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Anomalies from Solar Events

Solar Cycle 23 has entered its decline and has proven to be somewhat smaller by several measures when compared to earlier record-breakers. But the proliferation of technological systems affected by solar activity has continued to increase. As a result, the net effects of the solar cycle on our daily lives loom larger than ever, and the potential impacts show every sign of continuing to increase in societal consequence.

Anomalies from Solar Events

B. Poppe, A. Hilton, J. Kunches

NOAA Space Environment Center
325 Broadway
Boulder, CO 80305

1. Introduction

Solar Cycle 23 has proven to be a modest-sized cycle, and is currently about two years beyond its maximum. Geomagnetic storms are now occurring, and these have produced some notable effects. While the progress of the cycle is of interest, the extent of its effects are most important to customers. As revealed by customer contacts with Space Environment Center (SEC) staff at Space Weather Week 2002 (held April 15-19 in Boulder, Colorado), the customer base is growing, and the expanding uses of technology today are resulting in greater vulnerabilities to space weather disturbances.

Two examples of recent increases in susceptibility to space weather impacts include the wider use of GPS, and the growing amount of commercial air traffic in polar regions:

X Real time kinematic (RTK) techniques of high precision positioning in difficult terrain, in forest or urban canyon conditions, at different times of day, in different weather conditions, and in different seasons are being used by surveyors. These techniques require at least six visible GPS satellites and good ground-based communications either by UHF radio or by means of mobile telephones--and this in turn creates an increasing vulnerability to space weather.

X Airlines are increasingly interested in space weather disturbances interfering with HF and satellite communications, the possibility of losing GPS, and of radiation hazards to passengers and crew. During a 2001 proton event, one major airline reported losing both HF and SATCOM communication with their planes as they were entering Russian airspace. More recently, the airline diverted a flight on a polar route and went through Anchorage when there was another episode of high activity.

The effects presented in this paper are in a format that follows the description of the GOES SEM instruments described elsewhere in this volume: “Report on GOES Space Environment Monitor (SEM) Instruments: Overview, Plans and Benefits to Users” by H. J. Singer, S. Hill, T.G. Onsager, and R. Viereck. Not all known effects are listed; rather, we present some typical and unusual ones that have been reported over the course of the Cycle 23 maximum and the months that have followed.

2. Solar Cycle Update

Solar Cycle 23 attained its maximum, as measured by sunspot numbers, in April 2000. The smoothed sunspot number of 120.9 fell short of the predictions for a value closer to 160. By way of contrast, Cycle 19, which peaked in 1957, was the largest ever recorded; Cycle 21, which peaked in 1979, was the 2nd largest on record; and Cycle 22 was the 4th largest ever seen. With Cycle 23, the longstanding "odd-even" rule of thumb has been broken. This venerable rule, which says that an odd numbered cycle is larger than the preceding even numbered cycle, had persisted through six pairs of cycles, dating back to around 1850 with Cycle 8/9. The following table (Thompson, 2002 (in press)) lists some aspects of recent solar cycles.

Cycle Number	**Date of Cycle Start**	**Date of Cycle Maximum**	**Amplitude (Sunspot Number)**	**Length (Years)**
17	1933.8	1937.4	119	10.4
18	1944.2	1947.5	152	10.1
19	1954.3	1957.9	201	10.6
20	1964.9	1968.9	111	11.6
21	1976.5	1979.9	165	10.3
22	1986.8	1989.6	159	9.7
23	1996.3	2000.3$^{\#}$	121$^{\#}$	?

Currently, Cycle 23 is undergoing an expected pattern of decline but still producing noteworthy activity. On March 31, 2001, the strongest geomagnetic storm of the cycle occurred, with an Ap value of 192 observed. To this point in 2002, there have been 18 solar proton events (figure 1), the largest reaching 31,700 pfu (particle flux units) on November 4, 2001. Strong solar flares continue to occur.

Major geomagnetic storm activity, as depicted in figure 2, shows a bimodal behavior with a secondary peak in the decline of the cycle. This later pulse belies the perceived notion that geomagnetic storm occurrences track with the sunspot counts.

Figure 3 gives the history, over the past few cycles, of large solar x-ray flare occurrences. Although those events tend to cluster near solar maximum, they also occur, albeit at a decreasing frequency, at other points in the cycle.

Figure 1.

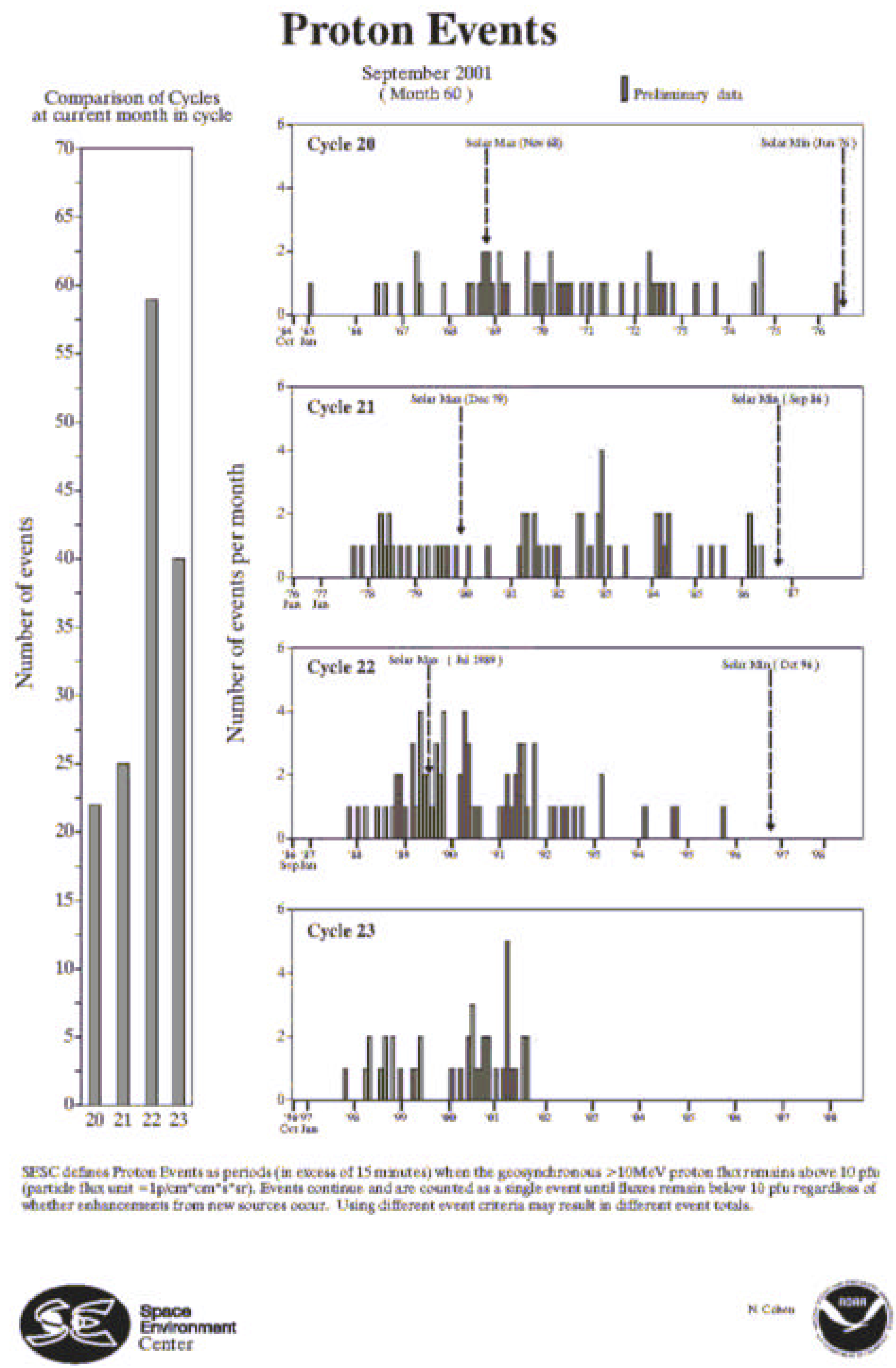
Proton Events
September 2001
(Month 60)
Preliminary data
Comparison of Cycles
at current month in cycle
Number of events
Number of events per month
Cycle 20
Cycle 21
Cycle 22
Cycle 23
SESC defines Proton Events as periods (in excess of 15 minutes) when the geosynchronous >10MeV proton flux remains above 10 pfu (particle flux unit = 1p/cm*cm*s*sr). Events continue and are counted as a single event until fluxes remain below 10 pfu regardless of whether enhancements from new sources occur. Using different event criteria may result in different event totals.
Space
Environment
Center

Figure 2.

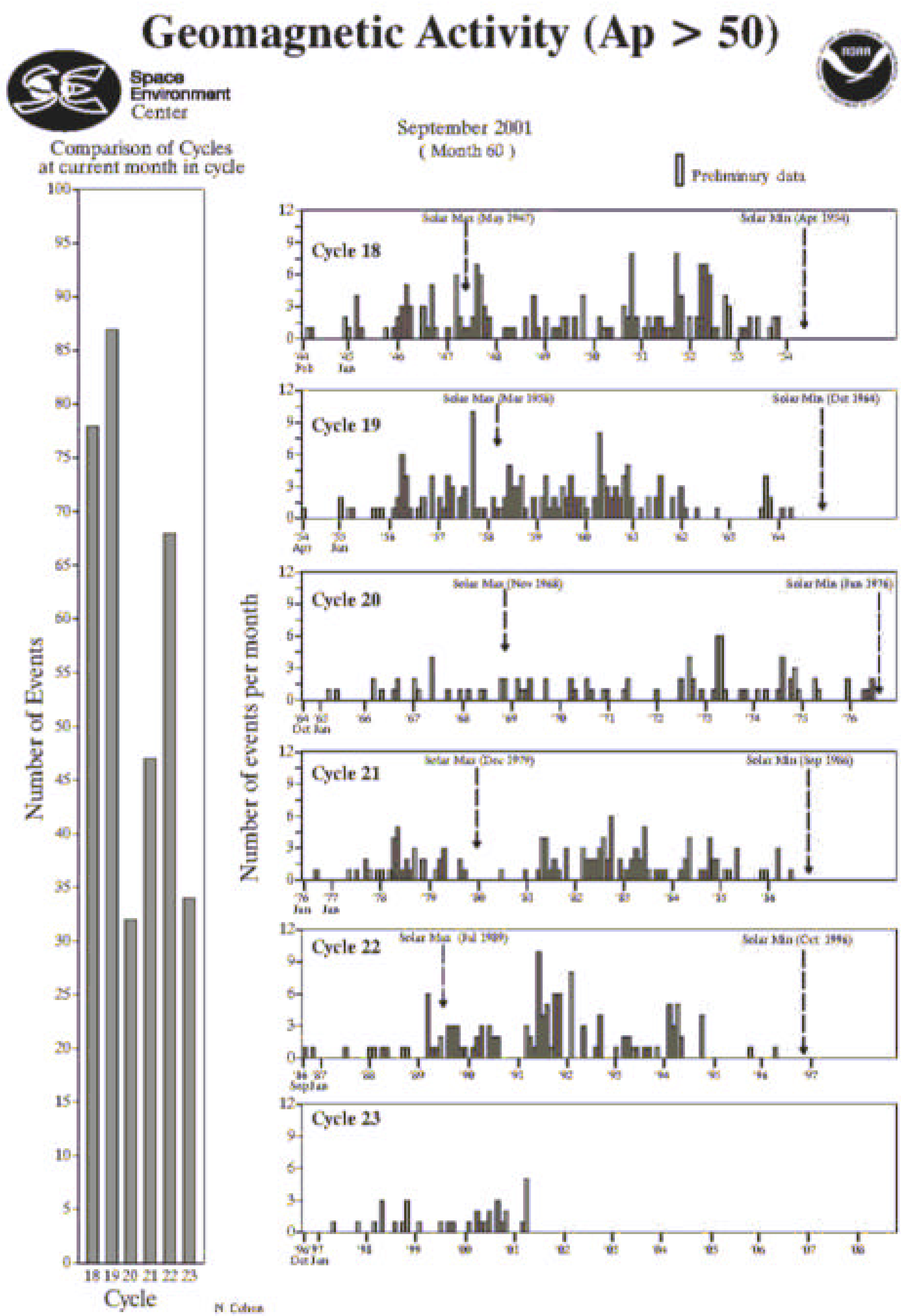
Geomagnetic Activity (Ap > 50)
Space Environment Center
September 2001
(Month 60)
Comparison of Cycles at current month in cycle
Preliminary data
Number of Events
Cycle
Number of events per month
Cycle 18
Cycle 19
Cycle 20
Cycle 21
Cycle 22
Cycle 23
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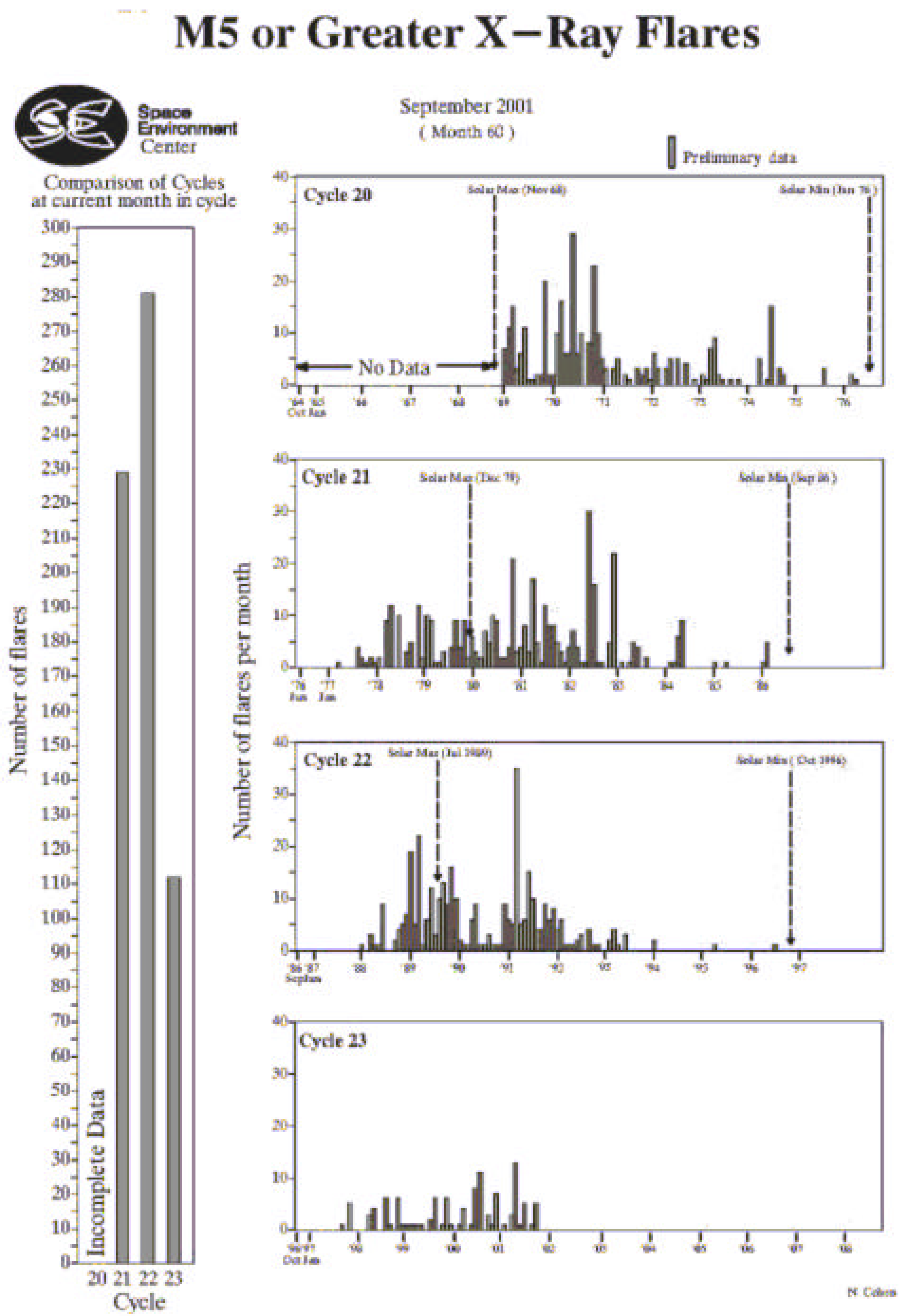
Figure 3.


M5 or Greater X−Ray Flares
Space Environment Center
Comparison of Cycles at current month in cycle
September 2001
(Month 60)
Preliminary data
Number of flares
Incomplete Data
20 21 22 23
Cycle
Number of flares per month
Cycle 20
No Data
Cycle 21
Cycle 22
Cycle 23

3. Effects on Technology and Humans

The GOES Spacecraft SEM instrument suite provides operational measurements of solar x-rays, energetic particles, and the geomagnetic field. Some particular aspects of event-based effects in these three categories, seen in Cycle 23, are detailed in the following sections. The effects listed are mostly taken from oral presentations given at Space Weather Week 2003 (see ref.).

3.1 Solar X-Ray Sensor (XRS)

Extreme Ultraviolet emissions from the sun (up to 230 nm wavelength) are absorbed in the upper atmosphere above 80 km. Sharp changes in emissions in these wavelengths can alter ionospheric conditions and adversely affect high-frequency radio communication and navigation technologies. Direct emissions of radiowave frequencies are also known to affect radio-based technologies. Solar X-ray emissions from energetic solar flares (measured by the XRS at wavelengths shorter than 1 nm) can significantly alter ionospheric conditions, and also serve as the defining basis for Radio Blackout events, as described in the NOAA Space Weather Scales.

Cellular Phone Communications During Solar Radio Bursts

Recent studies have found that bursts of energy from the Sun at microwave radio frequencies can disrupt cell phone communications up to several times a year. There have been reported instances of an enhanced rate of dropped cell-phone calls during solar bursts, and the design of current base station systems make them vulnerable to problems near sunrise and sunset for antennas facing in the direction of the Sun during outbursts. It is likely that many cases of interference have gone unreported and perhaps unrecognized. The level of radio noise that can cause potential problems occurs on average once every 3.5 days at solar maximum, but may also occur at a reduced rate of once every 18.5 days, on average, at solar minimum. Solar radio bursts can cover a wide range of the radio spectrum, and are a relevant concern in the design of future wireless systems that will operate at frequencies other than those used in present systems.

Air Traffic Control with HF Radio Communications

Air traffic controllers routinely use the online ionospheric “D-region absorption map,” produced by NOAA/SEC and driven by data from the GOES XRS, when assessing the potential impact of solar flare activity. The map predicts the frequencies and geographic regions on the daylight side of Earth most affected by evolving solar flare activity. If affected frequencies are currently in use, flight controllers can change communications to higher frequencies before blackouts occur. Depending on the severity of conditions, the New York Air Route Traffic Control may be advised of potential delays in getting information to and from aircraft, and delivering clearances within the required 3 minute time interval in the crowded airspace of that region. Early warning of activity is vital for effective air traffic control in these situations. Airline dispatchers also use the D-region absorption model real-time display, and find it to be a valuable and accurate representation of solar flare effects in their HF radio operations, as well as a good indicator of the possibility of subsequent space weather events (like flare-related proton events or geomagnetic storms) that can also affect their flight planning and operations.

3.2 Energetic Particle Sensor (EPS)

Energetic particle events at Earth generally follow the occurrence of major solar flares, usually within tens of minutes to hours, but sometimes earlier. The GOES-EPS data allow SEC's space environment forecasters to detect hazardous particle flux levels, assess event risks, and issue corresponding warnings and alerts. EPS data also serve as the defining basis for Solar Radiation Storms, as described in the NOAA Space Weather Scales. Some recent impacts and developments this year in uses of EPS instrument data and need for ongoing services are discussed below:

Satellite Operations

Solar Proton Events (SPEs) can significantly impact a wide variety of satellite systems, sometimes in permanently damaging ways. Even the very satellites that monitor solar activity report problems during major SPE's, when their optical sensors can become dazzled by the sparkling effects of energetic particle impacts, and their sensitive detectors of other components of the space environment can become overwhelmed with high energy particle contamination.

The "Bastille Day" event of July 14, 2000 was one of the most intense solar proton events ever recorded; it was also followed a day later by the second largest geomagnetic storm seen since 1989. During this event, GOES spacecraft control was affected by temporary increases in spacecraft momentum. Some electron flux data from GOES were lost due to energetic proton contamination and visible and IR wavelength sensors had adverse effects in their Image Navigation and Registration (INR) systems and image quality. Star tracker problems caused attitude anomalies on other geosynchronous satellites, and a commercial geosynchronous spacecraft lost a transponder, thought to be due to the solar proton event.

A number of other research satellites were also affected during this major SPE. Located one million miles sunward from Earth, in a stabilized orbit around the L1 Lagrangian point, the Advanced Composition Explorer (ACE) satellite's plasma ion detector output was contaminated by energetic ions from the solar radiation storm for 36 hours, invalidating its velocity, density and temperature measurements of the solar wind. The Solar and Heliospheric Observatory (SOHO) spacecraft, also at L1, suffered permanent degradation of its solar panel output (losing the equivalent of one year of normal degradation in just 24 hours). The WIND satellite solar wind sensors were similarly affected and data were lost for 2 days.

Effects from the Bastille Day event were also reported by overseas satellite operators. The Japanese ASCA research satellite shut down, resulting in a loss of orientation and a complete depletion of its battery. As a result of increased atmospheric drag, ASCA eventually re-entered the atmosphere and was destroyed on March 2, 2001. Another Japanese research satellite, Akebono, suffered high energy particle hits on its electronics, which disrupted the spacecraft computer operations.

Solar Radiation Hazard--Astronauts

The operation of the International Space Station has resulted in the need to develop the most efficient possible real-time radiological support system. The quantity and diversity of space weather data has increased dramatically in the past several years along with the technology to share, use, and interpret the data. For the first time in nearly 30 years, sophisticated instruments aboard a NASA spacecraft are making real-time and near real-time measurements of the local space radiation environment, and transferring these data to ground controllers. New techniques have been developed to ingest, analyze, display, and store the information. Studies of space radiation exposure have shown a greater than previously believed risk of potential health effects on astronauts, resulting in increased emphasis on minimizing astronaut exposures as much as possible. With the International Space Station, NASA must also now coordinate policies and procedures with foreign agencies, some with different approaches and priorities.

The Space Environment Center produces warnings and alerts for energetic proton events, as detected by the GOES EPS, which are of concern to NASA missions and to spacecraft operations, especially for astronauts on extra-vehicular activity (EVA) or "spacewalks." SEC has a long history of providing NASA with pre-EVA briefings during spaceflight missions, but recently augmented that support to provide additional, one-hour pre-EVA briefings during the Hubble Telescope upgrade mission (STS-109). The extent of this support has obviously increased with number of EVAs being done in support of the International Space Station activities.

Solar Radiation Hazard—Airlines

Although the potential radiation hazard to crews and passengers in high-altitude air travel has been recognized for decades, the recent opening of Russian airspace to commercial traffic, and the resulting increase in routine flights over the North pole, have brought greater attention to the issue. These flights, connecting the US and Europe to the Orient on non-stop, great-circle flight paths, are quicker and more efficient for airlines and travelers, but also pass through much higher geomagnetic latitudes where the possibility of radiation exposure is increased. Because of this, airlines are taking considerable interest in recognizing and mitigating the hazards posed by space weather.

The FAA is developing a "solar radiation alert" for cases when the GOES EPS satellite readings of energetic proton flux indicate that the ionizing radiation dose rate, at altitudes above 40,000 feet in areas of high geomagnetic latitude, could exceed 20 microsieverts per hour**.** (Dose-rate estimates are based on the relationship between high energy proton fluxes measured on the EPS and dose rate at aviation altitudes calculated for the large SPE of September 29-30, 1989.)

Under the European Union (EU) Directive 96/29/Euratom: Article 42 (effective May 13, 2000), the commercial airlines of the EU Member States are required to assess and limit their aircrew exposures to “cosmic radiation” sources, which create a persistent background of ionizing radiation at aviation altitudes. Computer-predicted dose estimates are considered adequate for providing moderately cautious overestimates of long-term mean doses. Capabilities for calculating the contribution to these estimates from transient SPE’s are needed, and are under development.

A large, private charter airline company, with 300+ aircraft, 1900 pilots, 175 flight attendants, and 30% annual growth, has taken recent action to deal with the radiation environment at high altitude. Their fleet of aircraft routinely flies higher than typical commercial airlines, partly so they can fly faster than the highly regulated traffic lanes at 30,000 feet. Concerns about potential radiation exposures from SPE’s at such altitudes have motivated the company to implement a policy to fly at lower altitudes, or even delay flights, if the current values of proton fluxes at energies greater than 10 MeV on the GOES EPS instrument are at 1,000 pfu or greater.

The very high altitude U-2 aircraft requires a 30-minute forecast of SPE’s before deployment on routine or flight-training missions. Such forecasts are produced by the Air Force Weather Agency (AFWA) space weather center in Omaha, and rely in part on data from the GOES EPS instrument. Decisions to fly missions are based on the expected radiation doses that would result from the mission.

Airline Communications Concerns

The newly established routine flights over the North pole have raised additional issues aside from the potential radiation exposure hazards. En route flights are required by FAA regulations to maintain contact with airline dispatchers and flight controllers at all times (within minutes). Communication technologies utilizing both HF radio and satellites are prone to negative impacts during space weather events, particularly in the polar regions. These effects are, in fact, a much more frequent cause of disruption in planned flight activities in polar regions when compared to the much stronger events involving potential risks of radiation exposure. Different commercial airlines rely on different types of communication technologies, but all are subjected to the extremely limited availability of alternative communication with VHF-equipped ground stations in the Arctic, as well as the primary reliance by Russian ground control operations on HF communications within their airspace. The net result is an airlines communications situation in the Arctic that is readily susceptible to space weather impacts.

For the period of October 26 to November 28, 2000, a major commercial airline reported two cases of HF communications losses and four periods of solar radiation storms that were causes for their planes on polar flight paths to be diverted to less optimal routes. Rerouting and general delays are costly to the airline. One example involving diversion of a flight from a polar route required an additional fuel stop at Tokyo, extended flight time, and an ultimate delay in final arrival of five and a half hours.

On April 15, 2001, another major carrier diverted a Detroit-Beijing flight from a polar route due to HF communications problems from a radio blackout and subsequent solar radiation storm, forcing an unscheduled stop at Fairbanks for fuel. This route change resulted in a three-hour delay and a $100,000 cost to the airline, plus the inconvenience of disrupting the passenger travel schedules.

The Director of Flight Operations for a US carrier reported diversions of their daily flight from Newark to Hong Kong on two consecutive days in April, 2001. Their decision was motivated by the strong (S3 on NOAA Space Weather Scale) level of solar radiation storm conditions that began on April 3, 2001. The direct impacts were an extra two hours of flight time for each diverted flight and the associated additional costs.

Spacecraft Design

The spacecraft design process attempts to accommodate the known variability and hazardous exposures that may occur due to the nature of the space environment. Trapped particles, SPE's, and galactic cosmic rays contribute to lifetime degradation of electronic parts, optical components and solar cells. This impacts the types of materials and technologies available to build spacecraft, and can require the use of costly mass for shielding purposes. High-energy particle impacts on modern integrated circuits can cause upsets and failures in spacecraft subsystems if not properly mitigated during the design process. Sensors in spacecraft instruments, particularly focal plane arrays, are very sensitive to the noise produced by high energy protons and heavy ions.

Launch Support for Rockets

Lockheed Martin's Atlas rocket support team are concerned with the possibility of SPE's causing "single-word multiple upsets" in the rocket control circuitry during launch. This condition could cause the navigation unit to fail, sending the vehicle off course, and possibly resulting in total loss of the rocket and payload. An Aerospace Corporation study notes that heavy ions are the primary concern for these problems, because they are energetic enough to cause the effect. While real-time heavy ion flux data are not directly measured by the GOES EPS instrument, the >50 MeV proton flux has been found to be useful as a reliable proxy. They have established a "red line" condition of >50 MeV proton flux at 100 pfu or greater, for advising the team at Cape Canaveral to hold the launch. Consequently, they are paying close attention to real-time data from the GOES EPS instrument.

An intense solar flare on Sept. 25, 2001 delayed the launch of the "Kodiak Star" satellite for NASA and the Department of Defense, on a Lockheed Martin Athena I rocket. The launch was held up until the solar radiation storm activity, which reached 1000 times the normal background particle flux levels, subsided to a level safe for launch criteria.

3.3 Magnetometer (MAG)

Geomagnetic storms due to major solar activity can occur with varying onset and intensity within a few days of major solar events. They can cause wide scale induction of potentially damaging electrical currents in utility power grids, and can alter neutral atmospheric density and create drag on low earth orbiting satellites. Geomagnetic field data from satellites and ground-based magnetometers are important for determining alert conditions and warning about possible effects such as those described for geomagnetic storms in the NOAA Space Weather Scales. The in-situ measurement of the geomagnetic field aboard the GOES spacecraft enables space environment forecasters to assess certain aspects of geomagnetic activity, providing information about magnetopause crossings and a remote monitor of solar-wind dynamic pressure, supporting analyses of geomagnetic storm events.

Power Grid Impacts due to Geomagnetic Storms

Geomagnetic storms cause currents to flow naturally through Earth's surface, and in "artificial" conductors on the ground, such as power lines, pipelines, railroads and bridges. These storms are more likely to disturb high-latitude systems. For example, during a geomagnetic storm in November 2001, a utility company in New Zealand experienced loss of service on one of its major transformers in the power system on the South Island. In addition, many overload alarms were activated on other transformers in the middle and lower parts of the South Island. The system damage occurred coincident with a large solar wind disturbance striking the dayside boundary of the magnetosphere.

Intensification of high altitude electrojet currents is known to cause severe local geomagnetic field disturbances at high- and mid-latitude locations. Electrojet intensifications, however, are not the only geomagnetic field disturbance capable of producing widespread and large geomagnetically induced current (GIC) flows in power grids. Shocks, such as high-speed magnetospheric compressions associated with Sudden Storm Commencements and Sudden Impulses, can also produce widespread disturbances in the geomagnetic field that extend to equatorial latitudes. These effects have been observed in Japanese magnetometer data. The magnitude of the geomagnetic field disturbance is not large, but it can have a very high rate-of-change and result in large voltage fluctuations even at very low latitudes.

Satellites and Atmospheric Drag

Retardation due to atmospheric drag is the largest single source of position prediction uncertainty for most satellites at altitudes below about 1000 km. This effect can result in a one-day prediction uncertainty up to several tens of kilometers, which limits collision hazard prediction as well as any application requiring precise prediction of satellite position. Present techniques involving solar indices and atmospheric models can produce an accuracy of about $\pm$ 5% in satellite drag prediction. Future satellite deployment capabilities will require significant improvements in atmospheric neutral density modeling and in the ability to produce reliable space environment forecasts.

4. The Future of GOES: Solar X-Ray Imager, Coronagraph, and EUV Spectrometer

The first of a planned series of soft x-ray imagers (SXI) is already in orbit on GOES-12. Once it becomes fully operational, images from SXI will help space environment forecasters anticipate the occurrence of solar flares and the associated radio blackouts, solar radiation storms, and geomagnetic storms. The scientific community has appreciated the great potential for improved space environment forecasts using solar X-ray imaging. That potential will be realized as GOES SXI begins to take data, presently scheduled for a start date in early 2003. The goals identified for operational use of the SXI include:

- Locate coronal holes for forecasts of recurring geomagnetic activity,
- Locate flares for forecasts of solar energetic particle events,
- Assess active region complexity for flare forecasts,
- Monitor active regions beyond the east limb for solar activity forecasts, and
- Determine occurrence, *speed, direction, and spatial extent* of coronal mass ejections

Speed, direction, and spatial extent of CME's represent the specific improvements that the addition of an operational white light coronagraph instrument, proposed for future GOES satellites, would be anticipated to provide when used in combination with the SXI. These valuable benefits have already been demonstrated through the near-realtime availability of white light coronagraph data from the research mission of the Large Angle Spectrometric Coronagraph (LASCO) instrument on the SOHO satellite.

The addition of an operational extreme ultraviolet (EUV) spectrometer instrument on GOES will, for the first time, allow for direct, ongoing measurement of the sun's emission in these wavelengths for improved assessment of the space environment effects involving atmospheric drag on low earth orbiting satellites and on ionospheric effects affecting technologies that rely on radio wave propagation.

5. Summary

Space weather affects many customers, and even the very instruments that are built to monitor it. The GOES Space Environment Monitor instruments provide vital operational measurements of the dynamic conditions in the space environment, and complement data available from other satellites like POES, ACE, and SOHO. The many users of space weather services are finding more need for space environment information as technology usage expands and evolves. NOAA/SEC will continue seek input from and provide services to the current and growing list of space weather customers.

6. References

Report on GOES Space Environment Monitor (SEM) Instruments: Overview, Plans and Benefits to Users", H. J. Singer, S. Hill, T.G. Onsager, R. Viereck: CGMS Proceedings, 2002 (in press)

Solar Cycle Number 23 – A Progress Report, R. Thompson, *GPS Solutions*, 2002 (in press)

Summary of Space Weather Week: http://www.sec.noaa.gov/sww

Information on NOAA Space Weather Scales: http://www.sec.noaa.gov/NOAAscales/