of solar events to the industry in countries like China and India differ from Europe and North America. Due to their latitude, less interdependent power infrastructure, and higher tolerance for regional outages, they are less concerned with potential effects. In these countries ownership and maintenance of critical infrastructure is generally a government issue, involving fewer companies (see Figure 5-6).

![Multi-Industry Region Specific Library](image)

Tailored presentation
For flyaway team

Figure 5-6: Region-specific library concept

5.4 Public awareness campaign

5.4.1 Introduction

Public interest in and support of space activities is widely acknowledged in the space community as being fundamental to sustaining long-term international space exploration programs. (Ehrenfreund et al, 2010). This is true for space exploration programs in general, but also for space applications and space-related hazards like space weather.

The purpose of public communication campaigns is to inform or influence the behavior of large audiences within a specified time period, using an organized set of communication activities, featuring an array of tailored messages, using multiple channels, generally to produce non-commercial benefits to individuals and society (Rice & Atkin, 2009; Rogers & Storey, 1987). There are several factors in this description of a public communication campaign which need to be defined. The purpose of the TP SolarMax public awareness campaign is primarily to inform the general public about the risks of space weather. This is based on the premise that information and knowledge are required before people are willing to take action. Because it is difficult for a small team of ISU students to reach out to seven billion people, our awareness campaign will use more powerful channels to relay our message. So although the products that we develop in the campaign are aimed at the general public, we will deliver these products to science communicators in governments, and the media and entertainment sector.
It is important to highlight that the Executive Summary that comes with this report is our primary awareness document. The title “Space weather survival guide” was chosen for this exact purpose. Many of the products developed in the campaign play a central role in the Executive Summary.

Due to time constraints it would be unwise to develop our campaign from scratch. There are many good lessons to be learned from other global public awareness campaigns, both inside and outside of the space sector. There are many examples of successful public campaigns, such as raising awareness for disease control, poverty reduction, and disaster management. This success can be measured as campaign reach, impressions, money raised, and/or awareness of the subject with the general population. The closest example of a space-hazard campaign is the asteroid or NEO (Near Earth Object) impact awareness campaign, as described in the next paragraph.

5.4.2 NEO Impact Awareness Campaign

“Cosmic impacts are both quantitatively and qualitatively different from other hazards. The death toll from the impact of a comet or asteroid no larger than [...] 1 mile across could reach hundreds of millions.” (D. Morrison et al., 2004). In his article on NEO risks, Morrison (2004) describes four elements of communication to the general public:

- **Use mass-media channels** to communicate knowledge of the NEO hazard itself in a variety of public forums such as hearings in US Congress and TV documentaries.
- **Use the internet** to answer public questions and provide up-to-date information. In 2004 social media was not included here, but in 2013 these are an important part of the campaign.
- **Use scientific bodies** to increase public interest in NEO hazards and real impact risks through scientific bodies like the International Astronomical Union (IAU).
- **Use a simple, one dimensional hazard scale**, which is easy to understand by the media and public. For NEO hazards the Torino Scale is used.

5.4.3 Applying lessons from the NEO campaign to solar risks

The NEO campaign contains a few simple lessons that can be immediately applied to the risk of solar events to society. The four key elements that Morrison (2004) mentions are especially useful. Obviously the nature of the hazard is very different, but the ‘low frequency, high consequence’ risk is very similar.

- **Mass media channels**: Team SolarMax proposes the use of mass media channels for public communication. As said, the immediate reach of the team itself is too limited to make a significant global impact. By using mass media (film, documentary, magazines) and political channels (like the UN, NASA, NOAA, ESA, risk management bodies in national governments, etc.) we will be able to reach millions of people.
- **Internet**: We will use the power and reach of digital social media like Twitter and Facebook for our campaign. There is a lot of good information about space weather available, which can be useful in social media campaigns. This part of the campaign will be supported by an informative website, which will act as a repository of space weather information and communication products, like those mentioned in this chapter.

- **Scientific bodies**: Institutes like UNCOUOS, the ISWI, NOAA and the newly formed ESA Space Situational Awareness group, could play an important role in distributing the material that team SolarMax has produced.

- **Hazard scale**: The space weather equivalent of the Torino Scale are the NOAA Space Weather scales (NOAA, 2005). These scales describe three distinct space weather events in five simple intensity levels. We propose to adopt these scales to become the standard global space weather scales, to be referred in all space weather events that reach the general public.

### 5.4.4 Engaging the general public

One of the oldest challenges in public understanding of science is how to convey the message to people so that they are genuinely interested. Simple scientific information distribution generally does not raise such interest. (Bauer et al, 2007)

The vision on public engagement has changed over the past years. Participatory education and outreach strategies “that transform the public stakeholder into an integral part of future space exploration endeavors” are the best strategy (Ehrenfreund et al, 2010). So rather than sending information to the public, or showing them examples, they need to be personally engaged. People need to see – and preferably feel – the impact of events in their personal lives.

### 5.4.5 Selecting channels

It is important to select the best suitable channels to reach the public. One of the Space Studies Program core lectures clearly showed that different media channels have different reach, attention level, stimulation, and overall effect (Peeters, 2013). These channels all come with different price tags, making channel selection an important task in a campaign. But instead of working with commercial media channels, we will influence public information channels and the media industry to collaborate with us to bring our important message to the masses.

In order to reach millions of people with our campaign, we will use several channels that can help us with our campaign. So although these channels are not the final customer for the awareness products, they are the main target group. Ultimately it will be these channels that reach the final audience in the general public. The selected audiences for the SolarMax public awareness campaign are the following:

- **Movie directors** – By supplying a sample movie script, we will create interest for a realistic and attractive ‘space weather disaster movie’. We believe that there is a good Hollywood-style story in the risk of space weather to the planet, with good opportunities for actors to ‘save the planet’. The impact of movies like Armageddon and Deep Impact for the NEO campaign is a good example. If nothing else, people
recognized the NEO problem in these movies.

- Scientific bodies – Team SolarMax will reach out to several space weather related organizations for relaying its awareness messages. The primary body will be the ISWI, followed by UNCOPUOS, NOAA, the ESA Space Situational Awareness organization and other scientific and political organizations that have an interest in space outreach and education.

### 5.4.6 SolarMax public awareness campaign products

The public awareness campaign consists of several communication products, all intended to get the general think about the risk that space weather imposes to their personal lives. There is a delicate balance between engaging people in the message and creating unnecessary fear. Nevertheless some level of fear may be effective to convey the relevance of the subject, as shown by the success of disaster movies.

The group of products that we developed contain different levels of entertainment, information, and fear. Ideally they are used in combination, showing the public different aspects of space weather and the risks to society. Table 5-1 shows these products and the implied messaging.

<table>
<thead>
<tr>
<th>Product</th>
<th>Audience</th>
<th>Channel</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Summary</td>
<td>Policy, industry, public</td>
<td>Personal</td>
<td>Multiple</td>
</tr>
<tr>
<td>Solarhazard.org website</td>
<td>Policy, industry, public</td>
<td>Website</td>
<td>Multiple</td>
</tr>
<tr>
<td>Movie storyboard</td>
<td>Public</td>
<td>Movie directors</td>
<td>Risk/Fear</td>
</tr>
<tr>
<td>Comic</td>
<td>Public</td>
<td>Social media</td>
<td>Entertainment</td>
</tr>
<tr>
<td>Elevator pitches</td>
<td>Policy, industry, public</td>
<td>Personal</td>
<td>Information</td>
</tr>
<tr>
<td>Disaster preparedness kit</td>
<td>Public</td>
<td>Government</td>
<td>Information</td>
</tr>
<tr>
<td>Timeline stories</td>
<td>Public</td>
<td>Executive Summary</td>
<td>Risk/fear</td>
</tr>
<tr>
<td>Info graphics</td>
<td>Public</td>
<td>Social media</td>
<td>Information</td>
</tr>
</tbody>
</table>

**Executive Summary**

The Executive Summary is designed so that it becomes an instrument in our awareness campaign. It summarizes the most important scientific findings (what is the problem?), the impact of space weather on different aspects of society (why should we care?) and examples of possible solutions to mitigate the risks of space weather (what can we do about it?) as we can see in figure XX. We intend to print as many copies of this document as possible, in an attempt to get it on the desks of as many critical political, industry and science communication decision makers and communicators as possible.
Solarhazard.org website
When we communicate the SolarMax project message it will be very beneficial to have a central repository and customer friendly portal for all relevant communication material. For this purpose we reserved a dedicated URL: “www.solarhazard.org”. Once all material is available we will build a simple website where different target audiences will be able to quickly find relevant information. Most of the products mentioned above will be available directly from our website, or via a link provided at our website.

Movie storyboard
One of the most powerful ways to reach a large audience with a scientific message is by packaging it in a thrilling blockbuster movie. The risk of a massive solar event disabling much of society on Earth offers an exciting backdrop for a great Hollywood disaster movie. We would love to see one of the large studios picking up this idea and work out the details of such endeavour. Inspired by the impressive trailer of the new (space debris-themed) movie Gravity (2013), we developed a sample script for a new movie about space weather as shown in below figure. A professional movie director will further develop this, where the SolarMax team is obviously ready to lend a (scientific) hand.
Infographics

Readers of popular science in the digital age do not want to read long texts explaining a situation. It is much more attractive to show a good picture of artistic interpretation of a situation, with little pieces of relevant information. These charts are called infographics. In the case of space weather risks there are many organizations that produce very good infographics, which are both attractive and contain good information. So rather than creating many new info graphics, team SolarMax is happy to help distribute the many existing graphs produced by NASA, NOAA, ESA and many other institutes, figure XX is an example. Our solarhazard.org website will contain links to the original work.

Infographics can be used in both traditional (magazine, paper, television) and new digital media. There are even special social media for sharing graphical information, like Pinterest. We will encourage our team members, as well as professional science communicators to use these media to the maximum extent.
Comic
Our comic is the result of a very short creative brainstorm and a “let’s just do this” idea. It took only half an hour to produce and is a funny way of representing one of the messages of team SolarMax. But more than just a joke, it is a good showcase of how another format can distribute a message to unexpected audiences. Being a one-page comic, this format is very easy to distribute via social media like Facebook and Twitter.
Storytelling
A good way to inform people about risks is by storytelling. A “what if” story triggers imagination and helps assess the risk level and possible consequences. Several good stories can be found in existing literature, for example in “Storms in Space” by John Freeman (2001). We were also inspired by the timeline presented in the ISU team project report “Common Horizons” (2013), describing a day without space. In order to express the different impacts of space weather events in different places in the world, we describe a
large solar event from the perspective of three different countries.

<table>
<thead>
<tr>
<th>The Carrington 2015 CME hits Europe in the heart</th>
<th>A story of Grady In Africa</th>
<th>A story of Li Liang In China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrington 2015: Massive power surges kill hundreds in power stations and near transformers. Several aircraft crash near the airport. All phone, internet and broadcast communication is knocked out instantly. Electronic circuits in cars and trucks are destroyed, stopping most of road, rail and air transport. A day later massive panic breaks out, as people are stuck without transport and communication. There is widespread confusion. Without power, hospitals struggle to save lives. Governments declare the state of emergency. Large scale food riots break out in the larger cities. A week from the CME only very small and local areas regain power. Military efforts are used to install power generators at hospitals. Too late for many patients. Lack of food and medical support, combined with water pollution cause outbreaks of contagious diseases. Medicine supplies from Asia are insufficient to suppress these outbreaks. Riots spread further and many are killed in food and water shootings.</td>
<td>Grady is from Sierra Leone. She lives in a rural farming community, where people live in mud huts with a dirt floor and a thatched roof, without electricity. Cooking is done on an outdoor fire. Laundry, washing, and bathing are done in the nearest river, or with water hauled from the closest water source. The CME creates massive red auroras. Grady assumes they are beautiful gifts from the gods. A day later Grady wakes up with the sun and starts her day by cleaning her house. She walks 2 hours to the river to get the daily supply of water. Later that week Grady pounds cassava leaves with her mother and has lunch with her family. After lunch, her task is to do the dishes. Then she walks to the river to get more water. Grady is unaware of what has happened to the far-away high-tech society. Her life depends on water, not electricity...</td>
<td>Li Liang is a teacher at school. He lives in Xi’an, one of the oldest cities in China. His apartment is on the 10th floor of a 31-floor building. He is shocked by the destructive effect of the solar flare. He tries to call his brother, who works in the USA, but fails. The Chinese government declares a state of emergency in the disaster areas. All supply routes are suspended. Li Liang learns more about the space weather on local radio. He is worried about his brother. A day later the Red Cross Society of China organizes a donation campaign. The Li Family donates $220, including $20 from their daughter. A month after the CME hits Europe, the Chinese government makes emergency plans on space disasters. Soon after the disaster China receives many refugees. The government urges companies to hire...</td>
</tr>
</tbody>
</table>
Half a year later refugee camps around rural communities have grown. Hunger and disease are common. People have set up primitive water purification and power generation plants, but food remains scarce. Western economies have come to a standstill. It will take at least 10 more years to repair society...

many of them to keep disaster relief production high.

A year after the CME the first satellites of the new Chinese space weather surveillance constellation are launched into space. Space cooperation across the world become closer and space weather data can be accessed by every country for free...

Figure 5-11: Timeline for public awareness campaign

Elevator pitch
An elevator pitch can be defined as a very concise presentation of an idea, covering all of its critical aspects, delivered within a few seconds. It is a form of storytelling, specifically tailored to very short interactions. A good elevator pitch is a great conversation starter at networking events, but can also be used in advertising, TV or radio presentations, opening speeches, or when meeting with important stakeholders on tight schedules. It can also be a good idea to put the elevator pitch on the back of an otherwise blank business card.

The opening quote in our Executive Summary is a good example of a first sentence of a space weather elevator pitch: “Space weather destroys stuff.” It clearly expresses the “What is the problem?” question. Here are a few examples of elevator pitches for different audiences, to be used when engaging in short conversations with stakeholders, and of course after introducing yourself:

For industry or policy makers
Space weather destroys things. It has in the past and it will again in the future. Current society is not prepared for a large solar event. Solar events are powerful enough to knock out the entire power infrastructure of a continent for months, impacting all aspects of modern society, costing billions of dollars in disaster management and repair. It is possible to protect ourselves against this danger, at a fraction of the disaster repair cost.

For the general public
Space weather destroys things. It has in the past, and it will again in the future. We are not prepared for a large scale solar flare. All electric devices in your house and in town will break down and you will be without electricity for weeks, possibly months. This imposes a great risk to you and your family. It is possible to protect yourself and your community against this risk. Please inform yourself about vulnerabilities in your environment and help your government and industry protect your community.
**Disaster Preparedness Kits**
Many governments around the world inform their citizens about disasters. This is usually part of a national disaster management plan, which usually follows the “detect-defend-mitigate-respond-recover” sequence. Research by the policy makers group revealed that only the US public disaster plans mention space weather risks.

The Chinese national government website has a section on emergency planning. For the average family, it gives basic information, a family disaster plan, and recommended safety kits. The Chinese Earthquake Administration has a handbook on safety survival. Among other things it has recommendations about storage for emergency, which can be referred to for space weather disasters.

We recommend adding a space weather section to all disaster management plans in the world. As an example we took the Dutch government “Prepare for Disaster” information leaflet, which lists many possible disasters to society. This chart should have a section on space weather.

**Figure 5-12**: Disaster management example (Government of the Netherlands, 2013)

**5.4.7 Discussion**
Space weather destroys things. This is the heart of the message that we want to bring to the population of the world. Once people are aware of the risk to their personal situation, they will be willing to help mitigate these risks. Awareness is a first step towards action. We have developed several products that help governments and other organizations to carry that message to the general public. Most of these products aim at informing people in an
entertaining yet serious way, but some may actually impose a certain feeling of fear. By combining these products into a campaign, we will find a good balance between information, engagement and fear. We will take these products to selected organizations that can help us distribute the messages to the public, such as movie directors, UNCOPUOS, ISWI and different national space weather institutes.

5.5 Conclusion

Governments, industry, and the population at large must be made aware of the threats of space weather. To this end, we have designed three awareness campaigns: the campaign to the Government emphasizes the national security problems that a loss of infrastructure could cause. The campaign to industry emphasizes the potential for massive financial losses. Finally, the campaign to reach the general public, we propose a sweeping multi-media campaign designed to make them aware of Space Weather as a potential problem in the same way that they are aware of Near Earth Objects.

Team SolarMax believes that once those three key audiences have been made aware of the danger, they will take steps to implement protective measures.
6 DISCUSSION AND RECOMMENDATIONS

With this report we answer a number of basic questions about the risks of space weather. We identify the most critical knowledge gaps, list ideas on how to protect the most vulnerable space and terrestrial assets and recommend an awareness campaign to trigger a sense of urgency with the most critical stakeholders. The effect of our work however lies in the futures. After finishing our Space Studies Program we will take these results home all over the world with us and share the most important outcomes with the stakeholders. We realize that stakeholder awareness and the implementation of our recommended solutions will require our persistence and our time. We also realize that we cannot save the world with our small group of ISU alumni alone. Many of our recommendations involve engaging others to multiply our message.

Here are some of the more immediate actions that we will take as a team to start implementing our recommendations:

1. **Executive Summary** – The primary instrument of our awareness campaign is the executive summary that comes with this report. We aim at printing our ‘Space Weather Survival Guide’ in large quantities, so we can distribute it to all stakeholders during all below events.

2. **International Astronautical Congress 2013** – We have the opportunity to present our team report at the IAC in Beijing in September 2013. Several of us will be present at this important conference. This will require an official paper, which we will write immediately after SSP.

3. **UNCOPUOS and ISWI** – Using our contacts at ISU and Secure World Foundation we will address the Technical and Scientific Subcommittee meeting of UNCOPUOS in February 2014.

4. **NASA** – We will present the idea for the HOCCOMOCO solar observation mission to NASA as an idea for a public-private partnership development with a commercial investor.

5. **Kepler Data** – We will be actively involved in continued research of space weather data, specifically starting with the Kepler database at NASA Ames. This database will unlock information on star activity outside our solar system.

6. **Inspiration Mars** – We will present our spacecraft interior design for radiation protection idea to Dennis Tito’s development team, which is currently in the preliminary design stages of the space craft for the 2018 Mars fly-by mission.

7. **Power companies** – We will promote smart grids and transformer protection measures, for example through our industry awareness campaign on social media.

8. **Website** – We will create basic website with all relevant information and awareness products at [www.solarhazard.org](http://www.solarhazard.org), as a public repository for all team project output.

9. **Social media** – We will actively use our social media channels to distribute NOAA, NASA, ESA and UN infographics, plus other products suitable for social media. We will write a basic set of guidelines and how-to instructions, so all team members will be easily able to use the tools to maximize effectiveness.

10. **ISU Alumni network** – We will actively engage the ISU alumni network to search for opportunities to present our work.

Some of these actions will require a certain level of funding. Financial support by interested organizations will greatly increase the effectiveness of our work. We invite potential sponsors to contact us to discuss opportunities for cooperation.
7 CONCLUSIONS

7.1 Threat

The threat of solar weather is real. Our own life-giving star may not always be the peaceful neighbor it now is. Furthermore, our increasingly technologically-based world is at real risk from this threat. Up to this point, our recent decades of industrial growth seem to have done more to put our fragile existence at risk than to protect us from a catastrophic solar event. Fortunately, the world’s foremost solar physicists and experts are learning more every day about the potential for an event like this. But, more can be done to help. When Dr Alan Title, one of the world’s leading solar experts, notes that his biggest fear is the growing gap in awareness between the solar science community and the rest of the population, it is time for us to listen. Despite small improvements over the last decade to terrestrial and space assets, our critical infrastructure is still at risk. These risks can be summarized as:

- Threat of space weather effects on Earth’s climate
- Threats to terrestrial infrastructure and cascading secondary effects
- Threat to space assets in the following categories:
  - Low Earth Orbit, Low Inclination
  - Low Earth Orbit, High Inclination
  - Medium Earth Orbit/Geostationary Orbit
  - Interplanetary Robotic Missions
  - Manned missions
  - Threat directly to humans on Earth

7.2 Technological Solutions

In the hopes of mitigating these threats, team SolarMax proposed a number of technologies that could be deployed to help protect our infrastructure and close the gaps in our knowledge of space weather.

Robust Smart Power Grids: A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it in order to efficiently deliver sustainable, economic and secure electricity to the customer. As the power industry transitions from the current power grid to a smart grid, there exists an opportunity to incorporate appropriate measures to mitigate the harmful effects of space weather on power distribution infrastructure. Smart grids are a natural progression for the currently outdated and overloaded power transmission networks. “Robust” smart grids will allow the mitigation of space weather effects such as GICs by utilizing real-time monitoring, reaction, event anticipation and instantaneous isolation of faults. Public and private support for robust smart grid adoption or upgrades will be required in order to realize these advantages.
HOCOMOCO: The Heliospheric Orbit Continuous Monitoring Constellation proposal is for a constellation of small satellites (around 50 kg each) designed to monitor solar weather and improve our ability to predict, and calculate our exposure to severe solar events. To complete the mission objectives, the constellation should be operational for at least 11 years in order to record data during the entire solar max-min cycle. The main goals are to continuously monitor the solar wind, map the Sun’s magnetic field so as to determine the trajectories of energetic particles relative to the Earth, and help to identify how and where satellite failure modes occur.

Inspiration Mars, A Radiation Mitigation Case Study: Leveraging the mission profile of the 2018 Inspiration Mars as a mission profile, this proposal examines methods for mitigating radiation exposure through redistributing the interior architecture of a spacecraft. More broadly discussed, but of importance in the context of this case study, are the risks associated with acute and chronic radiation dosages, ergonomic constraints in design for astronauts, and the implications of the success or failure of the manned Mars fly-by mission to government, space agencies, and the private industry around the world.

7.3 Awareness

We found that the primary obstacle to action against space weather was a lack of awareness of the problem amongst decision makers. Team SolarMax identified three distinct groups to target with tailored content and delivery vectors, leveraging not only traditional forums, such as conferences and tradeshows, but also disruptive social media. These groups are:

- **Policy Makers/Regulatory Agencies/Military**: Some in this community are aware of the threat, but the vast majority is still oblivious to this threat. This campaign aims to increase awareness through direct communication with relevant policy makers through our executive summary, which contains a tailored message to them: “More must be done to support our critical terrestrial infrastructure from the threat of solar weather.”
- **Industry**: In many domains, industry has often lead the way in making adjustments to resources and strategies to account for new information, adapt to changing environments, and generally done more with less in order to look out for shareholder interest and industry equities. Our message to them was simple, “Keep innovating and lead the way in:
  - Create awareness in customers, clients and leaders
  - Prioritize resilience into future engineering
  - Work to identify and prevent ‘dependency creep’ in own and clients’ systems
  - Prioritize resistance to solar weather effects in the design phase of all future projects
  - Design in and maintain “performance surplus” in systems to allow for future loading and surges
  - Educate regulators and policy makers to potential catastrophe and risk loading
  - Incentivize financial, medical, and energy industries
  - Modular distribution of downstream assets, clients and partners alike
  - Gather/interpret current and future data
  - Advocate data sharing between industry, science, and the general public”
• General Public: Information and knowledge are required before people are willing to take action. Space weather destroys things. This is the heart of the message that we want to bring to the population of the world. Multiple products designed for specific channels were created in order to deliver this message to the world. Standard products such as executive summaries and websites are needed, however innovative social media comics, movie storyboards, and disaster kits were also identified as vehicles to support this awareness campaign.

7.4 Final Remarks

While space weather can indeed be a major problem, it is important to remember that Human civilization is not powerless in the face of it. There are ways to mitigate the threat, either by protecting spacecraft and terrestrial infrastructure, or by closing the gaps in our knowledge of the Sun’s magnetic field. These technologies either exist today or are in development. In the final analysis, the primary danger lies not with the Sun, but with the ignorance of governments, industry, and the general public concerning space weather.
8 REFERENCES


U.S. Department of Commerce, National Oceanic And Atmospheric Administration in Service Assessment intense Space Weather Storms, October 19 – November 7 2003, Silverspring, Maryland


United Nations, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial bodies; 610 United Nations Treaty Series 205


9 APPENDICES

Appendix 1: Radiation mitigation supplementary information

9.1.1 Active Shielding
Concepts for active shields fall into four categories: electrostatic shields, plasma shields, confined magnetic shields and un-confined magnetic shields (Herr, 1994) and (Morozov, 1971). The most promising of these technologies are confined and unconfined magnetic shields. Confined magnetic field technology is based on using magnetic fields to deflect the cosmic rays from the crew quarters of the vehicle. To avoid exposing the crew to an intense magnetic field, it is confined in a double-walled torus. This surrounds the crew with a wall of magnetic field that deflects the radiation. Unconfined magnetic field technology is still based on deflecting the cosmic rays with a magnetic field, but in this case the field is allowed to become very large. Superconductors were initially considered as the magnetic field source but these would require cooling by liquid helium at a significant mass and volume penalty. For these reasons, coils were considered in early unconfined magnetic field generator concepts. Studies by Townsend (1983, 2000), Sussingham et al (1999), and Adams et al (2005) reviewed these approaches and found that the mass required for such a magnet greatly exceeded the mass of material shielding to achieve the same degree of protection. In addition active shielding posed two hazards: the magnetic field in the crew quarters was unacceptably high and the stored energy in the coil was so large that an unplanned quench of the superconductor would have been catastrophic (Adams et al, 2005).

Passive and active shielding systems are available today. A summary of the state of the art of passive shielding can be found (Hathaway, 2012). Error! Reference source not found. compares the radiation exposure rate for various materials as a function of their thickness in mass per unit area. In this figure we learn that the materials with the smallest mean atomic mass make the lightest shields (Adams et al, 2005). NASA’s belief is that active shielding is the best form of radiation protection during long-term missions (Kasler, 2011).

9.1.2 Synthetic Biology
Over the past few years, NASA and other space agencies have shown growing interest in the use of biotechnologies during manned space missions. Among others, this includes the design and construction of biological devices and systems for space applications (Schmidt, 2012). For example, NASA continues to sponsor innovative radiation biology research aimed at mitigating exposure risks posed to lunar or Mars-bound astronauts. In a collaborative effort with the National Cancer Institute, nano-scale monitors that can fit into white blood cells to measure cellular damage from radiation exposure are under development (O’Rangers and Logan, 2008). NASA also awarded Colorado State University a 5-year, $9.7 million grant to determine predictors of radiation side effects, such as cancer. Ideally, this would afford physicians who monitor astronauts the ability to initiate preventive treatments many years in advance of the appearance of disease. The research could also lead to better risk prediction for various durations of radiation exposure, which could improve NASA’s ability in determining radiation "career limits" for astronauts (Sparks, 2002).

NASA is also currently undergoing other space radiation research projects. In 2001, "Fred"
the Phantom Torso - "part-dummy, part dosimeter-imbedded torso that is a mock-up of a human's upper body, minus a set of arms" - was flown to the ISS and set up in Node 2 (the attachment point for the US Laboratory). Its purpose was to yield a more accurate portrait of human radiation exposure in the station (David, 2000). In 2002, ISS crew members undergoing EVAs participated in a year-long test of Canadian radiation monitors that were tucked into suit pockets. The dosimeters were measuring radiation exposure of astronauts working outside the station. Radiation levels, although higher than average earthbound annual exposures, were lower outside the station than anticipated (Malik, 2002).

9.1.3 Human factors
9.1.4 Human factors engineering process and its links to the NASA program/project life cycle (NASA/SP-2007-6105)

Human factors interaction model (NASA/SP-2007-6105)
9.1.5 Schematic Diagrams of Habitation Modules

Schematic of first and second floor of habitat module with distribution of time spent (%) in each segment, and total averaged location (●) over mission with $5^0$ segmentation cuts.

Schematic of first and second floor of modified habitat module with distribution of time spent (%) in each segment, and total averaged location (●) over mission with $5^0$ segmentation cuts.
9.1.6 Radiation Effects in Humans

Radiation effects in humans after chronic (received either continuously or intermittently over a prolonged period of time) whole body irradiation (Hellweg and Baumstark-Khan, 2007).

<table>
<thead>
<tr>
<th>Chronic Dose</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 0.2 Sv</td>
<td>First evidence of increased cancer risk as late effect from protracted radiation</td>
</tr>
<tr>
<td>2 - 4 Sv / year</td>
<td>Chronic radiation syndrome with complex clinical symptoms</td>
</tr>
</tbody>
</table>

Radiation effects in humans after single acute (radiation administered over such a short period) whole body irradiation (Hellweg and Baumstark-Khan, 2007).

<table>
<thead>
<tr>
<th>Acute Dose</th>
<th>Single Dose</th>
<th>Effect</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 0.2 Sv</td>
<td>Single Dose</td>
<td>First evidence of increased cancer risk as late effect</td>
<td></td>
</tr>
<tr>
<td>&lt; 0.25 Sv</td>
<td>Single Dose</td>
<td>No obvious direct clinical effects</td>
<td></td>
</tr>
<tr>
<td>&gt; 0.5 Sv</td>
<td>Single Dose</td>
<td>Nausea, vomiting</td>
<td>No early death anticipated</td>
</tr>
<tr>
<td>3 - 5 Sv</td>
<td>Single Dose</td>
<td>Bone marrow syndrome; Symptoms include internal bleeding, fatigue, bacterial infections and fever</td>
<td>Death rate for this syndrome peaks at 30 days, but continues out to 60 days. Death occurs from</td>
</tr>
<tr>
<td>Radiation Dose</td>
<td>Syndrome Description</td>
<td>Outcome</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>5 - 12 Sv</td>
<td>Gastrintestinal tract syndrome: Symptoms include nausea, vomiting, diarrhea, dehydration, electrolytic imbalance and bleeding ulcers</td>
<td>Deaths from this syndrome occur between 3 and 10 days post exposure. Death occurs from sepsis</td>
<td></td>
</tr>
<tr>
<td>&gt; 20 Sv</td>
<td>Central nervous system syndrome: Symptoms include loss of coordination, confusion, coma, convulsions and shock</td>
<td>No survivors expected</td>
<td></td>
</tr>
</tbody>
</table>

Percentage risk of cancer death. Current estimates (diamonds) and 95% confidence bands for adults of age 40 years (Cuccinota and Durante, 2009).
<table>
<thead>
<tr>
<th>Name of the event</th>
<th>Business Areas</th>
<th>Frequency</th>
<th>Host City (Present event)</th>
<th>Date</th>
<th>For more information</th>
</tr>
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<tbody>
<tr>
<td>HealthEx – Medical Exhibition – India</td>
<td>Healthcare</td>
<td>annual</td>
<td>Bangalore, India</td>
<td>5-7 Sept. 2013</td>
<td><a href="http://www.healthex.com/">http://www.healthex.com/</a></td>
</tr>
<tr>
<td>The AIAA SPACE Conference &amp; Exposition</td>
<td>Space</td>
<td>annual</td>
<td>San Diego, CA, USA</td>
<td>10 - 12 Sept 2013</td>
<td><a href="http://www.aiaa.org/SPACE2013/">http://www.aiaa.org/SPACE2013/</a></td>
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<td>FTR Transportation Conference</td>
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<td>annual</td>
<td>Indianapolis, Indiana</td>
<td>24-26 Sept 2013</td>
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<tr>
<td>Railway Interchange</td>
<td>Transportation</td>
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<td>Indianapolis, Indiana</td>
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<td>Transportation</td>
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<td>7-11 Oct 2013</td>
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<td>Latin American Tradeshow Expo</td>
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<td>annual</td>
<td>San Juan, USA</td>
<td>10 - 11, Oct 2013</td>
<td><a href="http://www.smartairports.com/">http://www.smartairports.com/</a></td>
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<td>The European Space</td>
<td>Space</td>
<td>annual</td>
<td>Munich,</td>
<td>5 - 7 Nov.</td>
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<td>Solutions conference</td>
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