Space Weather Effects on Communications

An overview of historical and contemporary impacts of the solar and geospace environments on communications systems.

Louis J. Lanzerotti
Center for Solar-Terrestrial Research, New Jersey Institute of Technology,
Newark, New Jersey 07102 USA,
and
Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA

Abstract

In the last century and one-half, since the invention and deployment of the first electrical communication system – the electrical telegraph, the variety of communications technologies that can be affected by natural processes occurring on the Sun and in the space environment around Earth have vastly increased. This chapter presents some of the history of the subject of "space weather" as it affects communications systems, beginning with the earliest electric telegraph systems and continuing to today's wireless communications using satellites and land links. An overview is presented of the present-day communications technologies that can be affected by solar-terrestrial phenomena such as solar and galactic charged particles, solar-produced plasmas, and geomagnetic disturbances in the Earth's magnetosphere and ionosphere.

Keywords

Solar disturbance, geomagnetic disturbance, communications technologies, cable communications, wireless communications, communication satellites, ionosphere currents, aurora, magnetosphere

1. Introduction

The discovery of magnetically-confined charged particles (electrons and ions) around Earth by Van Allen [Van Allen et al., 1958] and by Vernov and Chudakov [1960] demonstrated that the space environment around Earth, above the sensible atmosphere, was not benign. Measurements by spacecraft in the five decades since Van Allen's work has demonstrated that Earth's near space environment – inside the magnetosphere – is filled with particle radiation of sufficient intensity and energy to cause significant problems for satellite materials and electronics that might be placed into it.

And thus, because of the trapped radiation (augmented by trapped electrons from the high-altitude Starfish nuclear explosion on July 8, 1962), the world's first commercial telecommunications satellite, the low-orbit Telstar©1 [launched July 10, 1962; *Bell System Technical Journal*, 1963], suffered anomalies in one of its two command lines within a couple of months of its launch. And within five months both command lines had failed. While clever engineering by Bell Laboratories personnel resurrected the satellite for more than a month in early 1963, by the end of February of that year Telstar had gone silent for good – a victim of the solar-terrestrial radiation environment [Reid, 1963].

It was immediately clear from Van Allen's discovery and then from the Telstar experience that the Earth-orbiting telecommunications satellites that had been proposed by Arthur Clark [1945] and by John Pierce [1954] prior to the space age would now have to be designed to withstand the Earth's radiation environment. The semiconductor electronic parts (which were the obvious choice for even the earliest spacecraft and instrument designs) would have to be carefully evaluated and qualified for flight. Further, the space radiation environment would have to be carefully mapped, and time dependencies of the environment would need to be understood if adequate designs were to be implemented to ensure the success of the missions.

2. Early History of Effects on Wire-Line Telegraph Communications

The effects of the solar-terrestrial environment on communications technologies began long before the space age. In 1847, during the 8th solar cycle, telegraph systems that were just beginning to be deployed were found to frequently exhibit "anomalous currents" flowing in their wires. W. H. Barlow, a telegraph engineer with the Midland railroad in England appears to be the first to have recognized these currents. Since they were disturbing the operations of the railway's communications system, Barlow [1849] undertook a systematic study of the currents. Making use of a spare wire that connected Derby and Birmingham, Barlow recorded during a two-week interval (with the exception of the weekend) in May 1847 the deflections in the galvanometer at the Derby station that he installed specifically for his experiment. These data (taken from a Table in his paper) are plotted in Figure 1. The galvanometer deflections obviously varied from hour to hour and from day to day by a cause (or causes) that was (were) unknown to him and his fellow engineers.

The hourly means of Barlow's data for the Derby to Birmingham link, as well as for measurements on a dedicated wire from Derby to Rugby, are plotted in Figure 2. A very distinct diurnal variation is apparent in the galvanometer readings: the galvanometers exhibited large right-handed swings during local daytime and left handed swings during local night. The systematic daily change evident in Figure 2, while not explicitly recognized by Barlow in his paper, is likely the first measurement of the diurnal component of geomagnetically-induced Earth currents (these currents, of whatever time scale, were often referred to in subsequent literature in the 19th and early 20th centuries as "telluric currents"). Such diurnal variations in the telluric currents have been recognized for many decades to be produced by solar-induced effects on the Earth's dayside ionosphere [e.g., Chapman and Bartels, 1940].

Barlow, in further discussing his measurements, noted that "… in every case which has come under [his] observation, the telegraph needles have been deflected whenever aurora has been visible". Indeed, this was certainly the case during November 1847 as the peak of the sunspot cycle approached, but after Barlow's measurements on the two dedicated Midland railway wires apparently ceased. At that time, large auroral displays over Europe were accompanied by severe disruptions of the Midland railway telegraph lines, as well as of telegraph lines in other European locations, including the line from Florence to Pisa [Prescott, 1860]

Twelve years after Barlow's pioneering observations (at the end of August 1859 during the 10th solar cycle), while pursuing his systematic program of observations of spots on the sun, Richard Carrington, FRS, recorded an exceptionally large area of spots in the Sun's northern solar hemisphere. Figure 3 is a reproduction of Plate 80 from the comprehensive records of his studies, which were carried out over a more than seven year interval around the peak of that sunspot cycle [Carrington, 1863]. The large spot area at about 45º N solar latitude on August 31 is especially notable.

This observation of an extensive sunspot region on the solar face was more out of the ordinary than Carrington's past research would have originally suggested to him. Quoting from his description of this region, "…at [the observatory at] Redhill [I] witnessed … a singular outbreak of light which lasted about 5 minutes, and moved sensibly over the entire contour of the spot …." Some hours following this outburst of light from the large dark sunspot region (the first ever reported), disturbances were observed in magnetic measuring instruments on Earth, and the aurora borealis was seen as far south as Rome and Hawaii.

Although Barlow had remarked on the apparent association of auroral displays and the disturbances on his railway telegraph wires, the large and disruptive disturbances that were recorded in numerous telegraph systems within a few hours of Carrington's solar event were nevertheless a great surprise when the many sets of observations and of data began to be compared (unlike in the present day, communications between scientists and engineers in the nineteenth century were not nearly instantaneous as are now facilitated by the world-wide internet). Indeed, during the several day interval that large auroral displays were widely seen, strange effects were measured in telegraph systems all across Europe – from Scandinavia to Tuscany. In the Eastern United States, it was reported [Prescott, 1860] that on the telegraph line from Boston to Portland (Maine) during "…Friday, September 2d, 1859 [the operators] continued to use the line [without batteries] for about two hours when, the aurora having subsided, the batteries were resumed."

The early telegraph systems were also very vulnerable to atmospheric electrical disturbances in the form of thunderstorms, in addition to the "anomalous" electrical currents flowing in the Earth. As written by Silliman [1850], "One curious fact connected with the operation of the telegraph is the induction of atmospheric electricity upon the wires … often to cause the machines at several stations to record the approach of a thunderstorm." While disturbances by thunderstorms on the telegraph "machines" could be identified as to their source, the source(s) of the "anomalous currents" described by Barlow [1849] and as recorded following Carrington's solar event, remained largely a mystery.

The decades that followed the solar event of 1859 produced significant amounts of attention by telegraph engineers and operators to the effects on their systems of Earth electrical currents. Although little recognized for almost fifty years afterwards, the Sun was indeed seriously affecting the first electrical technology that was employed for communications.

3. Early Effects on Wireless Communications

Marconi demonstrated the feasibility of intercontinental wireless communications with his successful transmissions from Poldhu Station, Cornwall, to St. John's, Newfoundland, in December 1901. Marconi's achievement (for which he shared the Nobel Prize in Physics with Karl Ferdinand Braun in 1909) was only possible because of the high altitude reflecting layer, the ionosphere, which reflected the wireless signals. This reflecting layer was subsequently definitively identified by Briet and Tuve [1925] and by Appleton and Barnett [1925]. Because wireless remained the only method for cross-oceanic voice (in contrast to telegraph) communications until the laying of the first trans-Atlantic telecommunications cable, TAT-1 (Newfoundland to Scotland) in 1958, any physical changes in the radio wave-reflecting layer (even before it was "discovered") were critical to the success (or failure) of reliable transmissions.

The same ionosphere electrical currents that could produce "spontaneous" electrical currents within the Earth (and thus within the wires of the electrical telegraph) could also affect the reception and fidelity of the transmitted long-distance wireless signals. Indeed, Marconi [1928] commented on this phenomenon when he noted that "…times of bad fading [of radio signals] practically always coincide with the appearance of large sun-spots and intense aurora-boreali usually accompanied by magnetic storms …." These are "… the same periods when cables and land lines experience difficulties or are thrown out of action."

An example of the types of studies that were pursued in the early years of long-distance wireless is shown in Figure 4. Plotted here (reproduced from Fagen [1975], which contains historical notes on early wireless research in the old Bell Telephone System) are yearly average daylight cross-Atlantic transmission signal strengths for the years 1915 – 1932 (upper trace). The intensities in the signal strength curves were derived by averaging the values from about 10 European stations that were broadcasting in the ~15 to 23 kHz band (very long wave lengths), after reducing them to a common base (the signal from Nauen, Germany, was used as the base). Plotted in the lower trace of the Figure are the monthly average sunspot numbers per year. Clearly, there is an association between the two plotted quantities, but the physical reason for such an association was very incompletely understood at the time. Nevertheless, this relationship of the received electrical field strengths to the yearly solar activity as represented by the number of sunspots could be used by wireless engineers to provide them some expectation as to transmission quality on a gross, year to year, basis – a very early form of "prediction" of "space weather"..

The relationship of disturbed long wavelength radio transmissions and individual incidents of solar activity was first identified in 1923 [Anderson, 1928]. The technical literature of the early wireless era showed clearly that solar-originating disturbances were serious assaults on the integrity of these communications during the first decades of the twentieth century. Communications engineers pursued a number of methodologies to alleviate or mitigate the assaults. One of these methodologies that sought more basic understanding is illustrated in the context of the previously-discussed Figure 4. Another methodology utilized alternative wireless communications "routes". As Figure 5 illustrates for the radio electric field strength data recorded during a solar and subsequent geomagnetic disturbance on July 8, 1928 (day 0 on the horizontal axis), the transmissions at long wave length were relatively undisturbed while those at the shorter wavelength (16m) were seriously degraded [Anderson, 1929]. Such procedures are still employed today by amateur and other radio operators.

The practical effects of the technical conclusions of Figure 5 are well exemplified by a headline which appeared over a front page article in the Sunday, January 23, 1938, issue of *The New York Times*. This headline noted that "Violent magnetic storm disrupts short-wave radio communication." The subheadline related that "Transoceanic services transfer phone and other traffic to long wave lengths as sunspot disturbance strikes". The technical work-around that shifted the cross-Atlantic wireless traffic from short to longer wavelengths prevented the complete disruption of voice messages during the disturbance.

4. The Beginning of the Space Era

That the space environment (even before Van Allen's discovery) was not likely to be totally benign to technologies should not have been a surprise to those who may have considered the question. Victor Hess, an Austrian, had demonstrated from a series of balloon ascents during 1912 that cosmic rays originated outside the Earth's atmosphere. Many authors (see, for example, Chapman and Bartels [1941], Cliver [1994], and Siscoe [2005] for considerable historical perspective) had long discussed the possibility that charged particles, likely from the Sun, played a key role in producing the aurora and geomagnetic activity at Earth. Nevertheless, Van Allen's discovery, and the subsequent race to place instruments and humans in Earth orbit, spurred the need to study the new phenomena open by the advent of rocketry to very high altitudes.

Early in its existence, the U.S. National Aeronautics and Space Administration (NASA; established in 1958) initiated programs for examining the feasibility of satellite communications. This began with a contract to the Hughes Aircraft Corporation for geosynchronous (GEO) Syncom satellites (the first launched in February 1963) and a low orbit communications program (under the name Relay, the first of which was launched in December 1962). NASA also initiated an Applications Technology Satellite (ATS) program (ultimately six satellites were launched into various orbits; two were unsuccessful due to launch vehicle failures) to investigate and test technologies and concepts for a number of space applications. In addition to communications, applications included meteorology, navigation, and health delivery, although not all such topics were objectives for each spacecraft..

ATS-1 was launched into a geosynchronous (GEO) orbit in December 1966. Included in the payload were three separate instruments containing charged particle detectors that were designed specifically to characterize the space environment at GEO. The three sectors of society – commercial (AT&T Bell Laboratories), military (Aerospace Corporation), and academic (University of Minnesota) – who constructed the three instruments demonstrated the wide-ranging institutional interest in, and scientific importance of, space weather conditions around Earth. The experiments all provided exciting data on such topics as the diurnal variation of the trapped radiation at the geosynchronous orbit [Lanzerotti et al., 1967], the large changes in the radiation with geomagnetic activity [Paulikas et al., 1968; Lezniak and Winckler, 1968], and the ready access of solar-produced particles to GEO [Lanzerotti, 1968; Paulikas and Blake, 1969].

Indicated in Figure 6 are the times of disturbances on selected communications systems following solar-originating disturbances. Four of the communications disturbances indicated in Figure 6 occurred after the beginning of the space era. The magnetic storm of February 1958 disrupted voice communications on TAT-1, from Newfoundland to Scotland (and also plunged the Toronto region into darkness by the tripping of electrical power company circuits). The outage for nearly an hour of a major continental telecommunications cable (L4) that stretched from near Chicago to the west coast was disrupted between the Illinois and Iowa powering stations by the magnetic storm of August 1972 [Anderson et al., 1974; Boteler and van Beek, 1999].

In March 1989 the entire province of Quebec suffered a power outage for nearly a day as major transformers failed under the onslaught of a large geomagnetic storm [Czech et al., 1992]. At the same time the first cross-Atlantic fiber optic voice cable (TAT-8) was rendered nearly inoperative by the large potential difference that was established between the cable terminals on the coasts of New Jersey and England [Medford et al., 1989].

Point-to-point high frequency (HF) wireless communications links continue to be affected by ionosphere disturbances caused by solar-produced interactions with the

Earth's space environment. Users of such systems are familiar with many anecdotes up to the present day of solar-produced effects and disruptions. For example, in 1979 (near the peak of the 21st solar cycle) a distress signal from a downed commuter plane was received by an Orange County, California, fire department – which responded, only to discover that the signal had originated from an accident site in West Virginia [*Los Angeles Times*, 1979].   An Associated Press released that was posted on October 30, 2003 (during the declining phase of the 23rd solar cycle), noted that airplanes "flying north of the 57th parallel experienced some disruptions in high frequency radio communications … due to the geomagnetic storm from solar flares".

As technologies have increased in sophistication, as well as in miniaturization and in interconnectedness, more sophisticated understanding of the Earth's space environment continues to be required. In addition, the increasing diversity of communications systems that can be affected by space weather processes is accompanied by continual changes in the dominance of use of one technology over another for specific applications. For example, in 1988 satellites were the dominant carrier of transocean messages and data; only about two percent of this traffic was over ocean cables. By 1990, the wide bandwidths provided by fiber optic cable meant that 80% of the transocean traffic was now via ocean cables [Mandell, 2000].

5. Solar-Terrestrial environnemental effects on communications technologies

Many present-day communications technologies that include considerations of the solar-terrestrial environment in their designs and/or operations are listed in Table 1. Figure 7 schematically illustrates some of these effects.

5.1 Ionosphere and wireless

A century after Marconi's feat, the ionosphere remains both a facilitator and a disturber in numerous communications applications. The military, as well as police and fire emergency agencies in many nations, continue to rely on wireless links that make extensive use of frequencies from kHz to hundreds of MHz and that use the ionosphere as a reflector. Commercial air traffic over the north polar regions continues to grow following the political changes of the late 1980s-early 1990s, and this traffic relies heavily on RF communications. Changes in the ionosphere that affect RF signal propagation can be produced by many mechanisms including direct solar photon emissions (solar UV and x-ray emissions), solar particles directly impacting polar region ionospheres, and radiation belt particles precipitated from the trapped radiation environment during geomagnetic storms.

At higher (few GHz) frequencies the production of "bubbles" in ionosphere densities in equatorial regions of the Earth can be a prime source of scintillations in satellite-to-ground signals. Engineers at the COMSAT Corporation discovered these effects after the deployment of the INTELSAT network at geosynchronous orbit [Taur, 1973]. This discovery is an excellent example of the surprises that the solar-terrestrial environment can hold for new technologies and for services that are based upon new technologies. A major applications satellite program (C/NOFS), scheduled for launch in 2006, has been designed by the U.S. Department of Defense to explicitly study the causes and evolutions of the processes that produce equatorial region bubbles, and to examine means of mitigation.

Disturbed ionosphere currents during geomagnetic storms can also be the cause of considerable problems at all geomagnetic latitudes in the use of navigation signals from the Earth-orbiting Global Positioning System (GPS), which provides precise location determination on Earth. These ionosphere perturbations limit the accuracy of positional determinations, thus presently placing limits on some uses of space-based navigation techniques for applications ranging from air traffic control to ship navigation to many national security considerations. The future European Galileo Navigation Satellite System (GNSS) will also have to take into account ionosphere disturbances in order to ensure its successful operations.

As evidenced by the initiation of the C/NOFS mission, there remain large uncertainties in the knowledge base of the processes that determine the initiation and scale sizes of the ionosphere irregularities that are responsible for the scintillation of radio communications signals that propagate through the ionosphere. Thus, it remains difficult to define mitigation techniques (including multi-frequency broadcasts and receptions) that might be applicable for receivers and/or space-based transmitters under many ionosphere conditions. Further and deeper knowledge from planned research programs might ultimately yield clever mitigation strategies.

5.2 Ionosphere and Earth currents

The basic physical chain of events behind the production of large potential differences across the Earth's surface begins with greatly increased electrical currents flowing in the magnetosphere and the ionosphere. The temporal and spatial variations of these increased currents then cause large variations in the time rate of change of the magnetic field as seen at Earth's surface. The time variations in the field in turn induce potential differences across large areas of the surface that are spanned by cable communications systems (or any other systems that are grounded to Earth, such as power grids and pipelines). Telecommunications cable systems use the Earth itself as a ground return for their circuits, and these cables thus provide highly conducting paths for concentrating the electrical currents that flow between these newly established, but temporary, Earth "batteries". The precise effects of these "anomalous" electrical currents depend upon the technical system to which the long conductors are connected. In the case of long telecommunications lines, the Earth potentials can cause overruns of the compensating voltage swings that are designed into the power supplies [e.g., Anderson et al., 1974] that are used to power the signal repeaters and regenerators (the latter in the case of optical transmissions).

Major issues can arise in understanding in detail the effects of enhanced space-induced ground electrical currents on cable systems. At present, the time variations and spatial dependencies of these currents are not well understood or predicable from one geomagnetic storm to the next. This is of considerable importance since the induced Earth potentials are very much dependent upon the conductivity structure of the Earth underlying the affected ionosphere regions. Similar electrical current variations in the space/ionosphere environment can produce vastly different Earth potential drops depending upon the nature and orientation of underground Earth conductivity structures in relationship to the variable overhead currents.

Modeling of these effects is becoming advanced in many cases. This is an area of research that involves a close interplay between space plasma geophysics and solid Earth geophysics, and is one that is not often addressed collaboratively by these two very distinct research communities (except by the somewhat limited group of researchers who pursue electromagnetic investigations of the Earth).

5.3 Solar radio emissions

Solar radio noise and bursts were discovered more than six decades ago by Southworth [1945] and by Hey [1946] during the early research on radar at the time of the Second World War. Solar radio bursts produced unexpected (and initially unrecognized) jamming of this new technology that was under rapid development and deployment for war-time use for warnings of enemy aircraft [Hey, 1973]. Extensive post-war research established that solar radio emissions can exhibit a wide range of spectral shapes and intensity levels [e.g., Kundu, 1965; Castelli et al., 1973; Guidice and Castelli, 1975; Barron et al., 1985], knowledge of which is crucial for determining the nature and severity of solar emissions on specific technologies such as radar, radio, satellite ground communications receivers, or civilian wireless communications. Research on solar radio phenomena remains an active and productive field of research today [e.g., Bastian et al., 1998; Gary and Keller, 2004].

Some analyses of local noon time solar radio noise levels that are routinely taken by the U.S. Air Force and that are made available by the NOAA World Data Center have been carried out in order to assess the noise in the context of modern communications technologies. These analyses show that in 1991 (during the sunspot maximum interval of the 22nd cycle) the average noon fluxes measured at 1.145 GHz and at 15.4 GHz were –162.5 and –156 dBW/(m^2 4kHz), respectively [Lanzerotti et al., 1999]. These values are only about 6 dB and 12 dB above the 273º K (Earth's surface temperature) thermal noise of –168.2 dBW/(m^2 4kHz). Further, these two values are only about 20 dB and 14 dB, respectively, below the maximum flux of –142 dBW/(m^2 4kHz) that is allowed for satellite downlinks by the ITU regulation RR2566.

Solar radio bursts from solar activity can have much larger intensities. As an example of an extreme event, that of May 23, 1967, produced a radio flux level (as measured at Earth) of >10^5 solar flux units (1 SFU = 10^{-22} W/(m^2 Hz)) at 1 GHz, and perhaps much larger [Castelli et al., 1973]. Such a sfu level corresponds to –129 dBW/(m^2 4kHz), or 13 dB above the maximum limit of –142 dBW/(m^2 4kHz) noted above, and could cause considerable excess noise in any wireless cell site that might be pointed at the Sun at the time of the burst..

An example of a portion of a study of solar burst events that is directed towards understanding the distributions of events that might produce severe noise in radio receivers is shown in Figure 8 [Nita et al., 2004]. Plotted here is the cumulative distribution of intensities of 412 solar radio bursts measured in 2001-2002 (during the maximum of the 23rd solar cycle) at a frequency of 1.8 GHz at the NJIT Owens Valley Solar Array. The exponent of a power law fit to the distribution is shown; the roll-over of the distribution at the lowest flux density is believed to be a result of decreased instrument sensitivities at the very lowest levels. Using such distributions, and taking into account the time interval over which the data were acquired, the probability of a burst affecting a specific receiver can be estimated. Bala et al. [2002], in an analysis of forty years of solar burst data assembled by the NOAA National Geophysical Data Center, estimated that bursts with amplitudes $>10^3$ solar flux units (sfu) at f ~ 1 GHz could cause potential problems in a wireless cell site on average of once every three to four days during solar maximum, and perhaps once every twenty days or less during solar minimum.

Short term variations often occur within solar radio bursts, with time variations ranging from several milliseconds to seconds and more [e.g., Benz, 1986; Isliker and Benz, 1994]. Such short time variations can often be many tens of dB larger than the underlying solar burst intensities upon which they are superimposed. It would be useful to evaluate wireless systems in the context of such new scientific understanding.

5.4 Space radiation effects

As related in the Introduction, the discovery of the trapped radiation around Earth immediately implied that the space environment would not be benign for any communications technologies that might be placed within it. Some 200 or so in-use communications satellites now occupy the geosynchronous orbit. The charged particle radiation (over the entire range of energies) that permeates the Earth's space environment remains a difficult problem for the design and operations of these and other space-based systems [e.g., Shea and Smart, 1998; Koons et al., 1999]. A textbook discussion of the space environment and the implications for satellite design is contained in Tribble [1995].

The low energy (few eV to few keV) plasma particles in the Earth's magnetosphere plasma can be highly variable in time and in intensity levels, and can produce different levels of surface charging on the materials (principally for thermal control) that encase a satellite [Garrett, 1981]. If good electrical connections are not established between the various surface materials, and between the materials and the solar arrays, differential charging on the surfaces can produce lightning-like breakdown discharges between the materials. These discharges can produce electromagnetic interference and serious damage to components and subsystems [e.g., Vampola, 1987; Koons, 1980; Gussenhoven and Mullen, 1983].

Under conditions of enhanced geomagnetic activity, the cross-magnetosphere electric field will convect earthward the plasma sheet in the Earth's magnetotail. When this occurs, the plasma sheet will extend earthward to within the geosynchronous (GEO) spacecraft orbit. When this occurs, on-board anomalies from surface charging effects will occur; these tend to be most prevalent in the local midnight to dawn sector of the orbit [Mizera, 1983].

While some partial records of spacecraft anomalies exist, there are relatively few published data on the statistical characteristics of charging on spacecraft surfaces, especially from commercial satellites that are used so extensively for communications. Two surface-mounted charge plate sensors were specifically flown on the former AT&T Telstar 4 GEO satellite to monitor surface charging effects. Figure 9 shows the statistical distributions of charging on one of the sensors in January 1997 [Lanzerotti et al., 1998]. The solid line in each panel corresponds to the charging statistics for the entire month, while the dashed lines omit data from a magnetic storm event on January 10th (statistics shown by the solid lines). Charging voltages as large as –800 V were recorded on the charge plate sensor during the magnetic storm, an event during which a permanent failure of the Telstar 401 satellite occurred (although the failure has not been officially attributed specifically to the space conditions).

The intensities of higher energy particles in the magnetosphere (MeV energy protons and electrons to tens of MeV energy protons) can change by many orders of magnitude over the course of minutes, hours, and days. These intensity increases occur through a variety of processes, including plasma physics energization processes in the magnetosphere and ready access of solar particles to GEO. Generally it is prohibitively expensive to provide sufficient shielding of all interior spacecraft subsystems against high energy particles. Most often, increasing shielding would require a weight trade-off of the benefits of such shielding as compared to flying additional transponders or more orbit control gas, for example.

The range of a 100 MeV proton in aluminum (a typical spacecraft material) is ~ 40 mm. The range of a 3 MeV electron is ~ 6 mm. These particles can therefore penetrate deeply into the interior regions of a satellite. In addition to producing transient upsets and latch-ups in signal and control electronics, such particles can also cause electrical charges to build up in interior insulating materials such as those used in coax cables. If the charge buildup in interior dielectric materials is sufficiently large, electrical breakdowns will ultimately result. Electromagnetic interference and damage to the electronics will occur.

A number of spacecraft anomalies, and even failures, have been identified as having occurred following many days of significantly elevated fluxes of several MeV energy electrons [Baker et al., 1987; 1994; 1996; Reeves et al., 1998] at GEO. These enhanced fluxes occurred following sustained interplanetary disturbances called co-rotating interactions regions. The large solar flare and coronal mass ejection events of October-November 2003 produced anomalies on many spacecraft, as discussed by Barbieri and Mahmot [2004]. An adaptation of their listing of some of the affected satellites and the impacts is shown in Table 2. They note that, with the exception of the orbit change of the TRMM mission, all of the impacts were caused by "solar energetic particles … or similarly accelerated particles in geospace." The purely communications satellites included in the Table, the NASA Tracking and Data Relay Satellite System (TDRSS), suffered electronic errors during the interval of the solar-origin events.

No realistic shielding is possible for most communications systems in space that are under bombardment by galactic cosmic rays (energies ~ 1 GeV and greater). These very energetic particles can produce upsets and errors in spacecraft electronics (as well as in computer chips that are intended for use on Earth [IBM, 1996]). So-called ground-level solar particle events (order GeV energy) can produce errors in the avionics and communications equipment of an aircraft that might be flying over the polar region at the time of the event.

The significant uncertainties in placing, and retaining, a communications spacecraft in a revenue-returning orbital location has led to a large business in risk insurance and re-insurance for one or more of the stages in a satellite's history. The loss of a spacecraft, or one or more transponders, from adverse space weather conditions is only one of many contingencies that can be insured against. In some years the space insurance industry is quite profitable, and in some years there are serious losses in net revenue after paying claims [e.g., Todd, 2000]. For example, Todd [2000] states that in 1998 there were claims totaling more than $1.71 billion after salvage, an amount just less than about twice that received in premiums. These numbers vary by large amounts from year to year.

5.5 Magnetic field variations

Enhanced solar wind flow velocities and densities, such as those that can occur in coronal mass ejection events, can easily distort the dayside magnetopause and push it inside its normal location at about ten Earth radii distance. During large solar wind disturbances, the magnetopause can be pushed inside the geosynchronous orbit. At such times, the magnetic field at GEO increases to as much as twice its "quiescent" value. In addition, the magnetic field outside the magnetopause will have a polarity that is predominantly opposite to that inside the magnetosphere.

The highly varying in magnitude, space and time magnetic fields that occur at the boundary and outside the magnetosphere can seriously disrupt the stabilization of any GEO satellite that uses the Earth's magnetic field for attitude control. Such magnetically-stabilized GEO communications spacecraft must take into account the high probability that the satellite will on occasion, during a large magnetic disturbance, find itself near and even outside the magnetosphere on the sunward side of the Earth. Thus, appropriate GEO satellite attitude control designs must be implemented in order to cope with highly fluctuating magnetopause magnetic fields, and even the complete "flipping" of the field when the magnetopause is crossed.

5.6 Micrometeoroids and space debris

The impacts on communications spacecraft of solid objects, such as from mircrometeoroids and from debris left in orbit from space launches and from satellites that break up for whatever the reason, can seriously disorient a satellite and even cause a total loss [e.g., Beech et al., 1997; McBride, 1997]. The U.S. Air Force systematically tracks thousands of space debris items that are circling the Earth, most of which are in low altitude orbits.

5.7 Atmosphere: Low altitude spacecraft drag

The ultraviolet emissions from the sun change by more than a factor of two at wavelengths $\leq$ 170 nm during a solar cycle [Hunten et al, 1991]. This is significantly more than the ~ 0.1 % changes that are typical of the visible radiation. The heating of the atmosphere by the increased solar UV radiation causes the atmosphere to expand. The heating is sufficient to raise the "top" of the atmosphere by several hundred km during solar maximum. The greater densities at the higher altitudes result in increased drag on both space debris and on communications spacecraft in low Earth orbits (LEO). Telecommunications spacecraft that fly in LEO have to plan to use some amount of their orbit control fuel to maintain orbit altitude during the buildup to, and in, solar maximum conditions [e.g., Picholtz, 1996].

5.8 Atmosphere water vapor

At frequencies in the Ka (18 – 31 GHz) band that are planned for high bandwidth space-to-ground applications (as well as for point-to-point communications between ground terminals), water vapor in the neutral atmosphere is the most significant natural phenomenon that can serious affect the signals [e.g., Gordon and Morgan, 1993]. It would appear that, in general, the space environment can reasonably be ignored when designing around the limitations imposed by rain and water vapor in the atmosphere.

A caveat to this claim would certainly arise if it were definitely to be shown that there are effects of magnetosphere and ionosphere processes (and thus effects of the interplanetary medium) on terrestrial weather. It is well recognized that even at GHz frequencies the ionized channels caused by lightning strokes, and possibly even charge separations in clouds, can reflect radar signals. Lightning and cloud charging phenomena may produce as yet unrecognized noise sources for low-level wireless signals. Thus, if it were to be learned that ionosphere electrical fields influenced the production of weather disturbances in the troposphere, the space environment could be said to affect even those wireless signals that might be disturbed by lightning. Much further research is required in this area of speculation.

6. Summary

In the 150 years since the advent of the first electrical communication system – the electrical telegraph – the diversity of communications technologies that are embedded within space-affected environments have vastly increased. The increasing sophistication of these communications technologies, and how their installations and operations may relate to the environments in which they are embedded, means that ever more sophisticated understanding of the natural physical phenomena is needed. At the same time, the business environment for most present-day communications technologies that are affected by space phenomena is very dynamic. The commercial and national security deployment and use of these technologies do not wait for optimum knowledge of possible environmental effects to be acquired before new technological embodiments are created, implemented, and marketed. Indeed, those companies that might foolishly seek perfectionist understanding of natural effects can be left behind by the marketplace. A well-considered balance is needed between seeking ever deeper understanding of physical phenomena and implementing "engineering" solutions to current crises. The research community must try to understand, and operate in, this dynamic environment.

7. Acknowledgments

This chapter relies heavily on past research and engineering conducted over nearly four decades at Bell Laboratories. Some of these activities is recorded in several of the papers referenced in the text, as well as in overviews presented, for example, in Lanzerotti [2001a,b]. I also sincerely thank numerous colleagues for vigorous discussions on this topic over many years, including C. G. Maclennan, D. J. Thomson, G. Siscoe, J. H. Allen, J. B. Blake, G. A. Paulikas, A. Vampola, H. C. Koons, and L. J. Zanetti.

Table 1. Impacts of Solar-Terrestrial Processes on Communications

Ionosphere Variations
- Induction of electrical currents in the Earth
  - Long communications cables
- Wireless signal reflection, propagation, attenuation
  - Commercial radio and TV
  - Local and national safety and security entities
  - Aircraft communications
- Communication satellite signal interference, scintillation
  - Commercial telecom and broadcast

Magnetic Field Variations
- Attitude control of communications spacecraft

Solar Radio Bursts
- Excess noise in wireless communications systems
- Interference with radar and radio receivers

Charged Particle Radiation
- Solar cell damage
- Semiconductor device damage and failure
- Faulty operation of semiconductor devices
- Spacecraft charging, surface and interior materials
- Aircraft communications avionics

Micrometeoroids and Artificial Space Debris
- Spacecraft solar cell damage
- Damage to surfaces, materials, complete vehicles
- Attitude control of communications spacecraft

Atmosphere
- Drag on low altitude communications satellites
- Attenuation and scatter of wireless signals

Table 2. Summary of space weather impacts on selected spacecraft in October-November 2003 (adapted from Barbieri and Mahmot, 2004)

		SPACE WEATHER IMPACT				
Spacecraft Mission	Change in Operation Status	Electronic Errors	Noisy Housekeeping Data	Solar Array Degradation	Change in Orbit Dynamics	High Levels Accumulated Radiation
Aqua	None	X				
Chandra	Instrument safed					X
CHIPS	Control loss	X				
Cluster	None			X		
Genesis	Auto safed	X				
GOES 9,10	None		X			
ICESat	None	X				
INTEGRAL	Command safe					
Landsat 7	Instrument safed					
RHESSI	Abs. time seq. stop	X				
SOHO	Instrument safed			X		
Stardust	Auto safed	X				
TDRSS	None	X				
TRMM	Added delta V				X	
WIND	None			X		

8. References

Anderson, C. N., Correlation of radio transmission and solar activity, *Proc. I. R. E.*, **16**, 297, 1928.

Anderson, C. N., Notes on the effects of solar disturbances on transatlantic radio transmissions, *Proc. I. R. E.*, **17**, 1528, 1929.

Anderson, C. W., III, L. J. Lanzerotti, and C. G. Maclennan, Outage of the L4 system and the geomagnetic disturbance of 4 August 1972, *The Bell Sys. Tech. J*., **53**, 1817, 1974.

Appleton, E. V., and M. A. F. Barnett, Local reflection of wireless waves from the upper atmosphere, *Nature*, **115**, 333, 1925.

Baker, D. N., R. D. Balian, P. R. Higbie, et al., Deep dielectric charging effects due to high energy electrons in Earth's outer magnetosphere, *J. Electrost*., **20**, 3, 1987.

Baker, D. N., S. Kanekal, J. B. Blake, et al., Satellite anomaly linked to electron increase in the magnetosphere, *Eos Trans. Am. Geophys. Union*, **75**, 401, 1994.

Baker, D. N., An assessment of space environment conditions during the recent Anik E1 spacecraft operational failure, *ISTP Newsletter*, **6**, 8, 1996.

Baker, D. N., J. H. Allen, S. G. Kanekal, and G. D. Reeves, Disturbed space environment may have been related to pager satellite failure, *Eos Trans. Am. Geophys. Union*, **79**, 477, 1998.

Bala, B., L. J. Lanzerotti, D. E. Gary, and D. J. Thomson, Noise in wireless systems produced by solar radio bursts, *Radio Sci*., **37(2)**, 10.1029/2001RS002488, 2002.

Barbieri, L. P., and R. E. Mahmot, October-November 2003's space weather and operations lessons learned, *Space Weather*, Vol. 2, No. 9, S0900210.1029/2004SW000064, 2004.

Barlow, W. H., On the spontaneous electrical currents observed in the wires of the electric telegraph, *Phil. Trans. R. Soc*., **61A**, 61, 1849.

Barron, W. R., E. W. Cliver, J. P. Cronin, and D. A. Guidice, Solar radio emission, in *Handbook of Geophysics and the Space Environment*, ed. A. S. Jura, Chap. 11, AFGL, USAF, 1985.

Bastian, T. S., A. O. Benz, and D. E. Gary, Radio emission from solar flares, *Ann. Rev. Astron. Astrophys*., **36**, 131, 1998.

Beech, M., P. Brown, J. Jones, and A. R. Webster, The danger to satellites from meteor storms, *Adv. Space Res*., **20**, 1509, 1997.

Bell System Technical Journal, Special Telstar Issue, **42**, Parts 1, 2, 3, July 1963.

Benz, A. O., Millisecond radio spikes, *Solar Phys*., **104**, 99, 1986.

Beech, M., P. Brown, J. Jones, and A. R. Webster, The danger to satellites from meteor storms, *Adv. Space Res*., **20**, 1509, 1997.

Boteler, D. H., and G. Jansen van Beek, August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage, *Geophys. Res. Lett*., **26**, 577, 1999.

Breit, M. A., and M. A. Tuve, A test of the existence of the conducting layer, *Nature*, **116**, 357, 1925.

Carrington, R. C., *Observation of the Spots on the Sun from November 9, 1853, to March 24, 1863, Made at Redhill*, William and Norgate, London and Edinburgh, 167, 1863.

Castelli, J. P., J. Aarons, D. A., Guidice, and R. M. Straka, The solar radio patrol network of the USAF and its application, *Proc. IEEE*, **61**, 1307, 1973.

Chapman, S., and J. Bartels, *Geomagnetism*, 2 vols, Oxford Univ. Press, 1940.

Clark, Arthur C., Extra-Terrestrial Relays – Can Rocket Stations Give World-Wide Radio Coverage? *Wireless World*, 305, October 1945.

Cliver, E. W., Solar activity and geomagnetic storms, *Eos*, Trans. AGU, **75**, 569, 1994.

Czech, P., S. Chano, H. Huynh, and A. Dutil, The Hydro-Quebec system blackout of 13 March 1989: System response to geomagnetic disturbance, *Proc. EPRI Conf. Geomagnetically Induced Currents,* EPRI TR-100450, Burlingame, CA, 19, 1992.

Fagen, M. D., *A History of Science and Engineering in the Bell System*, Bell Tel. Labs., Inc., Murray Hill, NJ, 1975.

Garrett, H. B., The charging of spacecraft surfaces, *Revs. Geophys*., **19**, 577, 1981.

Gary, D. E., and C. U. Keller, eds., *Solar and Space Weather Radiophysics*, Springer, Heidelberg, 2004.

Gordon, G. D., and W. L. Morgan, *Principals of Communications Satellites*, John Wiley, New York, 178-192, 1993.

Guidice, D. A., and J. P. Castelli, Spectral characteristics of microwave bursts, in *Proc. NASA Symp. High Energy Phenomena on the Sun*, Goddard Space Flight Center, Greenbelt, MD, 1972.

Gussenhoven, M. S., and E. G. Mullen, Geosynchronous environment for severe spacecraft charging, *J. Spacecraft Rockets*, **20**, 26, 1983.

Hey, J. S., Solar radiations in the 4 – 6 metre radio wavelength band, *Nature*, **158**, 234, 1946.

Hey, J. S., *The Evolution of Radio Astronomy*, Neale Watson Academic Pub. Inc., New York, 1973.

Hunten, D. M., J.-C. Gerard, and L. M. Francois, The atmosphere's response to solar irradiation, in *The Sun in Time*, ed. C. P. Sonett, M. S. Giampapa, and M. S. Matthews, Univ. Arizona Press, Tucson, 463, 1991.

IBM Journal of Research and Development, **40,** 1-136, 1996.

Isliker, H., and A. O. Benz, Catalogue of 1 – 3 GHz solar flare radio emission, *Astron. Astrophys. Suppl. Ser*., **104**, 145, 1994.

Koons, H. C., Characteristics of electrical discharges on the P78-2 satellite (SCATHA), *18th Aerospace Sciences Meeting*, AIAA 80-0334, Pasadena, CA, 1980.

Koons, H., C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennel, J. L. Roeder, and P. C. Anderson, *The Impact of the Space Environment on Space Systems*, Engineering and Technology Group, The Aerospace Corp., Report TR-99(1670), El Segundo, CA, 1999.

Kundu, M. R., *Solar Radio Astronomy*, Interscience, New York, 1965.

Lanzerotti, L. J., C. S. Roberts, and W. L. Brown, Temporal Variations in the Electron Flux at Synchronous Altitudes, *J. Geophys. Res*., **72**, 5893, 1967.

Lanzerotti, L. J., Penetration of solar protons and alphas to the geomagnetic equator, *Phys. Rev. Lett.*, **21**, 929, 1968.

Lanzerotti, L. J., C. Breglia, D. W. Maurer, and C. G. Maclennan, Studies of spacecraft charging on a geosynchronous telecommunications satellite, *Adv. Space Res*., **22**, 79, 1998.

Lanzerotti, L. J., C. G. Maclennan, and D. J. Thomson, Engineering issues in space weather, in *Modern Radio Science*, ed. M. A. Stuchly, Oxford, 25, 1999.

Lanzerotti, Space weather effects on technologies, in *Space Weather*, ed. P. Song, H. J. Singer, and G. L. Siscoe, Am. Geophys. Union, Washington, 11, 2001a.

Lanzerotti, Space weather effects on communications, in *Space Storms and Space Weather Hazards*, ed. I. A. Daglis, Kluwer, Holland, 313, 2001b.

Lezniak, T. W. and J. R. Winckler, Structure of the Magnetopause at 6.6 R_E in Terms of 50- to 150-kev Electrons, J. Geophys. Res., 73, 5733, 1968.

Los Angeles Times, Sunspots playing tricks with radios, Metro Section, pg. 1, Febr. 13, 1979.

Mandell, M., 120000 leagues under the sea, *IEEE Spectrum*, 50, April 2000.

Marconi, G., Radio communication, *Proc. IRE*, **16**, 40, 1928.

McBride, N., The importance of the annual meteoroid streams to spacecraft and their detectors, *Adv. Space Res*., **20**, 1513, 1997.

Medford, L. V., L. J. Lanzerotti, J. S. Kraus, and C. G. Maclennan, Trans-Atlantic earth potential variations during the March 1989 magnetic storms, *Geophys. Res. Lett*., **16**, 1145, 1989.

Mizera, P. F., A summary of spacecraft charging results, *J. Spacecraft Rockets*, **20**, 438, 1983.

Nita, G. M., D. E. Gary, and L. J. Lanzerotti, Statistics of solar microwave burst spectra with implications for operations of microwave radio systems, Space Weather, 2, S11005, doi:10.1029/2004SW000090, 2004.

Paulikas, G. A., J. B. Blake, S. C. Freden, and S. S. Imamoto, Boundary of Energetic Electrons during the January 13-14, 1967, Magnetic Storm, *J. Geophys. Res*., **73**, 5743, 1968.

Paulikas, G. A. and J. B. Blake, Penetration of Solar Protons to Synchronous Altitude, *J. Geophys. Res.*, **74**, 2162, 1969.

Picholtz, R. L., Communications by means of low Earth orbiting satellites, *in Modern Radio Science 1996*, ed. J. Hamlin, Oxford U. Press, 133, 1996.

Pierce, John R., Orbital Radio Relays, *Jet Propulsion*, page 153, April 1955.

Prescott, G. B., *Theory and Practice of the Electric Telegraph*, IV ed., Tichnor and Fields, Boston, 1860.

Reeves, G. D., The relativistic electron response at geosynchronous orbit during January 1997 magnetic storm, *J. Geophys., Res*.,**103**, 17559, 1998.

Reid, E. J., How can we repair an orbiting satellite?, in *Satellite Communications Physics*, ed. R. M. Foster, Bell Telephone Laboratories, 78, 1963.

Shea, M. A., and D. F. Smart, Space weather: The effects on operations in space, *Adv. Space Res.*, 22, 29, 1998.

Silliman, Jr., B., *First Principals of Chemistry*, Peck and Bliss, Philadelphia, 1850.

Siscoe, G. L., Space weather forecasting historically through the lens of meteorology, *Space Weather, Physics and Effects*, ed. V. Bothmer and I. A. Daglis, Springer Praxis, 2005.

Southworth, G. C., Microwave radiation from the sun, *J. Franklin Inst*., **239**, 285, 1945.

Taur, R. R., Ionospheric scintillation at 4 and 6 GHz, *COMSAT Technical Review*, **3**, 145, 1973.

Todd, D., Letter to *Space News*, pg. 12, March 6, 2000.

Tribble, A. C., *The Space Environment, Implications for Spacecraft Design*, Princeton Univ. Press, Princeton, NJ, 1995.

Vampola, A., The aerospace environment at high altitudes and its implications for spacecraft charging and communications, *J. Electrost*., **20**, 21, 1987.

Van Allen, J. A., *Origins of Magnetospheric Physics*, Smithsonian Institution, Washington, 1983.

Vernov, S. N., and A. E. Chudakov, Terrestrial corpuscular radiation and cosmic rays, *Adv. Space Res*., **1**, 751, 1960.

Figure Captions

Figure 1. Hourly galvanometer recordings of voltage across a cable from Derby to Birmingham, England, May 1847.

Figure 2. Hourly mean galvanometer deflections recorded on telegraph cables from Derby to Birmingham (solid line) and to Rugby (dashed line) in May 1847.

Figure 3. Plate 80 from Carrington [1863] showing his sunspot drawings for August 11 to September 6, 1859. The large spot area at about 45º N solar latitude on August 31 is especially notable.

Figure 4. Yearly average daylight cross-Atlantic transmission signal strengths and monthly average sunspot numbers for the interval 1915 – 1932 [Fagen, 1975].

Figure 5. Trans-Atlantic wireless transmissions from the Eastern U. S. to the U. K. on two frequencies before and during a magnetic storm event in July 1928. Also shown are the values of the horizontal component of the Earth's magnetic field [Anderson, 1929].

Figure 6. Yearly sunspot numbers with indicated times of selected major impacts of the solar-terrestrial environment on largely ground-based technical systems. The numbers just above the horizontal axis are the conventional numbers of the sunspot cycles.

Figure 7. Some of the effects of space weather on communications systems that are deployed on the Earth's surface and in space, and/or whose signals propagate through the space environment.

Figure 8. Cumulative distribution of intensities of 412 solar radio bursts in 2001-2002 at a frequency of 1.8 GHz at the NJIT Owens Valley Solar Array [from Nita et al., 2004].

Figure 9. Statistical distribution of surface charging recorded on the northward-facing charge plate sensor on the Telstar 4 spacecraft during the month of January 1997 (solid line) and for the same month with data from January 10th (the date of a large magnetic storm) removed (dashed line). The upper panel records (in approximately 25 volt bins) the number of voltage occurrences in each voltage bin; the lower panel plots the cumulative percent voltage occurrence above 95% in order to illustrate the extreme events seen by the communications spacecraft.

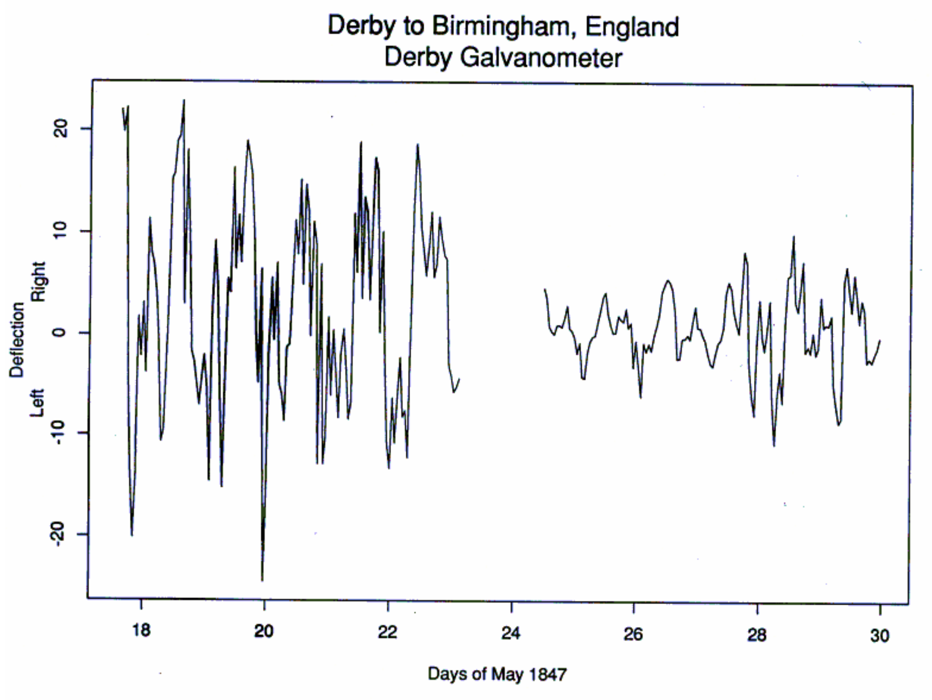

Figure 1. Hourly galvanometer recordings of voltage across a cable from Derby to Birmingham, England, May 1847.

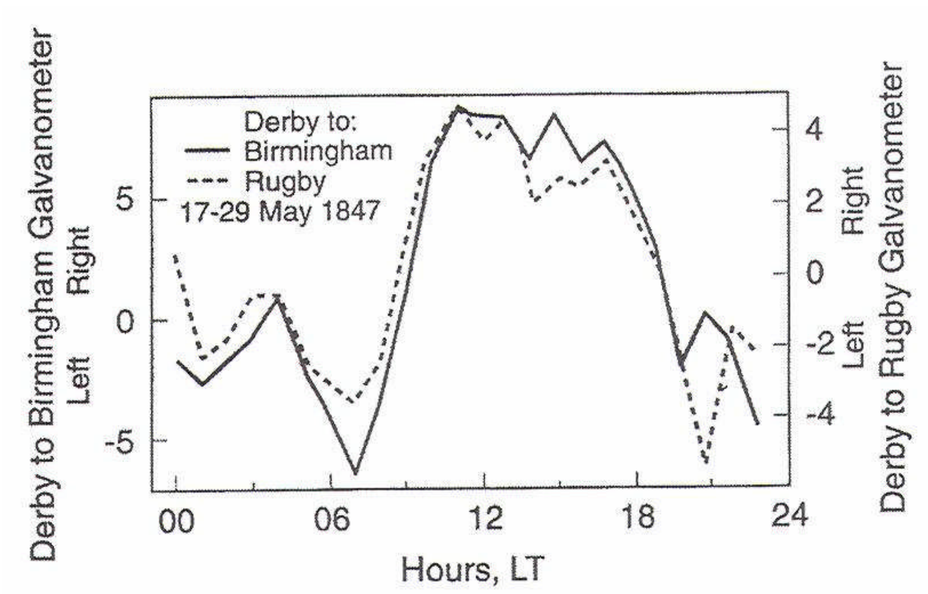

Figure 2. Hourly mean galvanometer deflections recorded on telegraph cables from Derby to Birmingham (solid line) and to Rugby (dashed line) in May 1847.

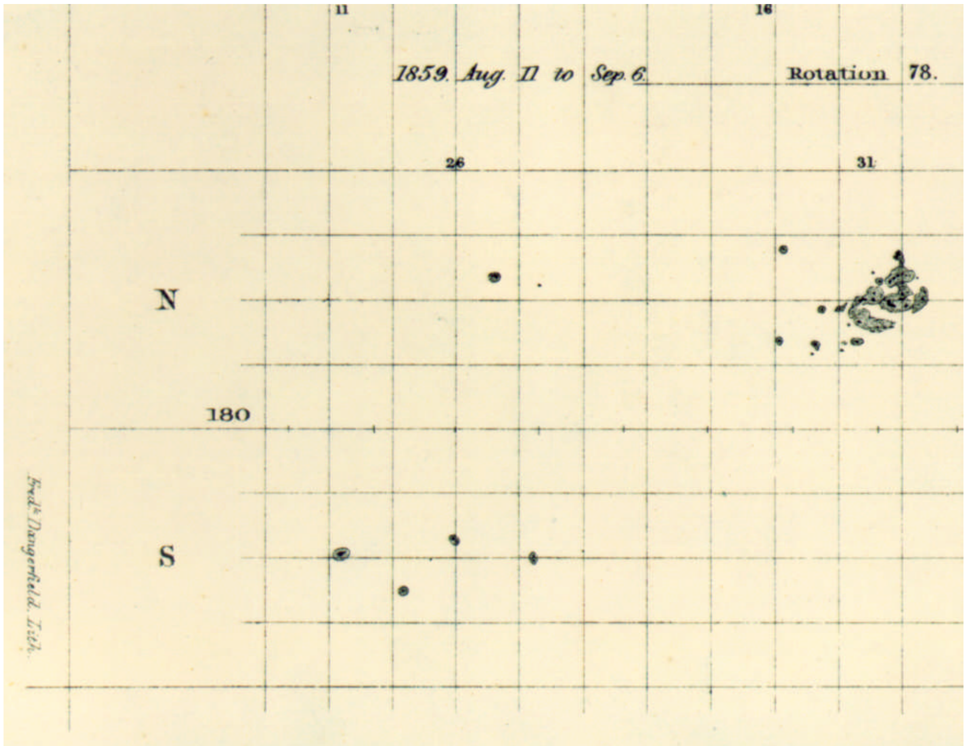

Figure 3. Plate 80 from Carrington [1863] showing his sunspot drawings for August 11 to September 6, 1859 (Carrington Rotation #78). The large spot area at about 45º N solar latitude on August 31 is especially notable.

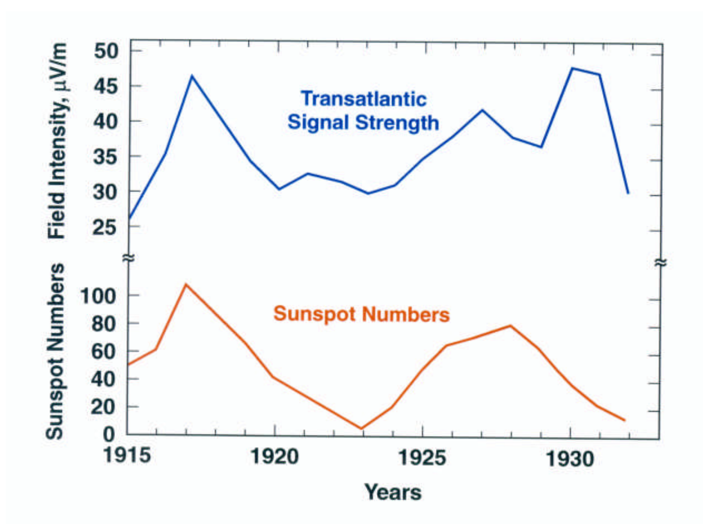

Figure 4. Yearly average daylight cross-Atlantic transmission signal strengths and monthly average sunspot numbers for the interval 1915 – 1932 [Fagen, 1975].

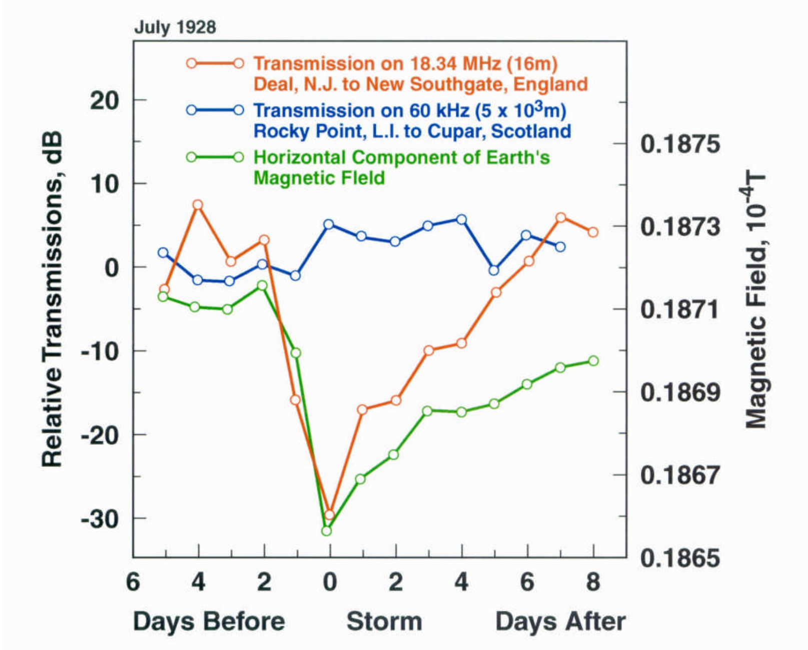

Figure 5. Trans-Atlantic wireless transmissions from the Eastern U. S. to the U. K. on two frequencies before and during a magnetic storm event in July 1928. Also shown are the values of the horizontal component of the Earth's magnetic field [Anderson, 1929].

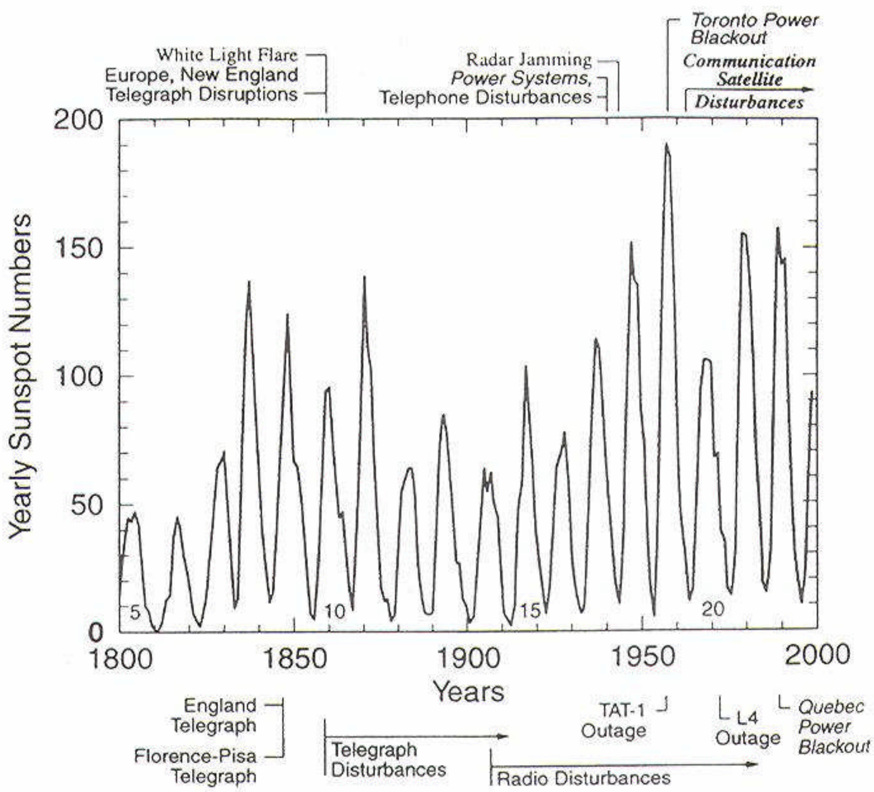

Figure 6. Yearly sunspot numbers with indicated times of selected major impacts of the solar-terrestrial environment on largely ground-based technical systems. The numbers just above the horizontal axis are the conventional numbers of the sunspot cycles.

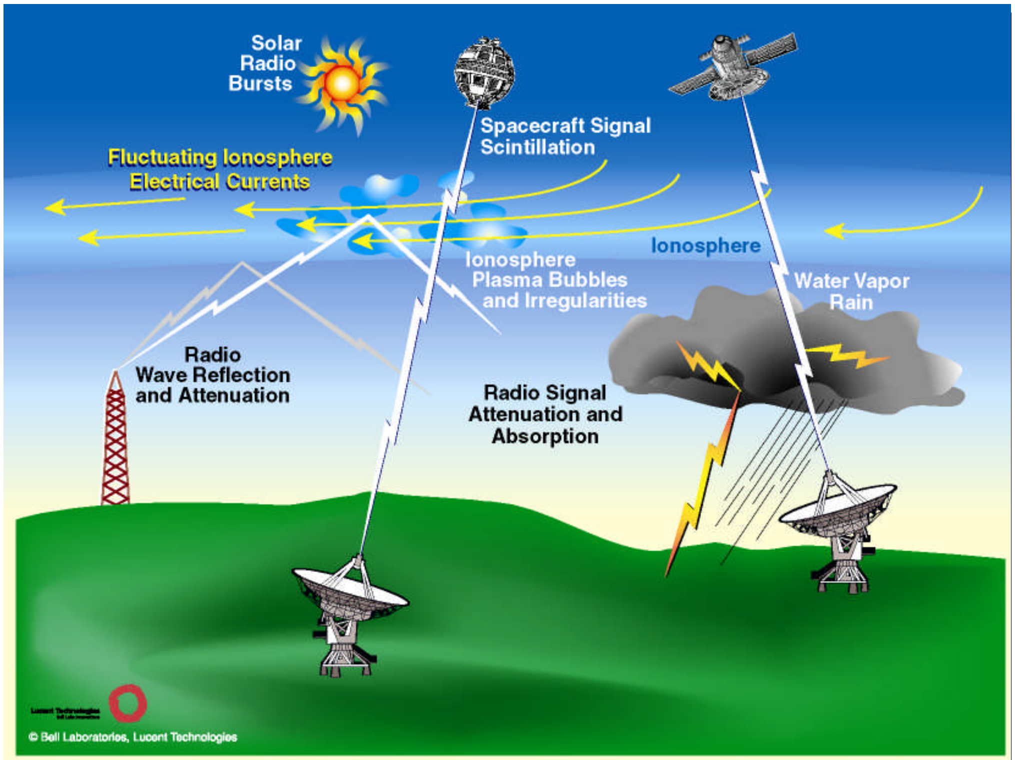

Figure 7. Some of the effects of space weather on communications systems that are deployed on the Earth's surface and in space, and/or whose signals propagate through the space environment.

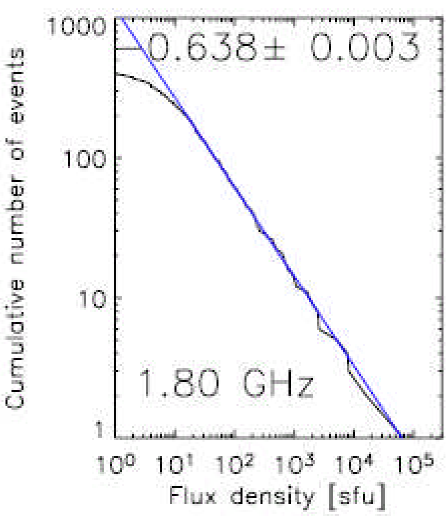

Figure 8. Cumulative distribution of intensities of 412 solar radio bursts in 2001-2002 at a frequency of 1.8 GHz at the NJIT Owens Valley Solar Array.

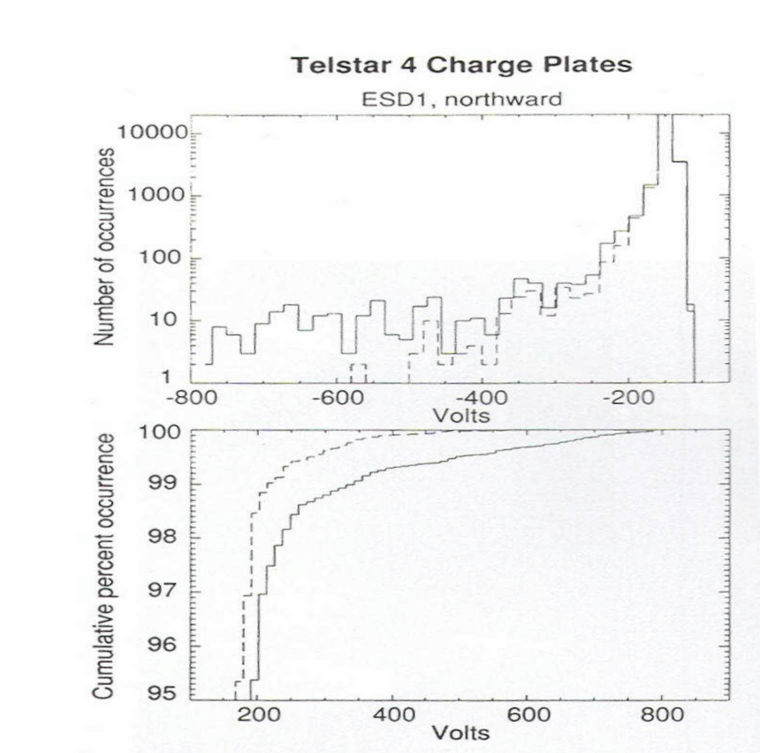

Figure 9. Statistical distribution of surface charging recorded on the northward-facing charge plate sensor on the Telstar 4 spacecraft during the month of January 1997 (solid line) and for the same month with data from January 10th (the date of a large magnetic storm) removed (dashed line). The upper panel records (in approximately 25 volt bins) the number of voltage occurrences in each voltage bin; the lower panel plots the cumulative percent voltage occurrence above 95% in order to illustrate the extreme events seen by the communications spacecraft