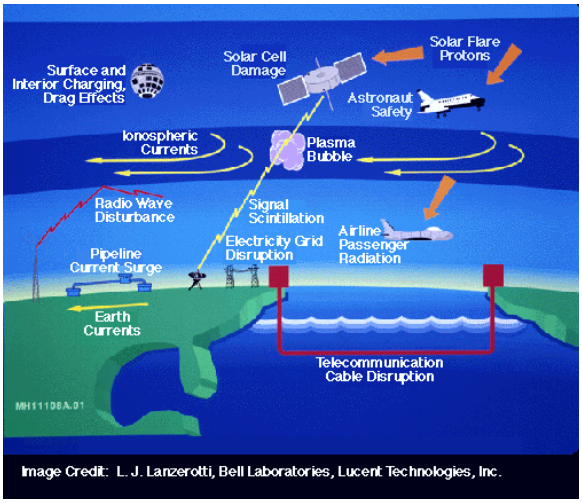
Space Weather effects on airline operations

(Captain Bryn Jones, VAA Cosmic Radiation Project Manager)

Recent press coverage regarding exposure to increased levels of radiation while flying at civil aircraft altitudes due to cosmic radiation, has raised the profile of an area of space science, known as "Space Weather", that was previously more likely to be linked only with NASA astronauts and the Space Shuttle. However, the fact that the Earth is immersed in an extremely tenuous bath of high-energy charged particles called cosmic rays (both galactic and solar in origin) is but just one of many physical processes going on in near-Earth space that can have a direct impact on airline operations. Most of the time space weather is of little concern in our everyday lives. However, when the space environment is disturbed by the variable outputs of the Sun, technologies that we depend on both in orbit and on the ground can be affected. So besides cosmic rays, what are the other Space Weather (SW) phenomena that could have a direct impact on airline operations?



A simple illustration of technological systems affected by Space Weather. (Courtesy of: L.J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.)

What is Space Weather: The Sun-Earth Connection

Firstly, what exactly do we mean by the term "Space Weather"? The internationally accepted definition is:

> *"Conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life and health".*
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> (From: US National Space Weather Strategic Plan, August 1995)

(Note: Within this definition we include the effects of galactic cosmic rays that originate from outside our solar system but which also affect technological systems, and endanger human life and health because their flux is modulated by solar processes.)

From this definition we can see that the main influence on our SW comes from our Sun and it's own "climate-like" variations, which occur on both the short term (hours, days) and the long term (roughly 11-year solar cycle). "Storms" in our SW generally follow severe solar disturbances such as solar flares on the photosphere and Coronal Mass Ejections (CMEs) from the outer solar atmosphere.

Solar Flares: Flares are our solar system's largest explosive events, which can be equivalent to approximately 40 billion Hiroshima-size atomic bombs. They have lifetimes ranging from hours for gradual events, down to tens of seconds for the most impulsive events. During very large flares, the solar ultraviolet, x-ray and radio emissions can be 10,000 times above the surrounding area of the flare site. (See Fig 1)

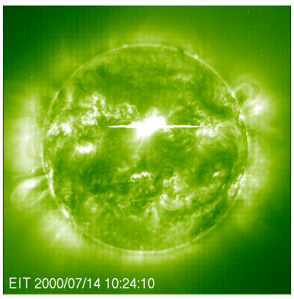
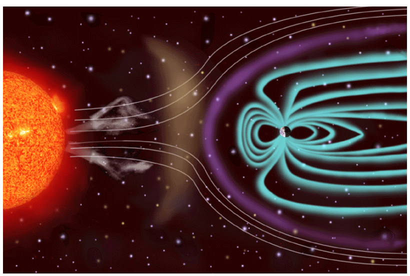


Fig 1. Extreme ultraviolet image of 14 July 2000 flare. (Courtesy of EIT Consortium)

Coronal Mass Ejections: CMEs are huge bubbles of gas threaded with magnetic field lines that are ejected from the Sun, at several million miles per hour, over the course of several hours. These explosions of material can contain the equivalent mass of Mount Everest!

Solar Wind: The interplanetary medium (or heliosphere – the region of space dominated by matter from the Sun), once considered to be a perfect vacuum, is now known to be a turbulent region dominated by the solar wind, which flows at approximately 250-1000km/s (about 600,000 to 2,000,000mph). Other characteristics of the solar wind (e.g., density,



composition, and magnetic field strength) vary with changing conditions on the Sun. The Earth's magnetic field (similar in shape to the pattern formed when iron filings align around a bar magnet) is influenced by the solar wind,

Fig 2. Illustrates effect of solar wind on Earth's magnetic field.

becoming compressed in the sunward direction and stretched out in the downwind direction. (See Fig 2) This creates the magnetosphere, a complex, teardrop-shaped cavity around Earth. Because the solar wind varies over time scales as short as seconds, the interface that separates interplanetary space from the magnetosphere is extremely dynamic.

Solar Effects at Earth

These solar events and variations can give rise to the following effects: the aurora, ionospheric disturbances, Solar Particle Events (SPEs), and geomagnetic storms.

Aurora: Probably the most well known effect from the solar-induced geomagnetic storms is the aurora borealis (northern lights) and aurora australis (southern lights). Aurorae begin between 60° and 80° latitude. As a storm intensifies, the aurorae spread toward the equator. During an unusually large storm in 1909, an aurora was visible at Singapore, on the geomagnetic equator. The aurorae provide pretty displays, but they are just a visible sign of atmospheric changes that may wreak havoc on technological systems.

Ionospheric Disturbances: The bursts of electromagnetic radiation (ultraviolet and x-ray) from a solar flare travel at the speed of light, and so arrive at Earth just 8 minutes after leaving the flare site. Unaffected by the Earth's magnetic field, these emissions directly effect the upper atmosphere (becoming significant below 100km) by producing a temporary increase in ionisation in the sunlit hemisphere of minutes to hours duration called a "sudden ionospheric disturbance".

Solar Particle Events: Certain major solar flares and CMEs can shower the Earth, within 30 minutes, with energetic particles (primarily protons). In this case the Earth's magnetic field does offer some protection, but some of these particles spiral down the field lines, entering the upper atmosphere in the polar regions where they produce additional ionisation in the ionosphere and below. Very energetic and intense events can also lead to increases at lower latitudes.

Geomagnetic Storms: One to four days after a major solar disturbance occurs, a slower cloud of solar material and magnetic field reaches Earth, buffeting the magnetosphere and resulting in a geomagnetic storm. The bi-polar magnetic field of the Earth points north but the field contained within the material expelled from the Sun can point in any direction. When the field is orientated in the opposite direction to that of the Earth's, the two magnetic systems interact and the solar material can enter the Earth's magnetosphere. These interactions can produce very large electrical currents, of up to a million amperes, flowing through the ionosphere and magnetosphere which can change the direction of the Earth's magnetic field at the surface by up to 1 or 2 degrees, mainly in the auroral regions.

Practical Consequences of Space Weather

Hazards to Humans

The principal space weather hazard to humans is exposure to radiation from Galactic Cosmic Rays (GCRs), Solar Energetic Particles (SEPs) and magnetospheric particles. GCRs are the prime source of the radiation environment at aircraft altitudes. These energetic particles start interacting with the significant atmosphere at around 130,000ft causing secondary particles to shower down into the denser atmosphere below. This "particle shower", and the corresponding level of radiation dose, reaches a maximum intensity at around 60,000ft (18km) and then slowly drops off to sea level. The average annual dose received depends on the routes flown (latitude, longitude and duration), the phase of the solar cycle (± 20% dose variations from solar minimum to maximum) and the impact of SPEs (from flares and CMEs). Most solar flares emit protons with energies up to 10's of MeV (electron volt [eV]: a measurement unit for energy, equal to the energy an electron (or proton) would gain when accelerated by an electric voltage of 1 volt). However, only protons with energies in excess of 500MeV may produce significant increases in radiation at aircraft altitudes and on average there are approximately 3 events per solar cycle (1 cycle = 11 years). Any increase in the radiation doses received from these geo-effective events cannot yet be predicted and will require retrospective additions following a post event analysis. During the SPE of 1956 it has been estimated that the radiation dose received at 40,000ft (12km) on a transatlantic flight could have been approximately 10mSv, exceeding the recommended annual dose of 6mSv. Such events are extremely rare, perhaps occurring once every 100 years. Recent studies of more typical events in September and October 1989 indicate 2mSv for a similar flight. (The ICRP recommended limit for aircrew is a 5-year average dose of 20 mSv per year, with no more than 50 mSv in a single year. For a pregnant crewmember, starting when she reports her pregnancy, her work schedule should be such that the equivalent dose to the child is as low as reasonably achievable and unlikely to exceed 1mSv during the remainder of the pregnancy).

The energetic particles that make up the radiation environment in the atmosphere are highly ionising, which means that they strip electrons from atoms in their path and hence generate charge. This process can lead to localised ionisation in human cells where they can lead to DNA rupture. If the cell damage is not repaired there is the possibility of producing cancers. However, the chances of developing cancer as a result of cosmic radiation is considered to be very low, as the total career dose is received in low doses per flight, and accumulated slowly over the length of a flying career. It is difficult through epidemiological studies to find causation of cancer due to cosmic radiation as other lifestyle risk factors exist, particularly with crew.

Radiation Damage to Avionics

As aircraft avionics continue to use increasingly smaller electronic components, systems are becoming more susceptible to damage from the highly ionising interactions of cosmic rays, solar particles and the secondary particles generated in the atmosphere. The heavier and most energetic particles can deposit enough charge in a small volume of silicon to change the state of a memory cell, a one becoming a zero and vice versa. Thus memories can become corrupted and this could lead to erroneous commands. Such soft errors are referred to as "single event upsets" (SEU). Certain devices could be triggered into a state of high current drain, leading to burnout and hardware failure; such effects are termed single event latch-up or single event burnout. These deleterious interactions of individual particles are referred to as single event effects (SEE). The space industry has had many years experience of such phenomena. Satellites incorporating sensitive RAM chips have had upset rates from one per day at quiet times to several hundred per day during SPEs, while commercial, unhardened systems are particularly vulnerable: laptop computers onboard the Space Shuttle have shown upset rates of one per hour. In-flight measurements of SEU sensitivity in 4Mb SRAM, produced a rate of 1 upset per 200 flight hours, and agreed well with the expected upset rate variations due to changing latitude. This problem is expected to increase as more, low power, small feature size electronics are deployed in "more electric" aircraft.

GPS Navigation

There are now plans to use GPS for area navigation so that the separation between aircraft can be reduced. Ultimately, this will be extended to approach and landing. However, the accuracy of the GPS signal, which must pass through the ionosphere, is obviously affected by any ionospheric variations due to solar and geomagnetic activity. Single-frequency GPS receivers suffer under these variations, but dual-frequency receivers actually measure the effect of the ionosphere on the GPS signals and make corrections. This is accomplished by using a network of fixed ground based GPS receivers, separated by a few hundred km, to derive a map of the ionosphere. The map is then transmitted to the aircraft so that the GPS receiver on board can make the necessary correction.

On a smaller scale, irregularities in the density of the ionosphere that produce scintillations occur in varying amounts, depending on latitude. For example, the equatorial region, (the latitude zone that spans 15-20° either side of the magnetic equator) is the site of some of the greatest ionospheric irregularities, even when magnetic storms do not occur. Seemingly unpredictable episodes of density enhancements in the upper ionosphere can occur there in the evening hours and can cause radio waves to be misdirected. These scintillations make GPS operations difficult, and they can affect both dual and single-frequency GPS receivers.

GPS signals are generally immune to ionospheric changes in response to large infusions of x-rays following a solar flare. However, GPS and all other satellites must contend with the detrimental effects the energetic solar particles have on the on-board systems.

Communication

Many communication systems utilise the ionosphere to reflect radio signals over long distances. Ionospheric storms can affect radio communication at all latitudes. Some radio frequencies are absorbed, while others are reflected, leading to rapidly fluctuating signals and unexpected propagation paths. Solar flare ultraviolet and x-ray bursts, solar energetic particles, or intense aurora can all bring on these conditions.

If the effects become especially strong, it can cause a total communications blackout. SPEs can produce a particular type of disturbance called Polar Cap Absorption (PCA) that can last for many days. When very energetic protons enter the atmosphere over the polar regions, the enhanced ionisation produced at these low altitudes is particularly effective in absorbing HF radio signals and can render HF communications impossible throughout the polar regions. At a recent SW conference, several US air carriers indicated that they might cancel trans-polar flights due to such space weather events.

National Grid & ATC Ground Facilities

The enhanced currents that flow in the magnetosphere-ionosphere system during geomagnetic storms can affect the National Grid. These currents cause magnetic field perturbations on the ground that in turn induce other currents in long transmission lines, especially those located at high latitudes. The slowly varying "DC" part of the currents can be large enough to cause overheating and damage to systems designed for "AC". The reliability of power supplies to critical ATC ground equipment cannot be overstated. The UK National Air Traffic Service (NATS) goes to great lengths to ensure they have installed adequate backup for failures of the commercial grid supply. They also require the grid operators to notify them when geomagnetic storms threaten the network.

Space Weather and Terrestrial Weather

The ionosphere also exhibits irregular variations related to the dynamics of the underlying atmosphere. These depend upon the combination of traditional "weather" near the ground, which produces waves in the atmosphere like the waves in the deep ocean, and the winds between the ground and the upper-atmosphere levels that act like a filter to the passage of those waves. These effects are most pronounced when the upper-atmosphere winds or lower-ionosphere composition is enhanced by the energy inputs from the active Sun or magnetosphere.

Optical phenomena called red sprites and blue jets have been observed at altitudes extending from the tops of large thunderstorms (at around 15-kilometers altitude) to the lower ionosphere (about 95-km altitude). Possibly related to these optical signatures, intense electromagnetic pulses (10,000 times stronger than lightning-related pulses) have been detected over thunderstorm regions by satellites. These observations suggest that there may be a stronger connection between global thunderstorm activity and the ionosphere and upper atmosphere than previously suspected.

A recent NASA-funded Earth Science study suggests that there may be a relationship between increased cloud cover over the USA and solar maximum. Results show that during solar maximum, the jet stream in the Northern Hemisphere moves Northward. The Sun's varying ultraviolet output effects the ozone production in the stratosphere. When the ozone absorbs ultraviolet radiation, it warms the stratosphere, which may affect movement of air in the troposphere where clouds form. It is the jet stream, which guides storms and plays an important role in cloudiness, precipitation and storm formation in the USA.

Space Weather – Future Developments

A useful set of descriptive scales for space weather have been devised by the Space Environment Center (SEC), part of the United States' National Oceanic and Atmospheric Administration (NOAA). The scales have numbered levels, 1 to 5, analogous to hurricanes and earthquakes that convey severity. They list possible effects at each level, how often such events may happen, and give a measure of the intensity of the physical causes. Visit: http://www.sec.noaa.gov/NOAAscales/index.html

There are separate National Space Weather Programmes underway in the USA and Japan, which include NASA's "Living With a Star Program" funded at $1.2 billion over 10 years, and a US SW Airline Workshop. Closer to home, the European Space Agency (ESA) is assessing the need for a separate European capability by sponsoring parallel consortium studies. The cosmic radiation monitoring project (involving Virgin Atlantic, Mullard Space Science Laboratory, CAA and National Physical Laboratory) is part of these studies.

The need for SW services is now being driven by many different market sectors that are adversely affected by SW events: power grids, geological prospecting, oil and gas pipelines, railways, defence, risk and insurance, tourism and aviation. The SW risks to airline operations, as outlined above, can only increase with future developments in the aerospace industry. At present, the major difficulty with providing a service to the end user is the accuracy of the science behind it.

However, with an increasing amount of research being spent on understanding the Sun-Earth connections, and technologically improved observational platforms now available or planned, it is likely we may see a useable SW system in place within the next decade.

VAA’s proposed Sonic Cruiser has driven up the need for space weather forecasting.

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