Advances in Space Research

Forecasting the Impact of an 1859-calibre Superstorm on Satellite Resources

Sten Odenwald[1,2], James Green[2], William Taylor[1,2]

1. QSS Group, Inc., 4500 Forbes Blvd., Lanham, MD, 20706.

2. NASA, Goddard Space Flight Center, Greenbelt, MD 20771

Submitted: June 30, 2005, Accepted: September 25, 2005

Abstract:

We have developed simple models to assess the economic impacts to the current satellite resource caused by the worst-case scenario of a hypothetical superstorm event occurring during the next sunspot cycle. Although the consequences may be severe, our worse-case scenario does not include the complete failure of the entire 937 operating satellites in the current population, which have a replacement value of ~$170-230 billion, and supporting a ~$90 billion/year industry. Our estimates suggest a potential economic loss of < $70 billion for lost revenue (~$44 billion) and satellite replacement for GEO satellites (~$24 billion) caused by a 'once a century' single storm similar to the 1859 superstorm. We estimate that 80 satellites (LEO, MEO, GEO) may be disabled as a consequence of a superstorm event. Additional impacts may include the failure of many of the GPS, GLONASS and Galileo satellite systems in MEO. Approximately 97 LEO satellites, which normally would not have re-entered for many decades, may prematurely de-orbit by ca 2021 as a result of the temporarily increased atmospheric drag caused by a superstorm event occurring in ca 2012. The $100 billion International Space Station may lose significant altitude, placing it in critical need for re-boosting by an amount potentially outside the range of typical Space Shuttle operations, which are in any case scheduled to end in 2010. Currently, the ability to forecast extreme particle events and coronal mass ejections, or predict their fluences and geoseverity in the 24-hrs prior to the event, appears to be no better than 50/50. Our analysis of economic impacts is a first attempt at estimation whose approach will suggest ways in which better estimates may eventually be obtained.

Keywords: Space Weather, satellite anomalies, satellite failures, technology impacts, superstorms, radiation sickness, economic impacts.

1.0 Introduction

Considerable attention has been paid to the many ways in which space weather can compromise satellite operations. A general overview is provided by Odenwald [2000; 2005a]. In addition, Baker [1986] and Allen and Wilkinson [1991] have assembled and analyzed satellite anomaly databases. Belov et al. [2004] and Iucci et al. [2005] have analyzed these, and other, anomaly databases in the context of various space weather drivers. Satellites appear to be remarkably robust against most space weather events encountered during the last 30 years, however, recent studies of historical events show that even more violent solar and geomagnetic storms are possible for which we have, as yet, no experience. During the current sunspot cycle (1996-2005) approximately 15 satellites have been damaged at a cost of ~$2 billion as a consequence of severe space weather events [Odenwald, 2000].

Although the economic impacts have been minimal, and largely recovered through satellite insurance, a reasonable question to ask is, what is the upper bound to economic losses from a truly extreme space weather event?

The paper is organized as follows: Section 2 defines the physical scale of a hypothetical superstorm; Section 3 discusses the economic dimensions of the commercial satellite resource; Section 4 quantifies, so far as is possible, the likely space weather influences that can be expected to play a dominant role in satellite functioning following a worst-case superstorm event; Section 5 assesses the consequences of these influences through a series of simple models; and in Section 6 we will draw conclusions based on these models by providing a possible scenario for a superstorm.

2.0 Historic Storms

A recent study of historical solar storms by Cliver and Svalgaard [2005] compared more than 50 major storms identified by their geomagnetic indices, Solar Proton Events (SPEs), and Coronal Mass Ejection (CME) speed. One storm stands out as the most impressive of all, namely the August-September 1859 Carrington-Hodgson event described in considerable detail by the Editors of the American Journal of Science [1859; 1860] and by Loomis [1860, 1861] and more recently by Green et al. [2005a,b] and Tsurutani et al. [2003]. It is often called a 'superstorm' because of its remarkable strength and global impact.

A study by Cliver and Svalgaard [2004] of the major space weather 'storms' since 1859 reveals a rather broad ranking of these events across the many physical parameters that characterize these events. Of these events, they have concluded that the Carrington-Hodgson 1859 storm appears as the most extreme event in nearly all categories.

The study of the record of historic solar proton events (SPEs) during the last 500 years by McCracken et al. [2001a, b] reveals over 125 such events that have left their traces in the nitrite abundances of polar ice cores from Antarctica, Greenland and the Arctic Region. The strongest of these, once again, coincided with the 1859 Carrington-Hodgson storm and white-light flare, and produced an equivalent fluence of 1.88 x 10^{10} particles/cm^2. The July 14, 2000 Bastille Day solar proton event (SPE) by comparison had a fluence of 6.3x 10^9 particles/cm^2 for protons with E> 30 MeV, and was observed to cause a 2% power decline in the SOHO satellite [Brekke, 2004].

McCracken et al. [2001b] have identified the solar activity cycles during the satellite era as being uncharacteristically weak in SPE events and fluences compared to the historical record of these events since the year 1567. The frequency of large events with > 30 MeV fluences > 2 x 10^9 particles /cm^2 between 1964-1996 averages one event per sunspot cycle, while 6 – 8 such events occurred for sunspot cycles near the years 1605 and 1893. The integrated fluence of the largest five SPEs between 1830-1910 was 5.49 x 10^{10} particles/cm^2 compared with only 6.7x 10^9 particles/cm^2 during the years 1910 to 1985. In particular, the satellite era (1967-1994) ranks sixth lowest in the integrated fluences of the strongest 6-8 SPEs. The implication is that, during the last 400 years, the sun is most certainly capable of producing a substantially more active satellite environment than what we have come to accept in recent decades. Depending on the assumptions made about the spectral hardness of the Carrington-Hodgson event, the fluence for >30 MeV protons may have reached levels near 3.6x 10^{10} particles/cm^2. Currently, this is considered to be a worst-case event [Townsend, 2003], but are even stronger events possible?

Reedy [1998] examined isotopic abundances in lunar rock surface layers to estimate the SPE fluence distributions for the last few million years. Apparently, the upper limits suggest that there have been no flares with fluences more than what has resulted from 10-times the average of flares seen during the last few decades. The 1859 flare is only 3-times more luminous than flares seen in recent decades, suggesting that the distribution of SPE fluences has a sharp turnover at levels just above the 1859-level. We can then assume that a storm more than 3 times as intense as the 1859 event is a reasonable upper limit 'worst case' event. This means the brightest SPE may have a fluence of about 5.6 x 10^{10} particles/cm^2. Once again, these events averaged over several million years are substantially less common than the 1859 event. Nevertheless, they represent an upper limit on the true worst case superstorm event, and so we will use this flux in the discussions to follow as an upper bound to what we could expect from a single, extreme space weather event.

A list of SPEs and their fluxes between 1976 and 2004 was obtained from NOAA [2004]. Table 1 summarizes this SPE history in terms of the peak proton fluxes of the strongest events each year, along with its date and associated flare, if any. We note that SPE events and, for example, X-class solar flares are not always correlated. The SPE fluxes are integral 5-minute averages for protons with energies >10 MeV, given in particle flux units (pfu), measured by GOES spacecraft at geosynchronous orbit. (1 pfu = 1 proton cm^{-2} sr^{-1} s^{-1}).

At what time during a solar activity cycle might we expect such major storms to occur? Table 2 shows the years for the 10 largest SPEs recorded since 1976 compared to the year of sunspot maximum.

Table 1: SPE fluxes for 1976 – 2004

Year	Peak	Date	X-flare
1976	12 pfu	May 1	X2
1977	200	Sep 19	X2
1978	2200	Sep 23	X1
1979	950	Jun 7	X2
1980	100	July 19	M3
1981	2000	Oct 13	X3
1982	2900	July 13	X9
1983	340	Feb 4	X4
1984	2500	April 26	X13
1985	160	April 26	X1
1986	130	Feb 14	X1
1987	120	Nov 8	M1
1988	92	Jan 3	X1
1989	40000	Oct 20	X13
1990	950	Mar 19	X1
1991	43000	March 24	X9
1992	4600	May 9	M7
1993	44	Mar 13	M7
1994	10000	Feb 21	M4
1995	63	Oct 20	M1
1996	0	---	---
1997	490	Nov 7	X9
1998	1700	April 21	M1
1999	64	June 4	M3
2000	24000	July 15	X5
2001	31700	Nov 6	X1
2002	2520	April 21	X1
2003	29500	Oct 29	X17
2004	2086		M1

Table 2 : SPE events and their correlation with the sunspot maximum

SPE Year	Flux	Maximum	Diff.
8-12-1989	9,200	1989.6	0.0
10-19-1989	40,000	1989.6	+0.2
3-23-1991	43,000	1989.6	+1.3
3-20-1994	10,000	1989.6	+4.6
7-14-2000	24,000	2000.5	+0.1
11-8-2000	14,800	2000.5	+0.3
9-24-2001	12,900	2000.5	+1.3
11-4-2001	31,700	2000.5	+1.4
11-22-2001	18,900	2000.5	+1.5
10-28-2003	29,500	2000.5	+3.3

Although the sample of large SPE events is statistically small, apparently, the largest storms occur within 2 years after sunspot maximum, with no major storms occurring in the two years prior to sunspot maximum. In the models to follow, we will consider the worst-case scenario for a superstorm, precipitating an 18% decline in solar panel power. Table 2 suggests that the window for extreme SPE events opens near sunspot maximum and persists for several years afterwards. Our models will therefore assume that a hypothetical 'worst-case' superstorm event occurs at the time of sunspot maximum in the year 2012, and with a proton fluence of ~5.6 x 10^{10} particles/cm^2 for E > 30 MeV. We next consider how many operational satellites may be deployed by 2012 to experience the superstorm.

3.0 The Satellite Database

The number of operating satellites is constantly changing, and published estimates are often out of date within months. Estimates found in the literature range from 300 operating satellites according to Todd [2004], to 700 according to Spotts [2003]. According to a recent compilation by Odenwald [2005b], as of December, 2004, there are 936 satellites which are apparently still in operation. This estimate is believed to be complete to about +/- 5%, with the operational status of military satellites being the largest uncertainty. Table 3, summarizes this inventory for each category and orbital location. LEO (Low Earth Orbit) satellites have orbital perigees below 2,000 km; GEO (Geosynchronous) satellites are located at 35,768 km, and MEO (Mid Earth Orbit) are found between 2,000 km and 35,768 km. Operating satellites above GEO orbit are not considered in this study.

4.0 Satellites as an Economic Asset.

To create a plausible model for the economic

Table 3 : Statistics for Working Satellites ca 2004.

Location	Com Sats	Military	Research	Total
LEO	273	94	70	**437**
MEO	19	101	12	**132**
GEO	308	51	8	**367**
Totals	**600**	**245**	**91**	**936**

consequences of a superstorm, we need to establish a baseline model against which to measure the superstorm impact.

We need to estimate the current productivity of the commercial satellite resource at the present time, and to extend this estimate to 2012 and beyond. This is a daunting challenge and cannot come to fruition as anything more than a rough estimate. Nevertheless, such a calculation can shed light on issues that need to be resolved for such a calculation to ultimately succeed. How do we define the economic value of a satellite? There are two aspects that readily suggest themselves: 1) the actual satellite hardware and launch costs; and 2) the revenue returned by the satellite during its operational life. The first of these is by far the easiest to estimate, though as we will discuss, there are some ambiguities in the definition of the term ‘cost’.

When satellite costs are published, they often appear in one of at least three possible forms: 1) satellite hardware cost alone; 2) hardware plus launch cost; or 3) satellite cost plus operations and insurance. Generally, little attempt is made in the literature to distinguish between these possibilities in a consistent way. The resulting ambiguities can, for example, cause a 30% variance in the quoted price of a satellite mission.

Our database contains actual published costs for 436 satellites collected from hundreds of web-based press releases and related sources. For satellites (specifically military systems) where such costs could not be determined, we estimated a cost based on published estimates for the particular satellite model (e.g. Galaxy, Iridium, GPS or bus type). If the satellite model could not be determined, we assumed a cost based on the satellite’s mass and orbit location.

This latter method is the most difficult to implement because a satellite mass can be quoted either as a ‘dry’ mass or a mass fully loaded with fuel, and little attempt is made in the literature to discriminate between them. Nevertheless, the median price per kilogram for a satellite is $70k at MEO and $178k at GEO. LEO satellites are far more diverse in function and cost than other satellites because these systems include 1 kg nanosatellites as well as 14,000 kg military surveillance satellites. For example, the LEO price per kg is $65k with Iridium and Globalstar satellites included, and $455k without Iridium and Globalstar included. The later cost is strongly biased in favor of large systems such as the Hubble Space Telescope and various DoD payloads.

We constructed a simple spreadsheet consisting of the satellite name, launch date, mass, cost, and orbital type (LEO, MEO, GEO) and simply summed the relevant entries. The estimated replacement cost (satellite plus launch) for the entire working satellite population is ~$190 billion. Given that only half of the satellites (GEO, MEL and LEO) had published costs, and that the price variance for the unreported systems can be up to 30%, the total replacement cost is likely to range from $170 billion to $230 billion**.**

As for the second component to our economic value calculation, we can assess the revenue generated by a satellite once we have determined which aspect or hardware is involved in generating the revenue. For communications satellites, this is a statement of the number of transponders in operation and their cost to lease. From Table 4 we see that the average transponder is leased at about $2 million/year. From the known transponder information for 235 of the 308 operating GEO satellites, we estimate that by December 2004, their 6,841 transponders have cumulatively generated approximately $74 billion in revenue. Figure 1 shows the cumulative asset value of all GEO satellites, which includes both the replacement cost (for all 308 GEO satellites) , and the revenue generated by those 235 systems with transponders. The total asset value of this GEO population is ~$170 billion. Note that the cumulative revenue exceeds the replacement cost for satellites currently older than ~5 years where the ‘Revenue’ and ‘Replacement’ curves cross. Younger systems have not had enough time to 'break even' since launch.

Table 4: Commercial transponder rental rates

Satellite	Bandwidth	Rental Rate per year	Usage
INSAT-2E	72, 36 MHz	$1.5 million	INTELSAT lease to customers
Skynet	36 MHz	$1.4 million	Average for 7 existing satellites in 2002.
SBS-6	36 MHz	$3.1 million	Ku-band leased for $350/hr
Telstar-5	27 MHz	$2.1 million	Auctioned at $175,000/mo
Telstar-5	54 MHz	$3.1 million	Auctioned at $255,000/mo
SatMex-5	36 MHz	$2.3 million	Auctioned at $195,000/mo

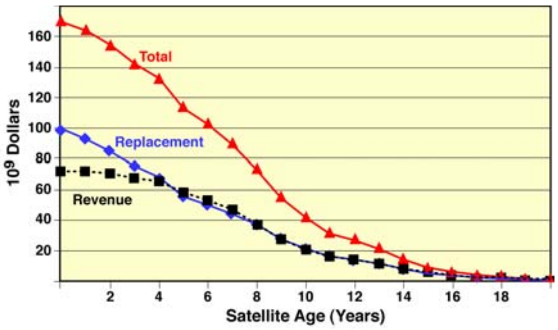

Figure 1: Cumulative value of the GEO satellites with ages less than 20 years by 2004. The total value (triangles) is a combination of the replacement cost, including launch, of the satellite (diamonds), and the revenue generated from the satellite transponders in service (squares).

Older satellites are ‘turning a profit’ (the difference between Revenue and Cost) for their owners. Figure 1 also shows that about half of the commercial GEO satellite resource, representing a replacement cost of about $100 billion to build and launch, is older than five years. Approximately $20 billion in revenue (with an asset value of $40 billion) is produced by satellites that are at least 10 years old and in most cases due for retirement. Meanwhile, the satellite communications industry by 2002 generates $86.8 billion in revenue annually (Space.com, 2003).

5.0 Modeling

A major impediment to creating a prediction of space weather economic loss for satellite resources is that the commercial satellite community does not publish details on the revenues, profits or losses incurred by their satellites. Moreover, the impacts to satellite systems by space weather events of any kind are rigorously kept from the open literature due to the very real concern that such reports will impact investor/client confidence. Nevertheless, there are a number of factors caused by space weather that are known to materially affect spacecraft operations, and these can be quantified: solar power erosion, single event upsets and other spacecraft anomalies, and orbit decay. These factors will be analyzed in the next three sections.

5.1 GEO Satellites and Solar Power Degradation

Most Earth-orbiting satellites require solar-electric power to operate. Solar panel power is degraded by cosmic rays at a steady rate each year, and this effect is usually built into the design of the solar panels. Satellite designers use a variety of statistical models (AP8, AE8, CRRESPRO, etc.) to predict solar panel radiation dosages over the planned lifetime of a satellite. This leads to the inclusion of beginning-of-life (BOL) power margins through oversizing the solar arrays to allow for adequate end-of-life (EOL) power. The pre-launch lifetime estimate for a satellite is usually based on the ~ 2% per year decline in satellite operating power due to cosmic rays following the analysis of Chetty [1991] and Crabbo [1994]. Satellites in MEO orbits within the Van Allen Belts can, however, experience ~5% power losses annually according to Patel [2000].

There are some well-known limitations to these radiation environment models. In most cases, only long-term effects are statistically modeled, and individual short-term events (flares, SPEs etc) are not treated in detail [National Academy of Science, 2000]. Nevertheless, the fact that satellites often survive well past their designed EOLs suggests that these space weather models provide a relatively accurate representation of the short and long term space weather environment.

In addition to cosmic rays, SPEs also cause solar panel degradation over time scales as short as a few hours, and represent a source of uncertainty in spacecraft solar panel design. This degradation is usually accommodated in solar panel designs by using proton event models (e.g. King, 1974, Feynmann et al. 1993 and Xapsos et al.. 1999, 2000) that average the properties of a worst-case storm such as, for example, the ones during August 1972, March 1991 and October 1989, or use a cumulative measure of SPE fluence based on limited data sets [SPENVIS Project, 2004]. An appropriate margin is then added to the solar panel design. During a superstorm event such as Carrington-Hodgson 1859, solar energetic particles are expected to be a major component to its impact, with fluences that are three-fold higher than the worst-case events experienced during the satellite era. We will need to estimate how big this impact is likely to be, in order to assess its economic consequences. To do so, we need to empirically calculate the relationship between SPE flux and solar power degradation.

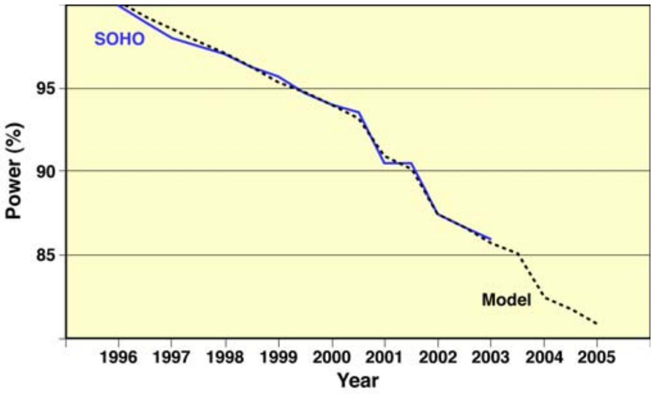

Figure 2: SOHO satellite operating power (solid line) compared to a model (dashed line), including cosmic ray and SPE degradation. SOHO data adapted from Brekke [2005].

The SPE flux history from Table 1 can be compared with the SOHO satellite power degradation shown in Figure 2, adapted from Brekke [2004]. We have modeled the power loss by assuming a simple combination of cosmic ray and SPE effects according to:

$$\text{Power}\ (\%) = 100 - \alpha T - (C/\beta)$$

where T is the number of 6-month intervals since launch and C is the cumulative sum of the peak SPE events in each half-year based on Table 1. In this analysis, C is, therefore, proportional to the total fluence of the strongest SPE events. The best fit to the SOHO data (Figure 2 dashed line) was obtained for $\alpha = 0.74$ and $\beta = 16000$. From the discrete event fit, we determine that at the L1 location of SOHO there is an annual cosmic ray decline of 1.5%.

We note that the SOHO fluxes are measured in interplanetary space, while the relevant GOES satellite fluxes at GEO should allow for partial shielding by Earth's magnetic field. It is known that the hardness of the particle spectrum is affected by location in the magnetosphere.

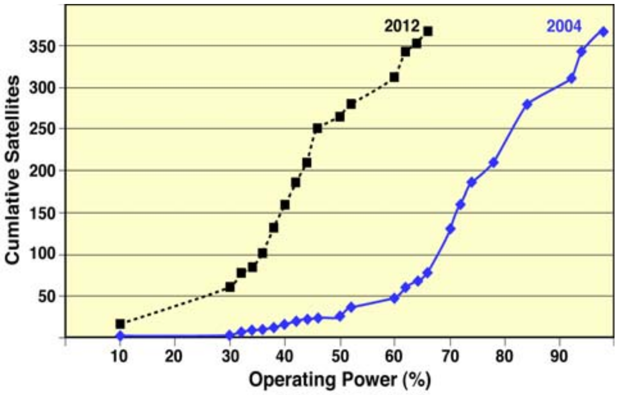

Figure 3: Cumulative GEO satellite population size compared to operating power for 2004 (diamond points) and 2012 (square points).

SPE particles with energies above 10 MeV are the most damaging to satellite electronics and solar panels (e.g. Iucci, 2005). GEO satellites are located at 6.6 Re where the spectral hardness change, compared to interplanetary space, is expected to be modest. In the models to follow, we will not attempt to correct for this effect.

Table 5 : Operational status of oldest GEO satellites by 2005

Satellite	Age	Pwr (%)	Trans.	Status
Marisat-3	28	11	2	Operating.
Farrah-5	20	29	---	Unknown
SBS-4	20	29	14	Operating
DSCS 3A2	19	31	7	Operating
DSCS 3A3	19	31	7	Operating
DSCS 3B5	19	31	7	Operating
Brasilsat-A2	18	33	30	Replaced
Optus-A3	17	35	15	Operating
Spacenet-3	16	35	28	Replaced
TDRS-3	16	37	48	Operating
Marecs-3	16	37	---	Unknown
DSCS 2-15	15	39	---	Operating-
Intelsat-602	15	39	64	Operating.
Marecs-4	15	39	---	Unknown
TDRS-4	15	39	48	Operating
FLTSATCOM-8C	15	39	12	Operating
DSP 3-2	14	49	---	Operating
Asiasat-1	14	49	24	Replaced
DSP 3-3	14	49	---	Operating
Inmarsat-2F1	14	49	8	Operating
Intelsat-604	14	49	38	Replaced
Palapa B2R	14	49	30	Operating
SBS-6	14	49	14	Operating
Skynet 4A	14	49	7	Operating
Skynet 4C	14	49	7	Operating
Leasat-5	14	49	13	Operating

Including both the cosmic ray and SPE effects, our model summarized in Figure 3 (lower curve) indicates that 26 of the 367 GEO satellites appear to be operating at below 50% BOL power levels by 2005. These satellites are listed in Table 5. There are few satellites older than 15 years in the current sample, and that as indicated in Table 5, there are no active Earth-orbiting research satellites or communications satellites older than 15 years. The preponderance of military systems among the oldest satellites may indicate a more robust satellite design, or simply that their actual state of functioning is poorly described in public documents.

The sharp drop in the number of old GEO satellites operating at what we would estimate as 30% BOL power suggests that this is a threshold below which most categories of GEO satellites are retired, replaced or otherwise become unusable. The relationship between satellite power and a satellite's continued use in generating revenue from, for example, transponders, is a complicated issue. This is mainly due to the fact that the true status of specific commercial satellites is not found in public documents. There are anecdotal indications that satellites can operate at as little as 50% BOL power and still be considered economically viable. For Arabsat 3A, a 50% reduction in power resulted in a loss of 8 transponders out of 20 [Space and Tech News, 2001]. However, for relatively young satellites this relationship between %BOL power and the number of operating transponders, and therefore its economic value, is probably not linear. According to our model, PAS-2 launched in 1994 operates at 90%BOL with no apparent reduction in the number of operating transponders (e.g. 20). Indeed, satellites are designed with BOL power margins of 30 – 50% so that actual economic impacts to satellite operation may be deferred to at least 50%BOL for some satellite designs. Our transponder calculations will generously assume that satellites remains in essentially full use of their transponders until the year they reach 30% BOL power, at which time they cease to be commercially viable and are retired.

We have calculated the revenue of the commercial GEO satellites through 2004 by subtracting the number of years lost due to cosmic rays and SPEs from the launch age of the satellite by the end of 2004. We multiply this difference by the number of transponders in each satellite, and by the transponder leasing price of $2 million/year. According to our database of working commercial GEO satellites, the 78 satellites (containing 1,860 transponders) launched in 1996 or earlier have a net revenue of $6 billion. They continue to operate well past their expected EOLs, which averages about 12 years.

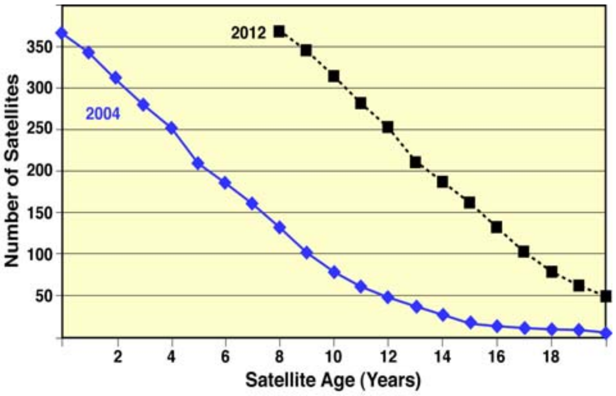

Figure 4: Cumulative GEO satellite ages for 2004 (diamond points) and 2012 (square points)

The additional 157 commercial satellites launched between 1997-2004 (inclusive) with ~4,980 transponders have average planned lifetimes of 15 years, which means that they are only half way through their expected operating lives. What effect will SPE and cosmic ray degradation have on this population just before sunspot maximum in ca 2012?

By 2012, the cumulative age distribution of the satellites launched before 2005 shown in Figure 4 (upper curve) will include more than 160 satellites older than 15 years. If we assume a distribution of SPEs similar to what was experienced between 1993-2004, we can predict that by 2011, about 310 satellites of the existing 367 GEO satellites will be operating at less than 60% BOL power according to Figure 3 (upper curve), and 60 satellites will be operating below the imminent-replacement threshold of 30% BOL power. To offset this normal rate of satellite aging, approximately 160 replacement satellites will need to be launched between 2005-2012, which corresponds to an annual launch rate of about 22 satellites. This is similar to the forecasted launch rates between 2004-2010 estimated by COMSTAC [2004], suggesting that our baseline satellite model (sans a superstorm event) is consistent with current market forecasts for the commercial GEO satellite sector. This is our baseline model. We now consider the impact of a hypothetical, worst-case storm.

The addition of the superstorm in 2012 brings the total to 152 satellites that would fall below the 30% limit after the event, and requiring immediate replacement. If we assume a distribution of SPEs similar to the 12-year period from 1992 to 2004, our baseline model suggests that by 2024, about 280 of the 367 satellites would require replacement under normal SPE and cosmic ray conditions. With the superstorm, all 367 satellites fall below the 30%BOL power level and require replacement. This means 87 additional satellites launched after ca 2002 would be affected by the superstorm and have to be prematurely retired at power levels below 30%. The replacement cost for these 87 satellites is $24 billion. Whether these satellites would actually be replaced or not depends on the specific economic role played by each satellite and is beyond the scope of this paper to assess.

Comparing the predicted retirement years for the satellites before and after the storm, we estimate 1,575 years of lost service for this affected population, resulting in $44 billion in lost transponder revenue. This revenue loss would be in addition to the $24 billion replacement cost for the additional 87 satellites affected through 2024, implying a total hardware plus revenue loss of about $68 billion through 2024 as a direct result of the superstorm.

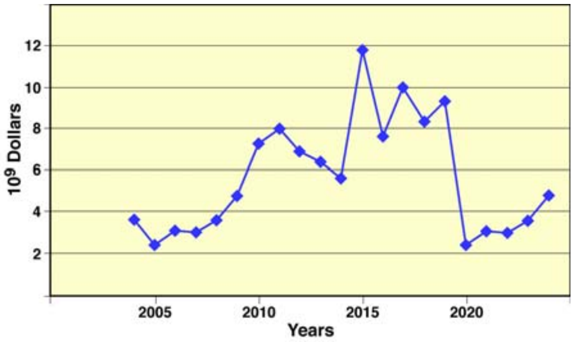

Figure 5: Distribution of replacement costs for GEO satellites assuming a 15-year lifetime.

A shortcoming of this model is that it does not include satellite launches after 2005. A portion of these future launches are slated to increase the capacity of the GEO satellite network to maximize service and profits. However, a second goal is to replace satellites to make room for newer-generation models with increased sophistication and capacity. If satellites are replaced on a fixed 15-year schedule, which is the average life span for satellites launched since 1995, our simple calculation of power declines suggests that they would be replaced before their power levels reach about 40%BOL. Our model based on this replacement strategy suggests that a worst-case superstorm near sunspot maximum in ca 2012 would actually have little effect on the total satellite revenue so long as this 15-year replacement schedule is strictly adhered to. Figure 5 shows that this replacement rate would be relatively expensive to implement because it would involve in some years far more satellite launches than we have experienced in previous years (e.g. 2015-2019). However, this rate is likely to be an upper limit because fewer, more capable, satellites will need to be launched to replace the older less-sophisticated models. The sudden decline after 2020 is due to the retirement of satellites launched after 2005 and is outside the scope of this paper.

A second shortcoming is that we did not properly account for the current satellite transponder overcapacity. We assumed in our model that 100% of the transponders generated revenue. Currently, only about half of the commercial satellite transponders are employed in revenue generation according to Futron [2003]. To correct for this effect would require, for each satellite, a detailed forecast of its transponder utilization from 2005 to post-2012, which is beyond the scope of this paper. We have to accept that our estimates for satellite revenue could be overestimating the actual situation by as much as 50%.

5.2 GEO Satellite Anomalies

In addition to solar panel degradation, GEO satellites are often victims of energetic particle showers (e.g. killer electrons) that lead to a variety of electrical systems and command disruptions. An inventory of these effects for the October-November 2003 storm has been produced by Webb and Allen [2004]. These, in turn, can produce satellite failure. This phenomenon has been exhaustively studied from the engineering standpoint, but also from case studies of known space weather events and their satellite impacts by Baker et al. [1997].

The most extensive studies of satellite anomalies were completed by Iucci et al. [2005] and Mountford and Sastry [2003]. The former study involved anomaly data for 220 satellites between 1971 – 1994. The second study used the twelve SKYNET satellites, and electrostatic discharge data between 1990-2001 correlated with Kp index and its first derivative, as a measure of environmental factors. Belov et al. [2004] have studied the statistics for 6000 anomalies occurring among 300 satellites in various orbital regions, and found no correlation between MeV proton fluences and anomalies for satellites in LEO. However, they found increasing correlations for MEO-type satellite orbits, and the highest correlations for GEO orbits. From this data, they were able to construct models predicting the number of anomalies for each satellite population as a function of proton and electron fluxes. For GEO satellites they obtained:

$$F\ (10^{-4}\ \text{anomalies/day/satellite}) = -54 + 1.4\text{x}10^{-9}\ \text{x}\ E_2^{1.2} + 0.83\ A_p + 0.19\ V - 0.15\ B_z + 1.1\ P_{100}^{0.35} + 1.6\ P_{60}^{0.75} + 20\ S_f + 1.5\ \text{da10}$$

where E_2 is the>2MeV electron fluence in units of electrons/day/cm^2/str averaged over the past 3 days from GOES; A_p is in units of nT averaged over the previous 4 days; B_z is in nT averaged over the previous 2 days; V = solar wind speed in km/sec averaged over the previous 2 days; P_{100} is the fluence of > 100 MeV protons in protons/day/cm^2/str from GOES; P_{60} is the daily averaged GOES proton flux above 60 MeV in protons/cm^2/sec/str; S_f is the seasonal factor with a value of 1 at the solstices, and 3 at the equinoxes, and da10 is in units of % and measures the cosmic ray intensity (e.g. Belov, 1999).

From the NOAA [2005] archive for the GOES satellite, the October 29, 2003 SPE resulted in $P(E > 10\ \text{MeV}) = 7.7 \times 10^8$ protons/cm^2/day/str and $P_{100} = 5.2 \times 10^6$ protons/day/cm^2/str and $E_2 = 1.9 \times 10^7$ electrons/cm2/day/str.

The estimated P_{60} would be ~10^8 protons/cm^2/day/str or for an hour-long maximum phase, ~30,000 protons/cm^2/sec/str. This yields about 0.5 anomalies per satellite per day.

For the superstorm SPE with a one-hour duration of its main phase producing a fluence of 5.6x 10^{10} particles/cm^2 over 4• steradians, we estimate P_{60} ~ 10^6 protons/cm^2/sec/str. We also assume a spectrum similar to the October 29, 2003 event for which P_{100} ~ E_2 ~ 0.01P_{60} so that P_{100} = E_2 = 10^9 particles/cm^2/day/str. Plausible ranges for the quantities, V(km/s)= [2500, 3500], B_z(nT)= [-100, -200], A_p(nT)= [10, 100], S_f =3 at the equinox, and Da10(%)= [20,100], yield contributions to the total anomaly rate which are of the order 0.005 anomalies/day/satellite for their maximal values, compared to the much larger contributions by the fluence terms, E_2, P_{60} and P_{100}, during a superstorm event. With these assumptions, the estimated superstorm anomaly rate F ~10 anomalies/day/satellite. The model suggests that a superstorm event could produce an anomaly rate ~50-100 times higher than seen in the 1972-1994 historical satellite anomaly records thus far. This estimation of the anomaly rate during a superstorm scenario may be more representative of a subset of the satellite population, than with the entire population as a whole.

Some satellite are more succeptible to anomalies than others, due to diverse factors such as satellite design, orbital location or degree of radiation hardness. Statistical studies of anomaly rates can be biased in favor of a small number of highly sensitive satellites. The studies by Iucci et al. [2005] and Belov et al. [2004], which form the basis for our estimates, are based on a statistically heterogenous sample of satellites, each with its own definition of what constitutes an ‘anomaly’. The analysis by Belov et al. [2004] is therefore an average prediction, which would be biased by satellites with a higher-than-average sensitivity to space environment factors. As a consequence, our estimate of 10 anomalies/day/satellite during the superstorm may only apply to a limited subset of the extant satellites, and not to the entire population as a whole.

The relationship between anomalies and SEUs is not given in the analysis by Belov et al. [2004], so one might conclude that SEU rates could actually be much higher than the ‘malfunction’ rates cited by Belov et al. [2004]. According to Brekke [2004], during the July 14, 2000 SPE event, the SOHO satellite’s 2 gigabyte memory encountered 76 SEUs per minute or an equivalent of 109,000 SEUs per day. The flux of that event was 24,000 particles/cm^2/sec. By extrapolation, the 1859 superstorm with a flux three times greater could have nearly 228 SEUs per minute or 328,000 per satellite day. Only some SEU events, however, might generate an actual mission-critical, satellite anomaly [see Bedingfiend et al., 1996]. The SEU production of, for example, 100 additional false-stars in a CCD image used by the attitude control system (ACS) might yield only one actual anomaly involving a satellite pointing error. The ASCA satellite was lost due to ACS anomalies caused by SEUs according to Space News [2002]. However, the issue for satellite operators is, what will the managing of satellite operations be like when the SEU event rates become thousands of times higher than conditions they have witnessed thus far in anomaly management?

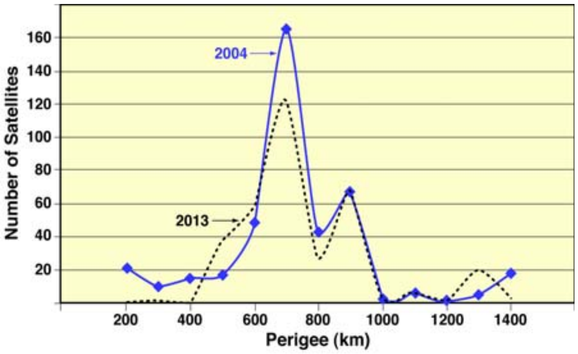

Figure 6: Distribution of LEO satellite orbits by 2004 (solid line) and predicted for 2013 (dashed line) after a superstorm event in 2012. Because of the 100-km perigee binning, variations in the >1200 km bins are spurious, and caused by 1-km shift in modeled satellite perigees across binning boundary.

The case of the TDRS-1 satellite described by Wilkinson et al. [1991] is perhaps a reasonable example of such effects, though on a satellite not optimally designed to minimize these effects.

If we scaled our operating fleet of 936 satellites to Belov's normal satellite anomaly rates, we might expect to experience about (0.13/satellite/day x 936 satellites) ~120 anomalies per day across the entire existing fleet of satellites. During the superstorm, the worst-case fluences suggest anomaly rates at least 50 times higher (several per day per satellite). The most intense phase of SPE events generally last only a few hours, so this clearly suggests that satellite anomaly mitigation by ground controllers will be a challenging and intense, short-term battle.

LEO satellites experience radiation damage primarily from the energetic electrons and protons from the inner van Allen belts. For example, UoSAT-2 in a 700 km polar orbit, experienced enhanced SEUs from cosmic rays during polar cap transits, and enhanced proton nuclear reactions causing SEUs during transits of the South Atlantic Anomaly [Daly et al., 1996]. The SAA generated the highest anomaly rates. During a superstorm event, the associated CME may be capable of driving the magnetopause well-inside GEO orbit, with likely consequences for the dynamics and stability of the inner van Allen belts, including the generation of new radiation belts (e.g. March 1991 event). Under these conditions, it is not unreasonable to expect that SAA particle fluxes would be greatly modified or even enhanced. LEO satellites normally designed to sustain years of exposure to the SAA under typical conditions may experience large increases in total radiation dosage and reduction in lifetime.

5.3 LEO Satellites and Orbit Decay

As of 2004, there are 437 satellites in LEO that appear to be still in operation. These satellites are primarily communication systems (e.g. Iridium, Globalstar), Earth resource mapping (e.g. Landsat-7), and imaging systems (e.g. Spot-5) that require LEO for the best mission outcomes.

Many astronomical research satellites and manned platforms (e.g. Hubble Space Telescope and ISS) are in LEO. Figure 6 shows the population distribution with perigees less than 1400 km. The large change near 600 km represents the members of the Iridium satellite constellation. Although LEO satellites are considerably less vulnerable to SPE and solar panel degradation, their largest risks come from atmospheric friction and orbit decay. These conditions are known to change markedly during the solar cycle.

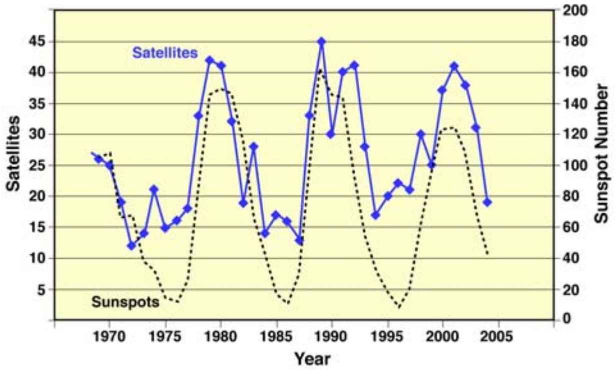

Figure 7: Satellite de-orbits (solid line) compared with solar activity cycles from 1967-2004 (dashed line).

Enhanced solar UV at solar maximum increases the heating of the atmosphere and increases its density. Figure 7 shows the impact that changes in atmospheric solar heating have had on the frequency of satellite re-entries since 1967, based on data from Space Track [2005]. A clear correlation is evident in which the largest numbers of re-entries occur during the peak years of sunspot cycles in 1968, 1979, 1989 and 2000. Although the time scale for these solar cycle variations is on the order of several months, individual space weather events lasting less than a day can significantly reduce satellite perigees. This can be seen in the altitude log of the International Space Station during the Bastille Day, 2001 storm shown in Figure 8 and also described by Hammons [2001].

Although the detailed re-entry behavior of LEO satellites depends on their

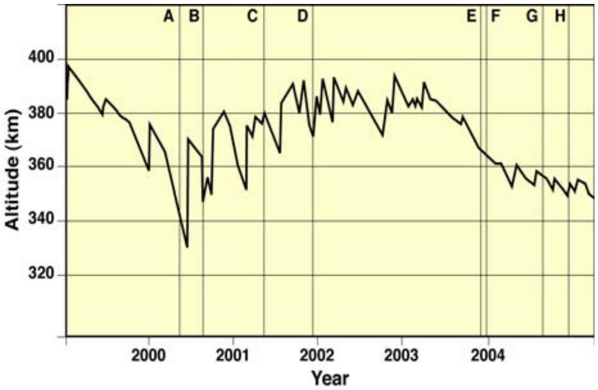

Figure 8: International Space Station altitude evolution between 1999-2005 adapted from NASA [2005]. Orbit decay rates are ~400 meters/day at solar maximum and ~90 meters/day near solar minimum. We represent the most severe geomegnatic storms (Kp = 9) by vertical lines as follows: A) April 6, 2000; B) July 14, 2000, C) March 30, 2001; D) November 5, 2001; E) October 28/29, 2003; F) November 19, 2003; G) July 27, 2004 and H) Nov 8/10, 2004.

Table 6 : Fitted orbit decay constants

Satellite	Mass (kg)	Perigee (km)	Solar Max.		Solar Min.	
		P_0	A	α	A	α
SNOE	115	580			1.3	0.18
HST	14,000	575	0.7	0.27	--	--
ASCA	420	570	0.2	0.24	--	--
Starshine	80	475			1.5	0.6
ISS	470,000	395	1.0	0.6	1.1	0.4

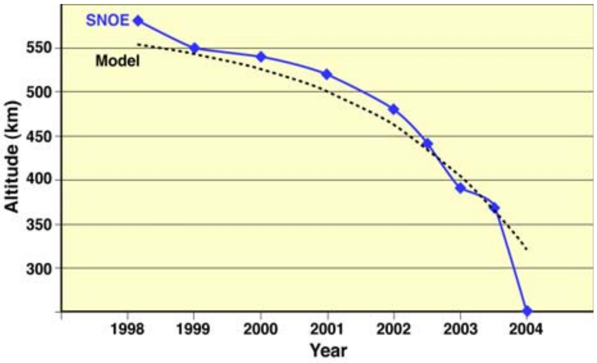

Figure 9: Comparison of SNOE satellite decay altitude profile, with a modeled approximation based on a simple power-law. Satellites with perigees below 300 km de-orbit within 1-year and a precise orbit evolution is not needed for the current analysis, which involves a 100-km binning resolution.

individual aerodynamic properties, specifically their area-to-mass ratio, calculations of orbit decay times for reasonable satellite geometries and masses suggests that at altitudes of 300 km, decay times under normal atmospheric conditions are of the order of a week. Some satellites are able to re-boost themselves, however it is not known which specific systems have this capability, or how much propellant remains at the present time to carry out this function beyond 2005.

A simple model for orbit decay was created and applied to the LEO satellites, HST [SpaceRef., 2003], Starshine-3 [Science@NASA , 2001], SNOE [SNOE Team, 2004], ASCA and ISS based on the formula:

$$P(t) = P_0 - A\, t^{\alpha}$$

where, P_0 is the initial orbit perigee, and A and α are constants that have been fitted to representative orbit decay plots for a small selection of satellites between 400 to 600 km. Satellites above 600 km are assumed to have orbit lifetimes longer than 25 years, even during solar maximum conditions, with only modest perigee changes of 1 km/yr. Below 600 km, our simple function, P(t), is assumed to take effect until altitudes of 300 km are reached, at which point un-boosted satellites have only a few weeks of remaining lifetime.

The fitting constants are shown in Table 6 for solar maximum and solar minimum conditions. A representative fit for the SNOE satellite de-orbit is shown in Figure 9 (dashed line). Although the range in mass for the satellites is a factor of 7000, the fitting coefficients fall in a very narrow range, with mean values of A = 0.6 +/- 0.3 and α = 0.4 +/- 0.2 during solar minimum and A = 1.3 +/- 0.2 and α = 0.4 +/- 0.2 during solar maximum. The constant A depends on solar cycle phase, however, the power-law index shows little solar cycle dependence. We have fitted a simple sinusoid with a period of 11 years to the constant A to determine an analytic formula for the solar cycle contribution, and obtained the following form:

$$A(t) = 0.9 + 0.6\cos(0.57(t-t_0))$$

Table 7: Possible ISS orbit-crossing candidates.

Satellite	Launch Year	Perigee at Launch (km)	Predicted Re-entry Year
Swift	2004	600	2013
ZY 2-3 (ZY-2C)	2004	472	2011
XSS-10	2003	518	2010
IGS-1A	2003	500	2010
Orbview-3	2003	470	2010
Cosmos 2405	2004	402	2010
ZY 2-2	2002	472	2009
RHESSI	2002	520	2008
GRACE-2	2001	500	2008
KORONAS-F	2001	500	2008
GRACE-1	2001	483	2008
QUICKBIRD-2	2001	460	2008
Ofeq-5	2002	370	2008
ZY 2-1	2000	472	2007
Cosmos-2383	2001	402	2007
Sicral 1	2001	328	2007
Cute-1	2003	320	2007
Rocsat-1	1999	600	2006
Ziyuan-2	1999	483	2006
EROS-A1	2000	480	2006
CHAMP	2000	400	2006
FSW 3-3	2004	284	2006
Mikron	2004	282	2006
CORIOLIS	2003	278	2006
NROL-1	2004	260	2006
TRACE	1998	602	2005

where t_0 is the sunspot minimum year 1996. The best-fit satellite decay function is therefore:

$$P(t-t_{launch}) = P_0 - (0.9 + 0.6\cos(0.57(t-1996)))\,(t-t_{launch})^{0.4}$$

With this albeit simple formula, we have determined the perigee evolution of the 437 LEO satellites below 600 km at launch, and through the year 2024 without the effect of a superstorm in 2012. We were able to obtain the launch dates and initial perigees for 422 satellites, of which 393 have apparently survived to 2004. The perigee distribution of these satellites is shown in Figure 6 (dashed line). According to our model, the remaining 29 non-surviving satellites were launched before 1996 and include only four civilian satellites (Hubble Space Telescope, BeppoSAX, SAMPEX, XTE). Because of the extreme ages of these operational satellites and their low initial perigees (130 km to 500 km), they are no doubt being actively maintained against orbital decay.

A superstorm event would be expected to temporarily increase the atmospheric drag for the lower-altitude LEO satellites. Assessing superstorm impact to the LEO population via orbital decay requires knowledge of the heating effectiveness of such a storm. X-rays from solar flares, and solar ultraviolet radiation increases during solar maximum conditions, heat the atmosphere directly, while magnetospheric currents entering the upper atmosphere do so through frictional heating. Without a more rigorous specification for the superstorm, it is not possible to do more than bracket the atmosphere response using extrapolation from previous storm events.

In simple terms, orbital drag (i.e. dynamic pressure) is proportional to the density of the ambient medium, which for the upper atmosphere can be approximated by an exponential model,

$$\rho = \rho_0 e^{-h/a}$$

where ρ_0 is the density at ground-level, a is the scale height, and h is the altitude. The scale height, a, is affected by virtue of atmospheric heating since a = kT/mg, where T is the atmospheric temperature, m is the mass of the dominant constituent, g is the acceleration constant and K is Boltzman's Constant. Detailed models (e.g. MSISE-90) during conditions of high solar activity appropriate to solar maximum [SPENVIS, 2001] suggest scale heights increase 10% from 87 to 100 km over the altitude range from 400 to 600 km. The dynamic pressure causing the drag force is proportional to the ambient density, so the drag force decreases by a factor of ~ exp(100/87) = 3. Meanwhile, the rate of orbit period decrease, $dP/dt = -3\pi a \rho A/m$ and since for circular orbits P^2 is proportional to h^3, the decrease in orbit altitude, dh/dt, is proportional to $-2P\rho/3h^2$, and is also linear in the density change. We infer from these approximations that, between 600 and 400 km, the altitude change increases by a factor of ~3.

The orbital perigee of the ISS was reduced by 15 kilometers within a few hours during the Bastille Day storm on July 14, 2000 [Hammons, 2001]. If we arbitrarily consider a superstorm effect that produces ~4 times the Bastille Day storm altitude change at the ISS orbit (e.g. 60 km), and scale this decrease to satellites in higher orbits, the result is that at 600km, the change is only ~20km, and not enough to de-orbit the satellite in a timescale less than ~25 years. In fact, most of the significant orbital changes will happen at orbits near 400 km, and so we will simply add to the LEO baseline model a uniform 60-kilometer orbit decrease in 2012 to all satellites below 600 km.

There appear to be two components to a superstorm impact: one prompt and the other delayed. Only a very small number of satellites in the existing population shown in Table 7 would be close enough to the 300-km threshold in 2012 for imminent re-entry following the superstorm. For example, the 1,500-kg Swift satellite was launched in 2004 into an orbit with an initial perigee of 600-km on a 2-year mission to study gamma-ray bursts. Were it to decay in a manner similar to the SNOE satellite [SNOE Team, 2004], Swift could reach an altitude of 380 km by 2012. An additional 60-km altitude reduction would place it at 320-km in the regime for rapid re-entry within a few weeks. This essentially accelerates its de-orbit time by a full year, similar to the unplanned re-entry of Skylab in 1979. We note, however, that Table 7 includes satellites capable of re-boosting their orbits against atmospheric decay, and therefore not likely to be relevant to such an analysis. A superstorm event may, however, exceed a satellite's ability to perform such a correction. Atmospheric drag mitigation is feasible for most commercial satellites. It is, however, a costly solution that must be implemented at the time of satellite design and fabrication (e.g. station-keeping thrusters and adequate fuel reserves), not post-launch.

Looking farther into the future, Table 8 shows that the superstorm event causes a second wave of re-entries involving ~97 satellites ca 2021. These satellites, with a replacement cost of $16 billion, were at altitudes from 600 to 700 km before the superstorm and should have remained in orbit for several decades afterwards.

Table 8: Possible additional LEO re-entries 2013-2021

Satellite		Altitude ranges (km)			
Most expensive examples	Number (Cost)	2011	2013	2019	2021
SPOT-2, ORBVIEW-1, AQUA, AURA, Oceansat-1, Misty-1e	19 ($3.0 billion)	761-700	684-623	579-516	341-278
ORBCOMM 2-28, Terra, EO-1, Landsat-7, GALEX, Tansuo-2	41 ($3.4 billion)	699-677	620-600	515-495	277-257
Helios-1A, Helios-2A, Ikonos-2, GP-B, Landsat-5, Fuji-2, Nazedhda-2	27 ($8.7 billion)	676-627	599-550	494-445	256-207
TIMED, Argos, USA-58, Okean-O1	10 ($1.1 billion)	626-600	549-520	444-415	206-177

Following the superstorm, the orbits reached the 177-341 km de-orbit range by ca 2021, assuming that the satellites are not equipped to compensate for atmospheric drag by the time of the superstorm. The most notable members of this population are the entire ORBCOMM network, the Ikonos, Landsat and SPOT imaging satellites, and research satellites such as Terra, Aqua, TIMED and GP-B. Of course, the average age of these systems by 2021 will be in excess of 20 years. It is plausible that they will be retired and replaced, or even intentionally de-orbited, long before the model suggests their orbits will passively decay.

Although the small number of LEO satellites immediately affected by the storm makes this analysis appear reassuring, the greatest practical concern actually relates to the International Space Station. Depending on the details of the atmospheric heating from a superstorm, the ISS perigee decay may well be near-catastrophic. It is currently scheduled for retirement sometime after 2014, so it would be operating during our model superstorm year.

The altitude history of the ISS from 1998-2005 [NASA, 2005] in Figure 8 shows the periodic ‘saw-tooth’ re-boosts needed to maintain its orbit between 340 - 400 km. During 2005, the ISS perigee is expected to decline about 90 meters per day and requires re-boosts every 10 to 45 days [JSC, 2002]. During the 2000 solar maximum, the decay rate was much higher: 400 meters per day. Re-boosts are currently provided by either the US Space Shuttle (~40 km altitude per event e.g. Science@NASA, 2000) or by the Russian Progress vehicle (~3 km altitude per event e.g. SpaceToday.net, 2005). The Shuttle will be decommissioned in 2010, leaving the ISS with no ability to maintain its altitude in the event of a superstorm in ca 2012 or beyond.

Another troubling issue is the collision between a re-entering satellite and the ISS. The ISS orbits within a range of altitudes from 320 km to 400 km, so likely impact threats could come from satellites passing through the ISS hazard ‘window’ with orbits between 320 km to 500 km by 2012. Our crude de-orbit calculation suggests that, in order for a satellite to enter this zone following a superstorm event in 2012, it would need to have a perigee in ca 2004 near ~600 km. Only the SciSat-1, Swift and Icesat satellites launched in 2003-2004 appear to be viable candidates, although satellite launches between 2005-2011 may change this estimate.

5.4 MEO Satellites

The GPS system is, by far, the most critical of the MEO systems. As a result of the de-classification of this technology and its rapid integration into a growing suite of civilian consumer items, it is estimated that there are 100 times more civilian users of GPS data than military consumers, and this market is rapidly expanding. By 2008 it is anticipated that revenues from GPS technology and consumer goods will exceed $22 billion, with over 8 million vehicles equipped with GPS systems worldwide [GPS World, 2004a]. In 2008, a European satellite network called Galileo is scheduled to join GPS and GLONASS as a new civilian global positioning system.

The completed GPS constellation has 24 spacecraft in 6 high-altitude orbit planes in addition to 5 spares, each with a 7.5 year lifespan for Block IIA satellites launched from 1990 to 1996. By 2005, all of these satellites are older than their planned lifetimes. Many of the 19, Block 2A satellites launched between 1990 and 1996 are still operational at ages of 12-14 years. The 13 Block IIR satellites launched between 1997 and 2004 are only now reaching their estimated EOLs, though they are expected to exceed this by a large margin as for Block IIA. Up to 12 Block IIR replacement satellites (called Block IIRM) were to be modified to use the new military M-code and are to be launched between 2005 and 2006, with initial operational capability by 2008 and full capability by 2010 [Global Defense, 2001]. Improvements in the Block IIF over previous satellites include a design life of 12.7 years and a dramatic increase in the growth for additional payloads and missions [GPS Fact Sheet, 2000]. The first of an estimated 12, Block IIF launches will start in 2007 [Guenthers Space Page, 2005].

Because age seems more verifiable in military satellite operations than predicted power level, or the satellite's response to power erosion, we will examine the age distributions of the US GPS satellites and assume that a replacement of services (by backup spare or new satellite) happens after 15 years. If the normal, annual power degradation rate for MEO satellites is 5% [Patel, 2000] , the 18% power degradation estimate for a superstorm implies a satellite life expectancy loss of 18/5 ~ 4 years. Actual power degradation for GPS satellites is not a function of SPE frequency or fluence, but primarily caused by the total radiation dosages by energetic protons and electrons experienced in the van Allen Belts during a satellite's lifetime, which are substantially higher than experienced by either GEO or LEO satellites. Once again, without a model for the van Allen Belt response to a superstorm event, we cannot properly estimate the added lifetime radiation dosage, and have to assume it is at least comparable to what an SPE would produce.

In 2004, 11 of the 29 GPS satellites are already past their nominal 8-year lifetimes. The older models are being replaced at the rate of 3 per year (ca 2003 and 2004), so by 2008 the entire Block IIA will be replaced by 12 newer models – the Block II-RMs. GLONASS, meanwhile, has 10 operational satellites in 2005 with a goal of restoring the full 24 by 2007. The European Galileo GPS system may have as many as 30 operational satellites by 2008.

By the time of an assumed superstorm in 2012, all 12 of the Block II-RM satellites would reach or exceed their 12-year replacement lifetime. The number of operating satellites will probably be lower than the 24 needed to maintain a fully operational GPS system, spanning all geographic locations, and available at all times at the designed accuracy. The GPS constellation will consist of satellites operating well beyond their predicted replacement lifetimes following the superstorm. Without replacements, it seems unlikely that the constellation would be able to provide the minimum of four satellites for ground-level GPS positioning at the designed accuracy, especially for military and aviation applications.

The relatively youthful Galileo system also would fare rather poorly for launches between 2006-2008. Galileo satellite ages in 2012 would be between 4-6 years. Following the superstorm, this would rise to 8-10 years which is near the planned life expectancy for this system. The new GLONASS satellites launched between 2005-2007, with their intrinsically short lifespans of about 7 years would most likely be eliminated from operational status by a superstorm in 2012. In addition to the premature retirement of some of the GPS satellites, and possibly the failure of the system to operate with a full satellite complement, the accuracy of the GPS system would be impaired regardless of whether satellites are lost or not.

Differential GPS (DGPS) measurements available to the more expensive ground-based navigation systems (military, marine, air navigation) are less sensitive to ionospheric disturbances, however they are not completely immune from large gradients in ionospheric total electron content (TEC) according to studies by Skone et al. [2004]. During the October 2003 storm, the DGPS errors reached 20 meters, compared to quiet-time conditions of only 1-2 meters. [Coster, et al. 2004]. During the Bastille Day-2000 storm, horizontal position errors of 20 to 40 meters were recorded for several hours using DGPS [Skone et al., 2004]. These position errors exceed the 5-10 meter limits for maritime navigation, and greatly exceed the 2-5 meter position errors for aviation and military applications.

During the superstorm, severe ionospheric and geomagnetic disturbances could be expected to prevail for 24-72 hours based on the durations of historical storms, causing GPS users to have severely degraded positions for extended periods of time. The magnitude and duration of such a storm would, doubtless, have large practical impacts to airlines, military, and rescue services worldwide. There will also be 10s of millions of automobiles and other civilian position-finding systems in place by 2010 for which 50 to 100-meter errors will render city driving by GPS useless, or even hazardous.

6.0 Superstorm Consequences

The consequences of a future 1859-calabre superstorm event, were it to occur near the peak of the next sunspot cycle, are quite extensive, and involve a range of human and technology impacts not unlike a major Force-5 hurricane or tsunami. However, an overall assessment of such a superstorm impact is complicated by the fact that there are favorable considerations which act to mitigate some of the worst of the unfavorable impacts.

Perhaps the best indication we have to suggest our satellite resource is a robust one, is that we have currently experienced nearly a dozen major space weather events since 1980, with no widespread loss of satellite resources. Satellites appear to have evolved into highly resistant systems that seem able to survive the significant storms of the last 20 years, with fluences nearly as large as the 1859 superstorm. The fact that there are at least a dozen different satellite designs now in operation may also be a large part of the reason why space weather events have not had a more widespread damaging effect.

We currently have more transponders available for producing revenue than are currently in use. Mitigating factors to transponder/satellite loss include transponder overcapacity and the vast improvements in satellite technology. Currently, there is a nearly 50% overcapacity in unused transponders according to Futron [2003], allowing many GEO satellites to operate at undercapacity. In some ways, the loss of excess capacity by a superstorm may actually allow some companies to recoup these losses via satellite insurance so that they are then free to move on to more profitable projects.

It is possible to mitigate many SEU effects by using software. Commercial 'off-the-shelf' processors that run sophisticated error-detection software have demonstrated the potential to reduce SEU events and their impacts to very low levels. NASA is exploring new technologies such as the Environmentally Adaptive Fault Tolerant Computing System to be flown on the ST-9 spacecraft in about 2010, which will detect and eliminate the effects of SEUs. This will reduce the need for radiation-hardened processors, and have a significant impact upon the reliability of commercial satellite systems during solar storm events. An important qualifier, however, is that such algorithms only work if there has been no actual destruction of the relevant logic junctions. According to Koons et al. [1999] and Barth [2004] , among ~300 spacecraft anomalies studied, 5.4% involve physical damage due to total radiation dosage. This suggests that, even during a superstorm, some satellite damage may be irreversible through software.

In time, GPS replacement satellites may become invulnerable to errors. The GPS system has rapidly become a major military and economic asset, depended upon by millions of military and civilian users. Although the current funding difficulties for this system may delay the installation of the GPS Block IIM, IIF and III systems, it seems unlikely for security reasons alone that this system will be placed at risk. There are, currently, a dozen backup satellites on the ground, and four deactivated as reserves on-orbit. Moreover, they have an impressive history of weathering the space environment in the midst of the Van Allen Radiation Belts for lifetimes exceeding 10 years in many cases. A superstorm event may not be enough to 'take down' this system, but it may produce unprecedented ionospheric disturbances and the temporary filling-in of the slot region itself, causing position errors globally. A mitigating factor is that the Block IIF satellites, when operational, will have a civilian 'L5' channel that has been added to provide Total Electron Content (TEC) information directly. In principle, this will be used to automatically correct the individual satellite signals for ionospheric disruption. The effect of a superstorm event on position errors may be entirely eliminated by this means.

Among the unfavorable consequences of a superstorm, even under the best of scenarios, satellite operators will be swamped with problems. A survey of satellite engineers and operators by Futron [2003] finds that satellite operators spend 40% of their time working with satellite anomalies. Because a single company may have more than one type of satellite in operation, and multiple types of spacecraft buses (e.g PanAmSat has five different types of satellite buses) the logistics of managing satellite anomalies has recently become complicated.

Table 8 : Current and Future Sun-Earth Missions

	SHO	WND	POL	ACE	TRA	IMG	TIM	HES	STE	TWN	THM	SolB	MMS	SDO	GEC	GOES
1995	L	P														
1996	P	P	L													
1997	P	E	P	L												
1998	P	E	P	P	L											
1999	E	E	E	P	P											
2000	E	E	E	E	P	L										
2001	E	E	E	E	E	P	L									M
2002	E	E	E	E	E	P	P	L								P
2003	E	E	E	E	E	E	P	P								P
2004	E	E	E	E	E	E	P	P	L							P
2005	E	E	E	E	E	E	E	E	P	L						N
2006	E	E	E	E	E	E	E	E	P	P	L	L	L			P
2007	E	E	E	E	E	E	E	E	E	P	P	P	P	L		O
2008						E			E	E	P	P	P	P	L	P
2009									E	E	E	E	E	P	P	P
2010									E	E	E	E	E	E	P	P
2011									E		E	E	E	E	E	P
2012									E		E	E	E	E	E	R
2013									E		E	E	E	E	E	P
2014									E		E	E	E	E	E	P
2015									E		E	E	E	E	E	

Our estimates for a substantial increase, by several orders of magnitude, for satellite anomalies all occurring during a superstorm would be a major hardship for satellite engineers and operators, and may well exceed their abilities to monitor, anticipate and correct severe malfunctions before they became fatal to the satellite. The ASCA satellite was lost during the October-November 2003 storm because ISAS could not react fast enough to the changing space weather conditions affecting the satellite. The ebb and flow of superstorm conditions will undoubtedly be very complex in time, forcing operators to experience intense periods of activity and intervention. The statistics of the large numbers of SEUs seem to demand that multiple, critical conditions (phantom commands, ACS upsets etc) may strike a single satellite at nearly the same time. The replacement time for satellite systems is not inconsequential, in the event of unanticipated, multiple satellite fatalities. For instance, it takes 12-14 months to build a Boeing-376 satellite bus, which is one of the most popular communications satellite buses now in service. If several dozen communications satellites have to be replaced to recover hundreds of failed transponders, this could be a significant near-term economic hardship, although if the trends for increasing transponder over-capacity continue as we previously mentioned, it may simply result in a beneficial weeding-out of unused systems. Nevertheless, it is unlikely that the superstorm impact will be mitigated by a large increase in new satellite systems and capacity according to launch forecasts by COMSTAC [2004].

Satellite power continues to increase, as does solar panel voltages, which leads to destructive electrical discharges as the satellite moves through a plasma environment. According to laboratory studies by Cho and Nozaki [2005], the buildup of a differential satellite potentials leads to the onset of an ESD 'trigger' arcing event. These events are normally self-limiting for power buses operating below 100 V. In current satellite designs, however, these voltages are exceeded so trigger arching leads to sustained discharge arcs. These discharges can physically damage solar array panel connections. This has caused several satellite systems to fail (for example, PAS-6 and Tempo-2 in 1997), forcing them to operate on only a fraction of their designed power. Arcing has been observed as low as 55-60 Volts in some LEO satellite systems [Ferguson and Hillard, 2003]. Some mitigation is possible by designing the architecture of the solar panels on LEO satellites so that, for example, adjacent cells do not have a voltage difference greater than 40 V [Ferguson and Hillard, 2003]. Nevertheless, the trend towards higher power and higher voltage systems continues, making these newer satellites susceptible to arcing, and consequent solar array damage.

7.0 The Status of Warnings and Forecasts

The most significant method for mitigating the effects of a superstorm will involve advanced warning and forecasting. The National Weather Service portion of the National Oceanic and Atmospheric Administration along with the U.S. Air Force currently operates the Space Environment Center (SEC). SEC, located in Boulder, Colorado, provides real-time monitoring and forecasting of solar and geophysical events, conducts research in solar-terrestrial physics, and develops techniques for forecasting solar and geophysical disturbances. Space Environment Center continually monitors and forecasts near Earth space weather and is the Nation's official source for space weather alerts and warnings. SEC works with many national and international partners who contribute data and observations such as NASA.

NASA currently maintains a fleet of space science missions in both their prime mission phase and their extended mission phase as shown in Table 9. NASA extends their missions beyond their prime mission phase into an extended phase after they have achieve their original science objectives and only after they have demonstrated (every two to three years) that they can continue to contribute to other NASA strategic science objectives in a cost effective manner and remain relatively healthy. NASA space science missions provide significant amounts of data to SEC to support space weather predictions and warnings.

Advanced warning may be problematical because of the expected retirement of nearly all of the current NASA Sun-Earth Connection fleet by 2008, and the slow launch of replacement systems to provide advanced warning, as summarized in Table 9. Although space weather research is an important part of NASA's strategic plan, by 2010 it is expected that NASA will no longer have ACE, SOHO, IMAGE, RHESSI, and TRACE as operational space weather assets. Severe budget cuts have threatened to nearly eliminate NASA's current space weather research fleet of missions. Assuming no budget cuts or programmatic delays, by 2012 NASA will have Solar-B, STEREO, GEO, SDO, Themis, MMS and GEC which will replace many, but not all, of the existing capacities. For example, the STEREO satellites are located well off the sun-earth line and would not provide *in situ* field measurements for earth-directed CME's as ACE currently does, though they would allow direct imaging of approaching CMEs. The arrival time of the CME could be calculated but not its geoeffectiveness, which is determined by observations of Bz.

There will be no years of overlapping coverage during the main mission phases (indicated by L or P in Table 9) of these satellites. Only during the extended (indicated by E in Table 8) mission phases will there exist the possibility for overlapping coverage. Overlapping coverage is crucial for successful space weather forecasting. For example, the ACE satellite to be retired ca 2007 is stationed at L1 and provides about 1-hour notice of approaching CMEs as well as measures of their magnetic field orientation. It is also the case that these satellites already will be 5-9 years old by the next sunspot maximum, with the most intense storms likely to arrive even later in the cycle.

So far, NASA satellites have been able to detect CMEs, allowing space weather forecasters at NOAA/SEC to estimate their arrival times with reasonable half-day accuracy. However, a superstorm CME could take less than 17 hours to reach Earth. STEREO and SDO will continue this ability to monitor CMEs during the run-up to solar maximum in 2012. However, there will be no way to determine the magnetic field orientation of the CME en-route since, presumably, none of the satellites will be equipped with *in situ* magnetometers to study the interplanetary medium. This means we will have no advanced warning of the southward orientation of the ICME and therefore its geoeffectiveness.

Magnetic storms can be studied from the ground, however forecasting these events remains an illusive goal. According to statistics compiled by Joselyn [2001], forecasters can predict that a Kp > 4 storm will occur on a particular day with about 95% accuracy. However, the probabilities decrease to 45% in predicting a K > 5 storm. Generally, more storms were detected (206) at a specific station (e.g. Fredericksberg) than were predicted (57) so that only 28% of the storms are actually predicted 24-hours in advance. Meanwhile, the number of false alarms was 62% which can have nearly as severe an economic impact as an actual storm, especially for electrical power grid operators subject to ground induced currents (GICs).

For satellites, however, it will not be the ICME or the ensuing geomagnetic storm that will provide the greatest immediate problem. The sun produces about 20,000 C-class flares, 2,000 M-class events, 200 X-class events and 100 SPE events per solar cycle according to tabulations by Joselyn [2001]. For large events capable of producing significant spacecraft disruption, solar power declines, or damage, CMEs are launched at about the same time as the flares, so it is important to predict the flaring onset event before a halo-type CME is detected.

Satellite X-ray and ground-based solar magnetic field imagers have provided 24-hour advanced notice of large flares. SPEs often , though not always, occur in concert with large CME or flare events, and reach earth within hours after the x-ray flare is detected. For the most dangerous ‘high rigidity’ SPE spectra with cut-offs above 1 GeV, however, the particles are relativistic and arrive at virtually the same time as the x-ray burst so the onset of the x-ray flare is already too late an event for SPE mitigation to be effective. More research needs to be done to identify the solar magnetic fields configurations that lead to flare events. Table 10 indicates the current records for X-class flare and SPE predictions among the most intense examples to date.

The most famous, and recent, of these events occurred on November 4, 2003. In the 5 days prior to the event, the 24-hour X-class flare probabilities [NOAA/SEC, 2003] were 50%, 40%, 35%, 75%, 75%. On the day of the flare, the probability remained at 75%, and in the three days after, dropped to 10%, 1%, 1%. Although the X-ray class had been anticipated, neither the exact luminosity nor the day of the event had been predicted. Contrast this with the X-class event on April 15, 2001, which was only anticipated at a 25% probability. Including false-positives, the best estimate of 24-hour forecast reliability seems to be below 50% for X-class flares. This implies a 1 in 2 chance a major X-class ‘superflare’ could not be anticipated within 24-hours of the event.

Would a superflare birth site have a distinctly different magnetic signature in a solar active region so that the forecast could be made more accurate? This is currently unknown. We do know that the 1859 event coincided with an impressively large sunspot group near meridian transit. These are also conditions that have been more impressively manifested for lesser storm events. Currently, space weather forecasters consider any large sunspot in the 1859-class a potential threat for the roughly 2 weeks that it is present on the earthward side of the sun, and especially threatening during the 5-days near solar meridian transit.

This decades-old technique of watching for very large sunspots may well be the best advanced warning we can achieve, given the changing capabilities of satellite-based sensors during the next 10-15 years.

Conclusions

All indications point to a potentially major economic and military impact on our space assets for the next major 1859-like superstorm event. Unlike previous historical events, our current reliance on satellite technology and human activities in space, place us in a unique and unprecedented nexus of vulnerabilities from such an event.

Although it is difficult to accurately assess the economic consequences due to incomplete data on military and commercial satellite systems, we can nevertheless bound the likely impacts by a worst-case scenario involving a superstorm about 3-fold more severe than the 1859 Carrington-Hodgson event. This scenario includes a < $70 billion financial impact on commercial satellite systems due to a combination of direct hardware loss, service loss and indirect profit loss. Satellite engineers and operators will experience thousands of satellite anomalies per day across the satellite fleet– an unprecedented rate never-before experienced during the Space Age. There may be a significant loss of ~15% of our operating satellites as a result of older systems already past their designed lifetime radiation dosages being impacted by a large new influx of radiation equal to 3 to 5 more years of annual dosage. The superstorm may result in a sharp rise in mission-critical anomalies in satellite power and orientation systems, which lead to complete satellite failure, especially for GEO and MEO satellites that are not as atmospherically well shielded as LEO systems. For satellites younger than about 5 years, the superstorm may actually double their accumulated dosages to date, and halve their operating lifetimes.

Current GPS systems may be rendered temporarily, or perhaps even permanently, unusable with, at the minimum, very large position errors perhaps approaching 100-meters being common for 24-72 hours. Unless the new generation Block IIM systems are in place that are able to compensate for ionospheric TEC variations, the GPS system may effectively go off-line for many civilian and military applications. There is also the possibility that a number of the older GPS satellites may fail so that the full compliment of 24 satellites needed to operate the network will be unavailable in the months following the storm. This means that even ionosphere-compensated position measurements may not be available for portions of the day when the requisite four to six satellites are not above the horizon for specific geographic locations. The realization of the expected position errors for military use with a minimum of four satellites above the horizon, will be a complex function of local time and geographic location requiring a detailed ephemeris to implement. It may take months or years to restore the GPS system to full operating status, depending on the number of satellite failures involved, and the number of spares available for launch.

The International Space Station will undoubtedly experience a major loss in altitude that could significantly exceed the 15 km decrease experienced during the 2001 Bastille-Day Storm. Existing re-boost systems involving the Space Shuttle can produce a maximum of only ~70 km of perigee change. If the superstorm occurs at the peak of the next sunspot cycle when re-boosts are more frequent and larger in magnitude, the required post-superstorm reboost may be at the limits of what can be accomplished during a single mission. With the planned retirement of the Space Shuttle in 2010, the ISS may be in danger of catastrophic orbit decay and have to be abandoned at least temporarily. The specific details depend on the amount of atmospheric heating and the duration of the superstorm event. There may also be an increased risk of collision with in-bound satellites affected by the temporarily increased atmospheric drag. Approximately 22 operating LEO satellites are currently in orbits that could be severely affected by superstorm atmospheric heating and high-drag conditions, and which could reach or pass through the ISS altitude range on de-orbit trajectories. Moreover, an additional 97 LEO satellites, worth an estimated $16 billion, may prematurely re-enter between 2013- 2021. Although many of these systems will doubtless have been replaced, thereby minimizing the economic and scientific impacts, their re-entry during the post-superstorm period will have been unplanned and premature by several decades at the normal rates of orbit decay.

Our resources for forecasting such a superstorm will be covered by a complicated constellation of satellites whose overlapping operational years will be generally well-beyond their planned mission lifetimes. These satellites will be relatively old systems near the end of their maximum lifespans. Unlike the coverage we have experienced during Cycle-23, satellite observations of the sun and geospace conditions during the next sunspot cycle may be far less complete.

Our forecasting methodologies in practice today must significantly improve, or the pre-conditions for a superstorm may actually be missed. There is currently a better than 50/50 chance that the X-ray and SPE events associated with a superstorm may not be anticipated in time to allow satellite operators to mitigate their worst impacts. Forecasts of the level of the geomagnetic effects, and the severity of the storm, may also lack certainty in the 24-hours leading up to the storm. This is especially true if there is no replacement for the ACE satellite capability of measuring Bz. The event may be preceded by several days of false-positive forecasts, which may have the undesirable effect of rendering satellite engineers and operators less engaged when the actual event arrives.

If the events of the 1859 Carrington-Hodgson storm serve as a guide, the scope of the storm will most certainly be a major event in our modern history, but one that the vast majority of our satellite resources may reasonably be expected to survive. Nevertheless, our simple models suggest there will be a considerable number of satellite systems damaged, or seriously degraded in operating lifetime and profitability. Further improvements in our models may refine these estimates so that they become a more rigorous and durable assessment of the likely impacts.

Acknowledgments

On July 16, 2005 Dr. William Taylor unexpectedly died. We will miss his passion for space science, and space science education, and the insight that he brought to the research in this paper. We would like to thank the Referees for their enthusiastic, and thorough reading of the manuscript. Their suggestions helped to improve the clarity and technical accuracy of this paper.

References

Allen, J. H., and D. C. Wilkinson, “Solar-terrestrial activity affecting systems in space and on Earth”, in Solar-Terrestrial Predictions -- IV, Vol. 1, edited by J. Hruska, M. A. Shea, D. F. Smart, and G. Heckman, (NOAA: Boulder), pp. 75--107, 1993.

Baker D.N., 1986 “Effects of the Solar-Terrestrial Environment on Satellite Operations”, in Proceedings of the Solar-Terrestrial Predictions Workshop”, Meudon France, 18-22 June 1984.

Baker D.N., X. Li, N. Turner, J.H. Allen, J.B. Blake, R.B. Sheldon, H.E. Spence, R.D. Belian, G.D. Reeves, S.G. Kanekal, B. Klecker, R.P. Lepping, K. Ogilvie, R.A. Mewaldt, T. Onsager, H.J. Singer, and G. Rostoker, “Recurrent Geomagnetic Storms and Relativistic Electron Enhancements in the Outer Magnetosphere”, J. Geophys. Res., vol. 102, pp. 14141-14148, 1997.

Barth, J. 2004, "Prevention of spacecraft anomalies", in "Space Weather Effects on SOHO and its Space Weather Warning Capabilities", in 'Effects of Space Weather on Technology Infrastructure', Ioannis Daglis Ed. (Kluwer Academic Publishers: Boston), pp. 123-145.

Bedingfield, K.L., R.D. Leach and M.B. Alexander 1996, "Spacecraft systems failures and anomalies attributed to the natural space environment", NASA Ref Pub 1390, p. 22.

Belov, A. L., E. Eroshenko, and V. Yanke, 'Indices of the cosmic ray activity as reflection of situation in interplanetary medium', ESA Space Weather Workshop papers, ESTEC, pp. 325-328, 1999.

Belov, A., L. Dorman, N. Iucci, O. Kryakunova, and N. Ptitsyna, "The Relation of High and Low-Orbit Satellite Anomalies to Different Geophysical Parameters", in 'Effects of Space Weather on Technology Infrastructure', Ioannis Daglis Ed. (Kluwer Academic Publishers: Boston), pp. 147-164, 2004.

Brekke, P., M. Chaloupy, B. Fleck, S. Huagan, T. van Overbek and H. Schweitzer, "Space Weather Effects on SOHO and its Space Weather Warning Capabilities", in 'Effects of Space Weather on Technology Infrastructure', Ioannis Daglis Ed. (Kluwer Academic Publishers: Boston), pp. 109-122, 2004.

Chetty, P. R. K., 'Satellite Technology and its Applications', 2ed. (McGraw-Hill). pp. 164-166, 1991.

Cho, M. and Y. Nozaki, 2005 "Number of arcs estimated on a solar array of a geostationary satellite", J. Spacecraft and Rockets, Vol 42, July-August, 2005, p. 740

Cliver, E.W. and L. Svalgaard, "The 1859 Solar-Terrestrial Disturbance and the Current Limits of Extreme Space Weather Activity", Solar Phys., vol. 224, No, 1-2, pp. 407-422, 2005.

Coster, A., Skone, S. and Yousuf, R., 2004, Improving Marine Differential GPS Accuracy with a Wide-Area Network", GPS World, October 1, 2004, http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=128321&pageID=7, based upon "Wide Area Navigation Algorithm for Marine Users," European Navigation Conference GNSS 2004, Rotterdam, The Netherlands, May 16-19, 2004.

COMSTAC: Commercial Space Transportation Advisory Committee, '2004 NGSO Commercial Space Transportation Forecasts', May 2004, (http://ast.faa.gov).

Crabb, R.L., Solar Cell Radiation Damage, Radiat. Phys. Chem. Vol. 43, pp93-103, 1994.

Daly, E.J., Hilgers, A., Drolshagen, G. and Evans, H.D.R., 1996, "Space Environment Analysis: Experience and trends" , ESA 1996 Symposium on Environment Modelling for Space-based Applications, Sept. 18-20, 1996, ESTEC, Noordwijk, The Netherlands http://www.estec.esa.nl/conferences/96a09/Abstracts/abstract45/paper/

Editors, Am. J. Sci., vol. 28, pp.385-408, 1859. Editors, Am. J. Sci., vol. 29, pp. 92-97, 249-265, 386-397, 1860.

Feynman, J., G. Spitale, J. Wang, and S. Gabriel, Interplanetary Proton Fluence Model: JPL 1991, *J. Geophys. Res., 98*, 13,281-13,294, 1993.

Ferguson, D.C. and G.B. Hillard, 2003, "New NASA SEE LEO Spacecraft Charging Design Guidelines – How to survive in LEO rather than GEO", NASA/TM-2003-212737, p. 4.

Futron Corporation, 2003, "Satellite Service Demand:Reloading the Matrix", http://www.futron.com/spaceandtelecom/src/whitepapers.htm

GPS World, http://www.w2forum.com/item/global_market_top_22_billion, February, 2004.

GPS Fact Sheet, http://www.losangeles.af.mil/smc/pa/fact_sheets/gps_fs.htm, 2000.

Green, J. L. and S. A. Boardsen, 2005, 'Duration and Extent of the Great Auroral Storm of 1859', Adv. Sp. Res. (In Press).

Green, J. , S. Boardsen, S. Odenwald, J., Humble, K.A. Pazamickas, 2005, 'Eyewitness Reports of the Great Auroral Storm of 1859', Adv. Sp. Res. (Submitted).

Hammons, C., 2001 'A Study of the Effects of Large Solar Events on the Atmospheric Drag of Low Earth Orbiting Satellites', http://ccar.colorado.edu/asen5050/projects/projects_2001/hammons/

HeavensAbove.com, 'Orbit decay plot for Starshine-3', http://heavens-above.com , 2005.

Iucci, A.E. , A. Levitin, A. Belov, E. Eroshenko, N. Ptitsyna, G. Villoresi, G. Chizhenhov, L. Dorman, L. Gromova, M. Parisi, M. Tyasto and V. Yanke, ‘Space Weather Conditions and Spacecraft Anomalies in Different Orbits’, Space Weather, vol. 3, S01001, doi:10.1029/2003 SW000056, 2005.

Joselyn, J., “State of the Art in Space Weather Services and Forecasting”, in ‘Space Storms and Space Weather Hazards’, I.A. Daglis (ed.), (Kluwer Academic Press : Netherlands), p. 419-425, 2001.

JSC, “ISS Environment: ISS Payload Information Source”, Johnson Spaceflight Center, http://stationpayloads.jsc.nasa.gov/D-aboutiss/D6.html, 2002.

King, J. H., 1974, “Solar Proton Fluences for 1977-1983 Space Missions”, *J. Spacecraft Rockets*, *11*, 401, 1974.

Koons, H.C., Mazur, J.E., Selesnick, R.S., Blake, J.B., Fennell, J.F., Roeder, J.L. and Anderson, P.C., 1999, “The Impact of the Space Environment on Space Systems”, Aerospace Technical Report TR-99(1670)-1.

Loomis, E., Am. J. Sci., vol. 30, pp. 79-94, 339-361, 1860.

________, Am. J. Sci., vol. 32, pp. 71-84, 318-331, 1861.

McCracken, K.G., G.A.M. Dreschhoff, E.J. Zeller, D.F. Smart, and M.A. Shea, ‘Solar Cosmic Ray Events for the Period 1561-1994’, J. Geophys. Res., vol. 106, pp. 21585-21598, 2001a.

McCracken, K.G., G.A.M. Dreschhoff, D.F.Smart, D.F. Smart, and M.A. Shea,“Solar Cosmic Rays for the Period 1561-1994; The Gleissberg periodicity”, J. Geophys. Res., vol. 106, pp. 21599-21610, 2001b.

Mountford, T.M.P, and V.S.S. Sastry, 2003, ‘On the Prediction of Anomalous Events Onboard Geostationary Spacecraft’ Simulation and Interoperability Workshop, Fall, 2003, Mitre Corporation, http://ms.ie.org/SIW_LOG/03F/03F-SIW-019.doc

NASA, “ISS Perigee Height”, http://www.hq.nasa.gov/osf/station/viewing/history.html , 2005.

National Academy of Science, 2000, ‘Radiation and the International Space Station: Recommendations to Reduce Risk’, Commission on Physical Sciences, Mathematics, and Applications, NAS Space Studies Board, Appendix A.2.

NOAA, http://www.sec.noaa.gov/weekly/weekly03.html, 2005.

NOAA, “Solar Proton Events Affecting the Earth Environment” http://www.sec.noaa.gov/alerts/SPE.html, 2004.

Odenwald, S.F., ‘The 23rd Cycle:Learning to live with a stormy star’, (Columbia University Press: NY), 2000.

Odenwald, S.F., “Space Weather: Technological and Human Impacts”, http://www.spaceweather.us , 2005a.

Odenwald, S.F., “Space Weather: Satellite Impacts: Excel Spreadsheet”, http://www.solarstorms.org/Sscope.html, 2005b.

Patel, M. R., ‘Spacecraft Power Systems’, (CRC Press, New York), pp.115-118 , 2000.

Reedy, R., “Solar Particle Events and their Radiation Threats’, in the ‘Conference on the High Energy Radiations Backgrounds in Space’, IEEE Nuclear and Space Radiation Effects Conference’, Snowmass, Colorado, pp. 317-323, July 22-23, 1998.

Science@NASA, A Disco Ball in Space, http://science.msfc.nasa.gov/headlines/y2001/ast09oct_1.htm, 2001.

Skone, S., El-Gizawy, M. and Shrestha, S. M., 2004, “Analysis of differential GPS performance for marine users during solar maximum, Radio Sci., *39*, RS1S17. www.agu.org/journals/rs/rs0401/2002RS002844/2002002844.pdf

SNOE Team, 2004, http://www.colorado.edu/ASEN/asen5519/SNOE.pdf

Space.com, 2003, http://www.space.com/news/nss_sia_030409.html, April 9.

Space and Tech News, 2001, ‘Arabsat 3A power cut in half’, http://www.spaceandtech.com/digest/flash2001/flash2001-109.shtml

Space News, 'Japanese facing uphill battle to save damaged spacecraft’, Sept 22, 2002.

Spacetoday.net, “Progress Increases ISS Orbit”, http://www.spacetoday.net/Summary/2798 , 2005.

SpaceRef.com, ‘Expected Hubble Space Telescope Science Lifetime after SM4’, HST Program Office, http://www.spaceref.com/news/viewsr.html?pid=9911, July 21, 2003.

Space Track, http://www.space-track.org/perl/login.pl, 2005.

SPENVIS Project, 2004, “Solar Proton Models”, “http://www.spenvis.oma.be/spenvis/help/background/flare/flare.html

SPENVIS Project, 2001 “The Neutral Earth Atmosphere”, http://www.spenvis.oma.be/spenvis/ecss/ecss07/ecss07.html#_TOC711

Spotts, P., Christian Science Monitor, Aerospace Corporation Study. http://www.csmonitor.com/2003/1009/

Todd, L. and T. Bowling, 2004, ‘Debris Mitigation in Geostationary Earth Orbit’, Cranfield Space Research Center, Dynamics and Control of Systems and Structures in Space (DCSSS), 6th conference, Riomaggiore, Italy, July 2004 http://www.cranfield.ac.uk/soe/space/publications.htm

Townsend, L. W., “Carrington Flare of 1859 as a Prototypical Worst-Case Solar Energetic Particle Event”, IEEE Transactions on Nuclear Science, v. 50, p. 2307-2313, 2003.

Tsurutani, B.T., W.D. Gonzalez, G.S. Lakhina, and S. Alex, ‘The extreme magnetic storm of 1–2 September 1859’, J. Geophys. Res., Vol. 108, No. A7, 1268, 2003.

Webb, D. and J. Allen, “Spacecraft and Ground Anomalies Related to the October-November 2003 Solar Activity”, Space Weather, Vol. 2, 2004.

Wilkinson, D., S. C. Daughtridge, J. L. Stone, H. H. Sauer, and P. Darling, “TDRS-1 Single Event Upsets And The Effect Of The Space Environment,” IEEE Trans. Nuc. Sci., Vol. 38, No. 6, pp. 1708-1712, December, 1991.

Xapsos, M. A., G. P. Summers, J. L. Barth, E. G. Stassinopoulos, and E. A. Burke, 1999, “Probability Model for Worst Case Solar Proton Event Fluences”, *IEEE Trans. Nucl. Sci.*, *46*, 1481-1485.

Xapsos, M. A., G. P. Summers, J. L. Barth, E. G. Stassinopoulos, and E. A. Burke, 2000, “Probability Model for Cumulative Solar Proton Event Fluences”, *IEEE Trans. Nucl. Sci.*, *47*, 486-490.