Chapter 5 – SPACE WEATHER

5.1 IONOSPHERIC EFFECTS OF SEVERE GEOMAGNETIC STORMS

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Abstract

Earth's ionosphere responds dramatically to severe geomagnetic storms. Coupled closely to the neutral thermosphere and the overlying magnetosphere, stormtime ionospheric effects appear with a wide variety of scale sizes, characteristics, time histories, and associated drivers. The strong interconnection between the magnetosphere and ionosphere points to the need to take a global perspective in characterizing and understanding this system. Penetrating electric fields and plasma redistribution combine to produce severe enhancements and reductions of ionospheric TEC (total electron content), steep localized density gradients, and stormtime space weather effects.

5.1.1 Introduction

Earth's ionosphere responds dramatically to severe geomagnetic storms. Coupled closely to the neutral thermosphere and the overlying magnetosphere, stormtime ionospheric effects appear with a wide variety of scale sizes, characteristics, time histories, and associated drivers. This report provides an overview of recent developments in observing, identifying, and understanding the causes of such phenomena. In keeping with the author's experience, the emphasis is placed meso-scale (100s – 1000s kilometer) ionospheric perturbations and the use of ground and space-based diagnostics to characterize them. As often occurs in a topical review, the work reported and illustrations used will reflect those areas most familiar to the author. Accordingly, emphasis is placed on recent observations of mid-latitude ionospheric disturbances and their relationship to the complex system of stormtime magnetosphere-ionosphere coupling.

Recent studies highlighting the disturbance effects observed in the ionosphere and magnetosphere during geomagnetic disturbances, and their space weather effects, have heightened interest in the processes occurring in the plasmasphere boundary layer (PBL) [Carpenter and Lemaire, 2004], the boundary between the corotating field lines of the plasmasphere and the outer magnetosphere. During storms, the effects of magnetospheric electric field and ExB plasma convection extend deep into the mid-latitude ionosphere producing dramatic effects. At the PBL, strong electric fields contribute to the formation of the deep mid-latitude density trough which spans the nightside while penetration electric fields uplift, destabilize, and perturb the low-latitude ionosphere. For example, Foster and Rich [1998] reported a sudden uplifting of the mid-latitude ionosphere, equatorward of the trough, during the early phase of strong storms due to the effects of prompt penetration electric fields. Destabilization of the F region at mid latitudes (up to ~35° invariant latitude) followed (cf. Figure 5-1).

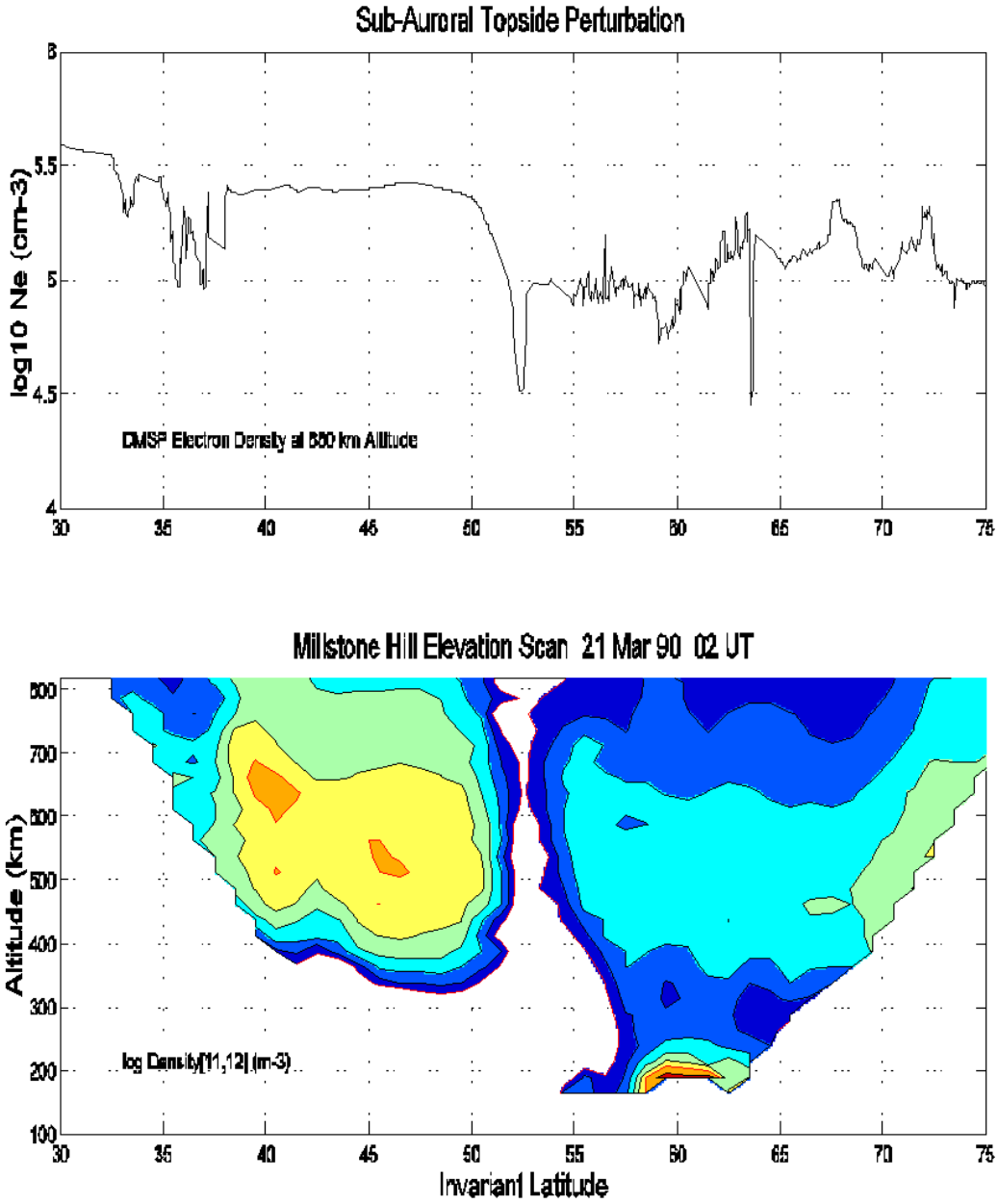

Figure 5-1: Millstone Hill ISR Elevation Scan (bottom) Identified a Deep Mid-Latitude Ionospheric Trough Near 53 deg Invariant Latitude at 21 MLT (02 UT) During the March 21, 1990 Storm. A pronounced low-latitude topside ionosphere density depletion was observed by both the radar and by the DMSP F-9 satellite more than 15° equatorward of the normal mid-latitude trough during the March, 1990 event. The destabilizing effects of a penetrating electric field were discussed by Foster et al. [1990].

5.1.2 Storm Positive Phase

Ionospheric storms are large global disturbances of the *F*-region electron density in response to geomagnetic storms. The terms positive and negative storm phase are used to describe large-scale increases (early storm phase) and decreases (late storm phase) in the ionospheric electron density regularly observed during geomagnetic storms. During the negative phase (usually beginning the second day of and event), the *F*-peak electron density in the mid-latitude ionosphere may be reduced by a factor of 2-5.

The magnetospheric energy input to the atmosphere at auroral latitudes is greatly increased during magnetic storms. Enhanced Joule heating at high latitudes reduces the normal poleward wind on the dayside and reinforces the regular equatorward wind on the nightside, creating a storm circulation that can transport air with increased molecular species to mid latitudes. As these neutral composition disturbances move to lower latitudes, the associated enhanced ion loss rate can result in significant decreases in the *F*-region electron density.

Large increases in the mid-latitude ionospheric *F*-region electron density and total electron content (TEC) are often observed in local dusk sector during magnetic storms. It was proposed in early investigations [Evans, 1973; Mendillo, 1973] that an uplifting of the F-layer by an eastward electric field and convergence in the east-west direction might be responsible for such dusk effect enhancements. Foster [1993] examined Millstone Hill incoherent scatter radar observations and suggested that the dusk effect during disturbed conditions can be associated with sunward convection (towards noon and poleward at ionospheric heights) of high-density plasma originating from lower latitudes. The resultant density enhancements at the equatorward edge of the dusk-sector ionospheric trough are termed storm-enhanced density (SED). The study of Buonsanto [1995] showed that both wind-induced uplift and advection from lower latitudes can be involved in the dusk-sector stormtime enhancements.

Huang et al [2005a] give a detailed review of the range of mechanisms which can give rise to positive phase mid and low-latitude density increases during storms. Foster et al. [2005a] and Yin et al., 2004] suggest that storm time TEC enhancements may corotate with the Earth once they are formed. However, some features observed by Huang et al [2005a] cannot be fully explained by a corotation process. During a particular storm being investigated, they noted that no positive phase enhancement occurred over the daytime US continent, although a pronounced enhancement was observed at east-coast longitudes. The driving eastward electric field lasted for many hours during the event and should have been effective in uplifting the ionosphere and continuously generating a dayside positive storm signature. The presence of positive phase in the Atlantic sector and its non-existence over the US continent implied that the associated processes might be more effective in generating a positive storm enhancement in the Atlantic sector. Similar observations of the longitudinal localization of stormtime electric field effects (with largest enhancement in the Atlantic sector) had been noted by Foster and Rich [1998]. Most recently, Foster and Coster [2006] investigated such a discrete localized enhancements of total electron content at dusk in the American sector. They found that the repeatability and geographic localization of this feature indicate a longitudinal specificity for the process associated with its formation.

5.1.3 Penetration Electric Fields

Under disturbed conditions the interplanetary electric field (IEF) can penetrate to the low- latitude ionosphere. Penetration of the IEF to the middle- and low-latitude ionosphere has been extensively studied through geomagnetic field perturbations and using the incoherent scatter radar chain at ~75° W geographic longitude which includes the Sondrestrom, Millstone Hill, Arecibo, and Jicamarca radars [Kelley et al., 1979; Gonzales et al., 1978; Buonsanto et al., 1999]. A shielding/overshielding mechanism has been proposed to explain how the interplanetary/magnetospheric electric field can, or cannot penetrate to the low-latitude ionosphere [Jaggi and Wolf, 1973]. The shielding of the inner magnetosphere/ionosphere from the high-latitude disturbance electric fields involves the magnetospheric ring current and current systems which interconnect the magnetosphere and ionosphere near the PBL. Penetration electric fields can uplift and perturb the low and mid-latitude ionosphere (cf. Figure 5-1) and lead to plasma redistribution (see Section 5.1.6 below) which circulates low-latitude ionospheric plasma to mid, high, and polar latitudes during strong storms(e.g. Foster et al [2005a;b]; Mannucci et al. [2005]).

Whereas a time scale for shielding/overshielding effects of ~30 min is usual, recent work by Huang et al. [2005b;2006] finds that when the IMF turns southward and remains stably southward for several hours, the dayside eastward ionospheric electric field at low latitudes is enhanced throughout the entire interval

of southward IMF. A similar enhancement of the westward ionospheric electric field is observed when the IMF turns northward and remains stably northward. That study indicates that the ionospheric electric field at low latitudes can be continuously enhanced over many hours during the main phase of magnetic storms. In sunlight, an eastward electric field will cause increases in the mid-latitude ionospheric electron density by moving the plasma particles upward into regions of decreased recombination loss, while additional ionization is produced at lower altitude. Decreases in the equatorial ionospheric electron density occur as the low-latitude plasma is redistributed poleward by an enhanced fountain effect.

5.1.4 Storm Enhanced Density (SED)

The overall stormtime enhancement of TEC at low and mid latitudes consists of two parts (cf. Figure 5-2 which presents a schematic representation.). First is the increase of TEC seen at and poleward of the crests of the equatorial anomalies associated with plasma uplift and redistribution from low to mid latitudes under the influence of the penetration electric field. This occurs inside the plasmasphere boundary layer and serves as an enhanced source population for the plumes of storm enhanced density (SED) [Foster, 1993] that are eroded from the lower-latitude ionosphere/ plasmasphere by disturbance electric fields.

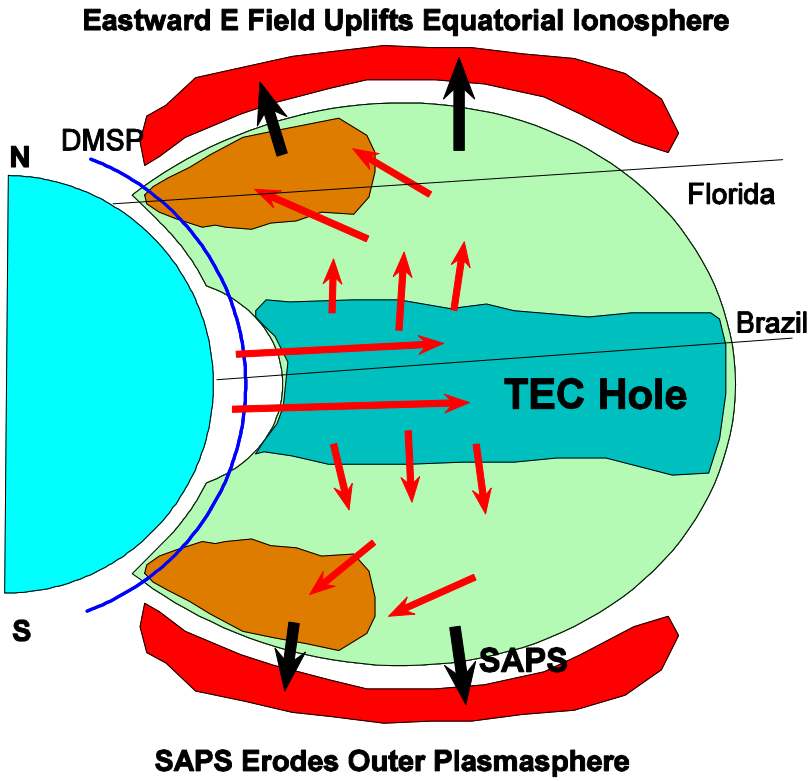

Figure 5-2: The Dual Effects of Disturbance Electric Fields are Presented Schematically. Undershielded penetration electric fields uplift the equatorial ionosphere redistributing equatorial plasma poleward, while SAPS electric fields strip away the enhanced outer layers of the plasmasphere.

Enhanced cold plasma total electron content (TEC) is observed at mid latitudes, inside the PBL, in the post-noon beginning in the early phases of the storms, while Dst is falling (e.g. Buonsanto and Foster, 1993; Tsurutani et al., 2004). At the poleward extent of this region, elevated TEC is carried sunward and poleward in plumes of storm enhanced density (SED [Foster, 1993]). Figure 5-3 presents Millstone Hill incoherent scatter radar (ISR) elevation-scan observations of the latitude/altitude structure observed across

such a plume of storm enhanced density. F-region TEC (calculated for the ISR density-altitude profiles) approached 100 TECu within the SED plume and sharp TEC gradients (~50 TECu/deg latitude) were observed bordering the SED feature.

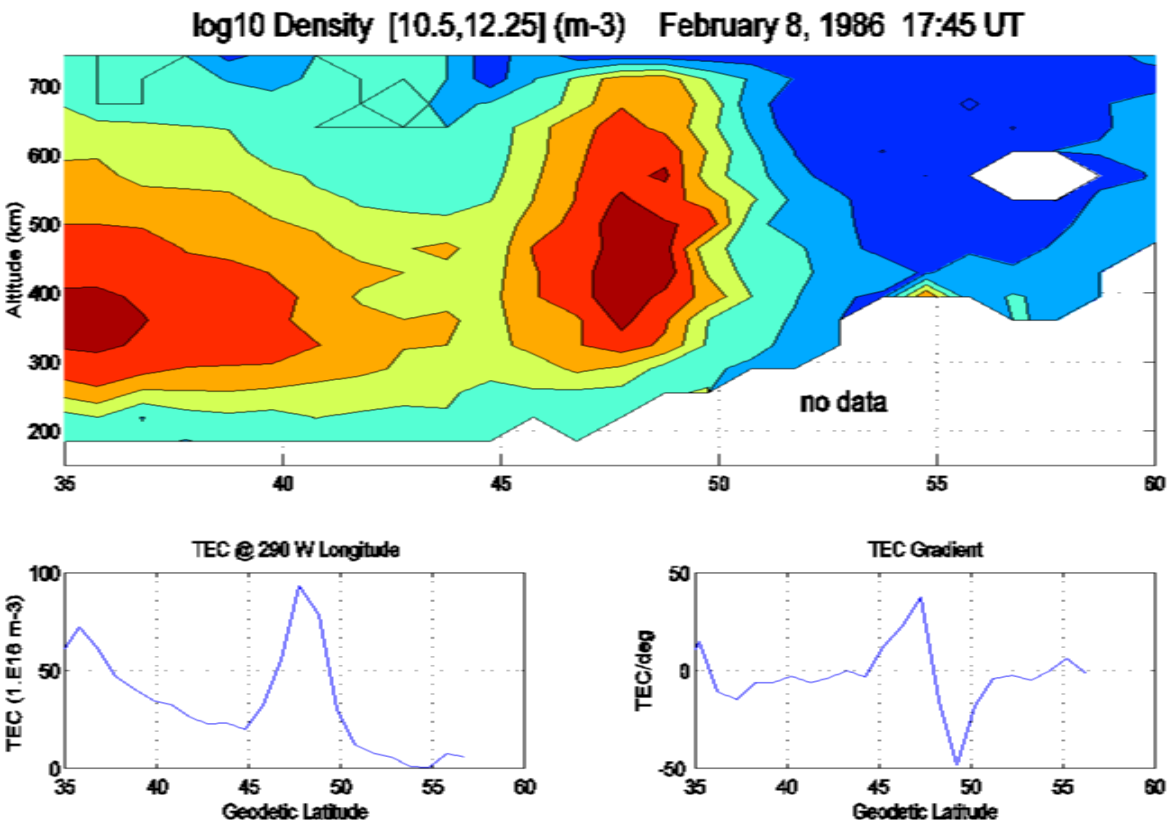

Figure 5-3: Iso-Density Contours Observed by the Millstone Hill Radar Scanning N-S Across a Region of Strong SED (Storm-Enhanced Density) Near Local Noon are Presented as a Function of Geodetic Latitude (Invariant Latitude = Geodetic Latitude + 11°). F-region TEC and TEC gradient across the region are derived from the radar elevation scan and are shown in the bottom panels. TEC near 48° N geodetic latitude is ~100 TEC units and the latitude gradient in TEC associated with the region of SED near 45° latitude was ~50 TEC/deg.

In the dusk sector where they are formed, the SED plumes are associated with the stripping away of the outer layers of the plasmasphere/ionosphere by the disturbance electric field. Storm enhanced density occurs when low-latitude cold plasma is transported sunward (towards noon) at the inner edge of the convection electric field. This process produces narrow plasmasphere drainage plumes (Sandel et al., 2001) of cold plasma which extend along magnetic field lines between the plasmasphere and the ionosphere (e.g. Chi et al., 2005). Figure 5-4 depicts the location and spatial extent of the SED features during a typical event. Ground-based GPS-TEC observations depict the SED plume spanning the North American continent from a source region over the US east coast. Mapping this feature into the magnetospheric equatorial plane (Figure 5-4 right) shows the relationship of the ionospheric SED plume to stormtime plasmasphere erosion. Combining ground (GPS TEC) and space-based (IMAGE EUV) thermal plasma imaging techniques, Foster et al. [2002] demonstrated that this ionospheric SED plume mapped into the low-altitude signature of a plasmaspheric drainage plume viewed from space. Cold plasma within the plume at both ionospheric and magnetospheric heights is streaming sunward towards the cusp (at low altitudes) and the dayside magnetopause (at high altitudes). Foster et al. [2004a] used direct radar observations of the sunward **ExB** plasma convection to quantify the flux of ions carried by the

SED plume to the noontime F-region in the vicinity of the cusp. Foster et al. [2005b] report observations which indicate that this streaming low-latitude plasma is also a source for the tongues of ionization which appear at polar latitudes during disturbed conditions (see Section 5.1.7 below).

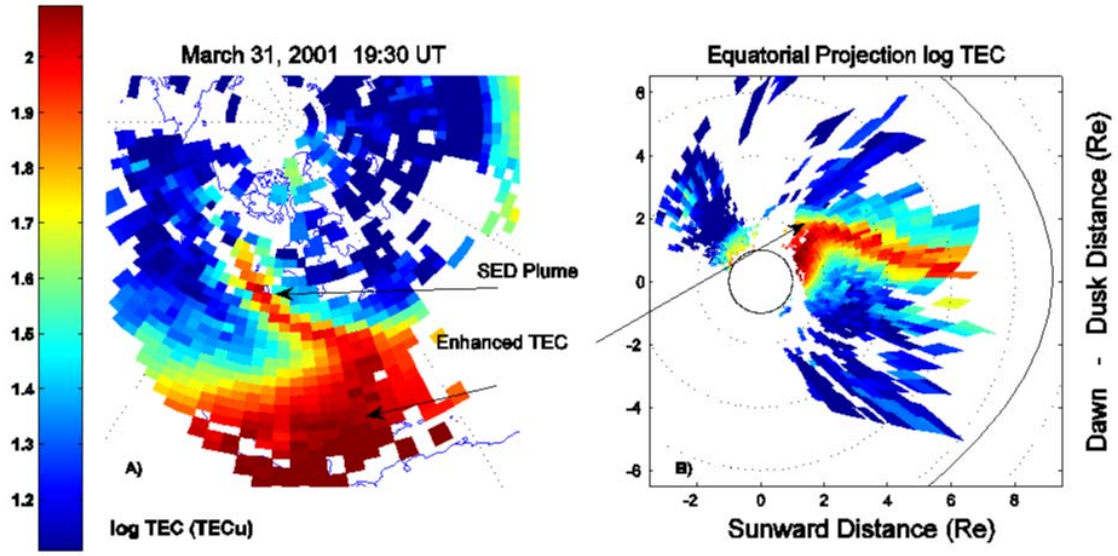

Figure 5-4: (A) A Region of Enhanced GPS TEC was Observed at the Base of the Plume of Storm Enhanced Density Seen over North America During the March 31, 2001 Event. (B) Projecting the GPS TEC Observations into the Magnetospheric Equatorial Plane Using Tysganenko Mapping (with the sun at the right), Indicates that the Enhancement at the Base of the Plume is Field Lines Threading the Outer Plasmasphere.

5.1.5 Sub-Auroral Polarization Stream (SAPS)

Electric fields are of prime importance in the formation and transport of stormtime ionospheric disturbances. The sub-auroral polarization stream (SAPS) electric field [Foster and Burke, 2002] refers to the region of enhanced poleward electric field which forms equatorward of electron precipitation in the dusk to midnight sector in disturbed conditions. SAPS is a magnetospheric electric field, whose characteristics are controlled by ionospheric conductance. SAPS forms as pressure gradients at the inner edge of the disturbance-enhanced ring current drive Region 2 field-aligned currents into the evening-sector ionosphere. Large poleward-directed electric fields are set up to drive closure currents across the low-conductivity region equatorward of the auroral electron precipitation. Observations of this phenomenon at ionospheric altitudes [Yeh et al., 1991; Foster and Burke, 2002; Foster and Vo, 2002] describe the occurrence characteristics and persistence of the SAPS electric field whose latitude extent spans the region between the electron plasma sheet and the outer reaches of the plasmasphere (the PBL). Significant magnetospheric effects occur as the SAPS electric field maps along field lines and is observed at higher altitudes (e.g. Rowland and Wygant [1998]).

Foster et al [2006] used magnetic field-aligned mapping between the ionosphere and the magnetosphere to intercompare ground-based observations of storm enhanced density (SED), and plasmasphere drainage plumes imaged from space by the IMAGE EUV imager, with the enhanced inner-magnetosphere/ ionosphere SAPS electric field which develops during large storms. They found that the inner edge of the SAPS electric field overlaps the erosion plume and that plume material is carried sunward in the SAPS overlap region. The two phenomena, SED in the ionosphere and the erosion plume at magnetospheric heights, define a common trajectory for sunward-propagating cold plasma fluxes in the midnight-dusk-postnoon sector. The SAPS channel at ionospheric heights and its projection into the equatorial plane

serve to define the sharp outer boundary of the erosion plume. The SAPS electric field abuts and overlaps both the plasmasphere boundary layer and the plasmasphere erosion plume from pre-midnight through post-noon local times.

5.1.6 Plasma Redistribution

While some ionospheric disturbances during geomagnetic storms are local effects, recent studies using ground-based ionospheric observations have found that the equatorial, mid-latitude, auroral, and polar regions are coupled by processes which redistribute cold ionospheric and plasmaspheric material throughout the interconnected system. In particular, cold plasma enhancements, created at equatorial and mid-latitudes by storm time processes, are carried poleward by disturbance electric fields through mid latitudes to the strong ion outflow regions located at cusp, auroral, and polar cap latitudes. Due to the widespread nature of this system, an inherently global perspective is necessary to describe adequately the key elements in the overall physical picture.

Foster et al. [2005a] discussed a localized enhancement of total electron content (TEC) seen at the base of the erosion plume. Ground based observations with GPS TEC and incoherent scatter radar, and in situ DMSP measurements in the topside ionosphere, suggested that this enhanced TEC results from a poleward redistribution of post-noon sector low latitude ionospheric plasma during the early stages of a strong geomagnetic disturbance. Down-looking IMAGE FUV ionospheric observations [Immel et al., 2005] showed that the TEC enhancement seen from the ground was associated with a localized enhancement somewhat poleward of the equatorial anomaly peak. The enhanced features, seen both from the ground and from space, corotate (approximately) with the Earth once they are formed. These effects are especially pronounced over the Americas, and Foster et al [2005a] suggested that this results from a strengthening of the equatorial ion fountain due to undershielded (penetrating) electric fields in the vicinity of the South Atlantic magnetic anomaly.

Vlasov et al. [2003] considered both observations and model simulations of such a mid- latitude TEC enhancement during the July 15, 2000 storm and concluded that both sunward and poleward convection of the low latitude plasma must be taken into account in addressing such events. They found that the early-event increase of TEC on the dayside could be explained by a small enhancement of the equatorial anomaly combined with the effects of either an equatorward wind or an eastward electric field. However, the large increase in TEC near dusk at mid latitudes indicated both a large enhancement of the equatorial ion fountain (by some combination of dynamo and penetration eastward electric fields) and the effects of a poleward electric field, leading to a sunward and poleward redistribution of plasma. An earlier study by Buonsanto and Foster [1993] examined Arecibo radar observations during a similar event and noted that the high density plasma in the enhanced-TEC region moved approximately horizontally, with a strong poleward and westward component to its motion. For the July, 2000 and similar events, Foster et al. [2005a] described the simultaneous increase in TEC over Florida with a complementary decrease in TEC near the magnetic equator (Brazil) at the edge of the south Atlantic magnetic anomaly (SAA). Further observations and discussion of the redistribution of low-latitude plasma during the July 15, 2000 event have been presented by Yin et al. [2004] and Kelley et al. [2004].

Figure 5-5 presents combined GPS TEC maps of the stormtime perturbations over the Americas and DMSP in-situ observations of topside (~830 km altitude) density during the May 30, 2003 event. A deep electron density/TEC depletion at magnetic equatorial latitudes over Brazil formed near sunset, as in the July, 2000 event described above. Simultaneously, TEC increased dramatically over the northern Caribbean, near the coast of Florida. The SED erosion plume formed at the poleward extent of the mid-latitude TEC enhancement. This progression of events, with the same local time and UT characteristics and spatial localization occurred for a number of the large storm events in the most recent solar cycle maximum. The study of Foster and Coster [2006] found that near sunset during the expansion phase of large geomagnetic storms, a localized enhancement of total electron content (TEC) takes place in

American longitude sector off the coast of Florida and in its magnetically conjugate region. These enhancements lie poleward of the crests of the equatorial ionization anomaly and on field lines mapping into the plasmasphere boundary layer. They concluded that horizontal plasma transport associated with disturbance electric fields is the dominant mechanism for producing the conjugate TEC enhancements. They found these effects to be repeatable in space and time and to create a conjugate intensification of TEC in the outer plasmasphere which serves as a corotating source for the erosion plumes of storm enhanced density which are observed during such events. Figure 5-6, taken from that study, depicts the synchronous decrease in equatorial TEC near the sunset terminator, and simultaneous enhancement of TEC near the PBL at magnetic conjugate points.

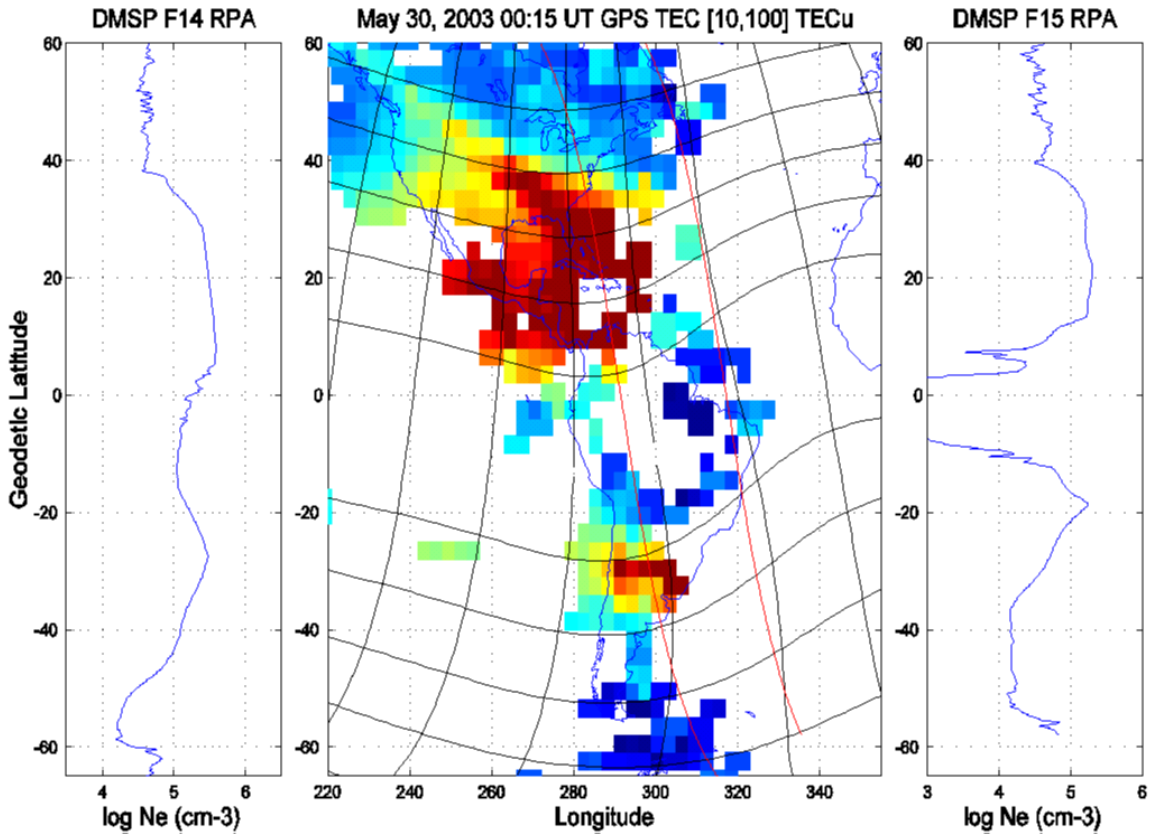

Figure 5-5: Simultaneous GPS TEC and DMSP In Situ Plasma Density Observations Illustrate the Effects of Plasma-Redistribution Shown Schematically in Figure 5-2. The orbital tracks for DMSP F14 (left) and F15 (right) are shown in red. A deep total content hole is formed at the magnetic equator over eastern Brazil while greatly enhanced plasma is relocated to the vicinity of the Florida coast.

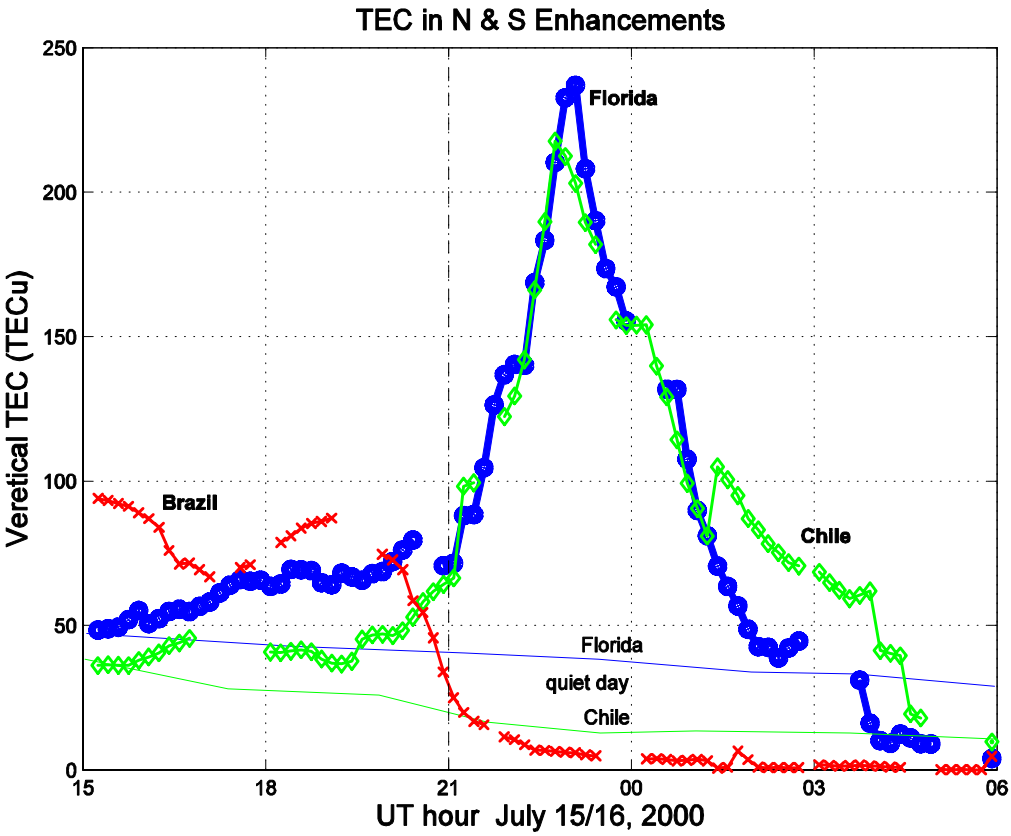

Figure 5-6: The Temporal Variation of TEC in the N-S Conjugate Enhancements During the July 2000 Event Indicates a Close Similarity. TEC over Florida and Chile increase sharply as the equatorial TEC over Brazil drops during storm intensification. Conjugate enhancements of ~ 200 TECu above the quiet-day background (July 13/14) were observed.

5.1.7 Polar Tongue of Ionization

The global character of large-scale ionospheric disturbances during the main phase of a major geomagnetic storm is emphasized by the findings of Foster et al. [2005b]. For the large geomagnetic storm on November 20, 2003, they examined data from the high-latitude incoherent scatter radars at Millstone Hill, Sondrestrom, and EISCAT Tromso, with SuperDARN HF radar observations of the high-latitude convection pattern and DMSP observations of in situ plasma parameters in the topside ionosphere. These were combined with north-hemisphere polar maps of stormtime plumes of enhanced total electron content (TEC) derived from a network of GPS receivers. Figure 5-7, taken from that study, shows the polar tongue of ionization (TOI) to be a continuous stream of dense cold plasma entrained in the global convection pattern. The dayside source of the TOI is the plume of storm enhanced density (SED) transported from low latitudes in the post-noon sector by the sub-auroral disturbance electric field. Convection carries this material through the dayside cusp and across the polar cap to the nightside where the auroral F region is significantly enhanced by the SED material.

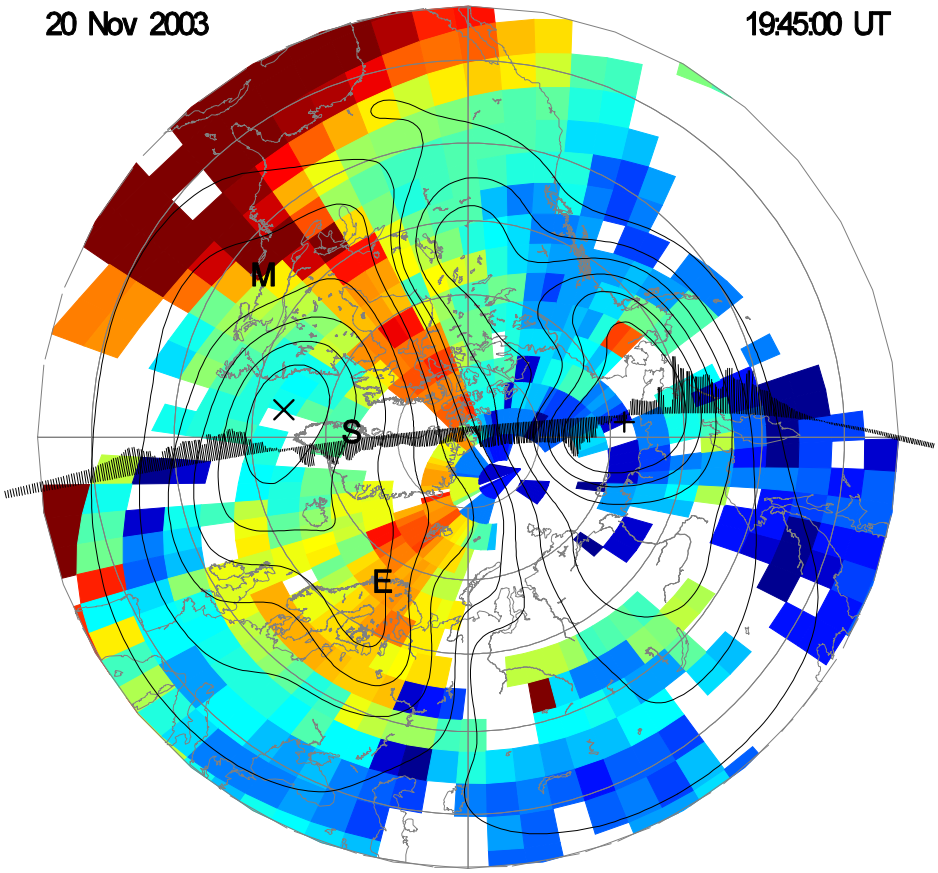

Figure 5-7: Combined GPS TEC and Convection Observations are Displayed in Polar Projection (mag lat/MLT coordinates; 10-deg latitude circles; with noon at the top).

The positions of the three IS radars are indicated (M, S, E). Data are shown for 19:45 UT when the SED/ TOI plume is seen to extend continuously from its low-latitude source in the pre-noon sector, through the dayside cusp and across the polar cap to the midnight sector over the EISCAT facility (E). Vertical TEC observations binned by lat/long at 350 km altitude are displayed with the simultaneous, independent convection pattern derived from combined SuperDARN and DMSP observations. Ion drift meter cross-track velocity data from a trans-polar cap DMSP pass are shown, indicating anti- sunward convection above 60 deg latitude spanning the polar region.

5.1.8 Gradients

Such severe ionospheric perturbations lead to significant space weather effects as steep density gradients and associated regions of ionospheric irregularities form along their edges. Vo and Foster [2001] performed a statistical analysis of 15 years of Millstone Hill ISR observations for the occurrence of density-gradient regions. Density and TEC gradients were observed at sub-auroral and mid latitudes associated with the ionospheric trough and with advecting density enhancements during geomagnetically disturbed conditions. Latitude gradients in TEC associated with the equatorward wall of the trough in the dusk sector were approximately 10 TEC units/degree of latitude for solar max conditions, while gradients associated with regions of greatly-enhanced TEC (storm enhanced density, SED) were observed as great as ~50 TEC units/deg.

Foster and Rideout [2005] used observations from the array of North American GPS receivers to examine the formation and severity of mid-latitude enhancements and steep gradients in total electron content

(TEC) during the October 30-31, 2003 superstorm. A large (~10x) enhancement in dayside TEC was observed over the US mainland during these events as Dst decreased sharply and strong SAPS electric fields eroded the outer reaches of the post-noon plasmasphere boundary layer (PBL) forming poleward-streaming plumes of storm enhanced density. Figure 5-8 shows TEC increased to >250 TECu over the SW USA during the event. TEC gradients across the PBL over the central US (cf. Figure 5-9) exceeded 60 TECu per deg latitude. Basu et al. [2005] identified simultaneous occurrence of scintillations at mid-latitude and in the equatorial region during that event. Mitchell et al. [2005] describe the occurrence of polar-latitude scintillations associated high- gradient regions as the enhanced-TEC material streamed back over the northern polar cap during the October, 2003 event. While intense, the features observed during that superstorm are qualitatively similar to those seen in lesser events. Communications and navigation systems relying on trans-ionospheric propagation must be able to compensate for the effects of such sharp gradients in total electron content in the North American sector.

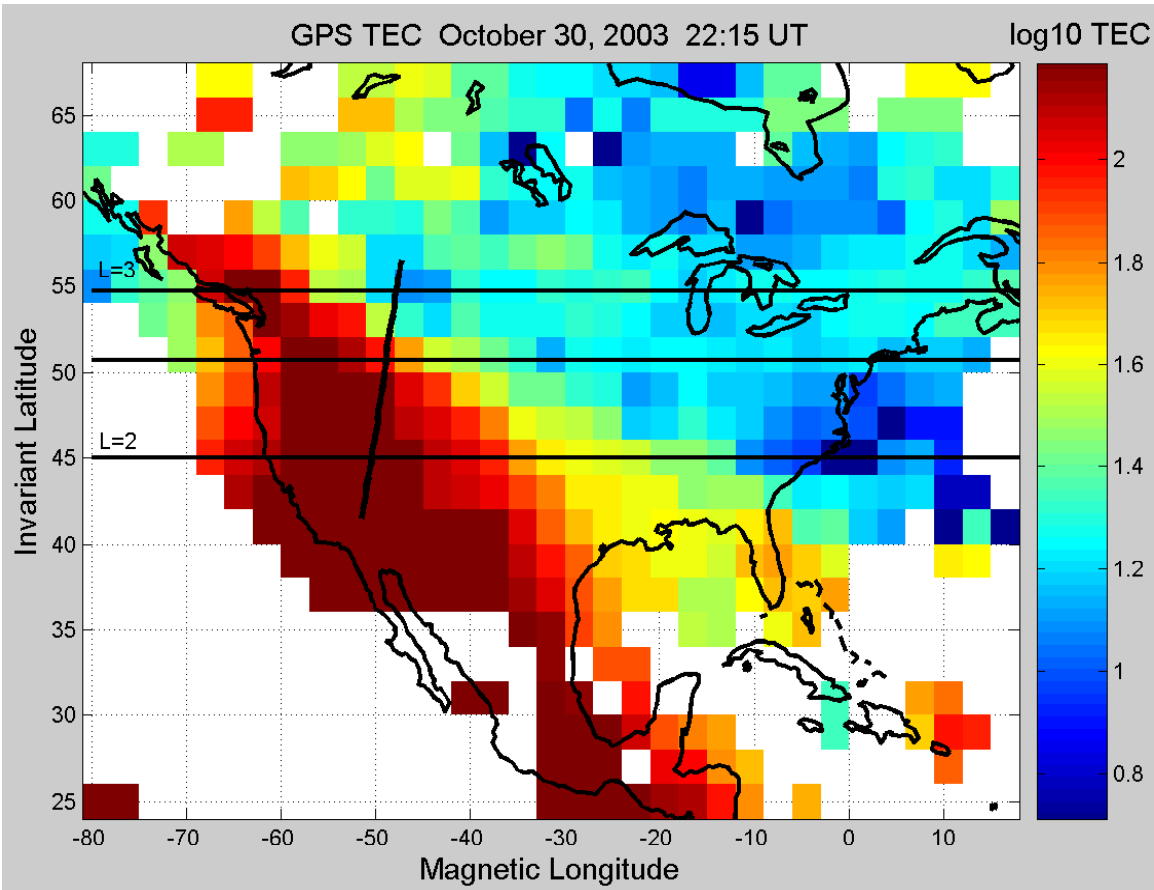

Figure 5-8: TEC Derived from an Array of ~450 GPS Receivers is Displayed in Magnetic Coordinates as a Major Ionospheric Disturbance Forms over the US Mainland During the October 30, 2003 Superstorm. The enhancements of TEC over the US mainland at 22:15 UT is displayed. The SED plume extends into the Pacific NW, TEC exceeds 250 TECu over the US southwest equatorward of L = 2 and the steep gradient region associated with the PBL (cf Figure 5-9).

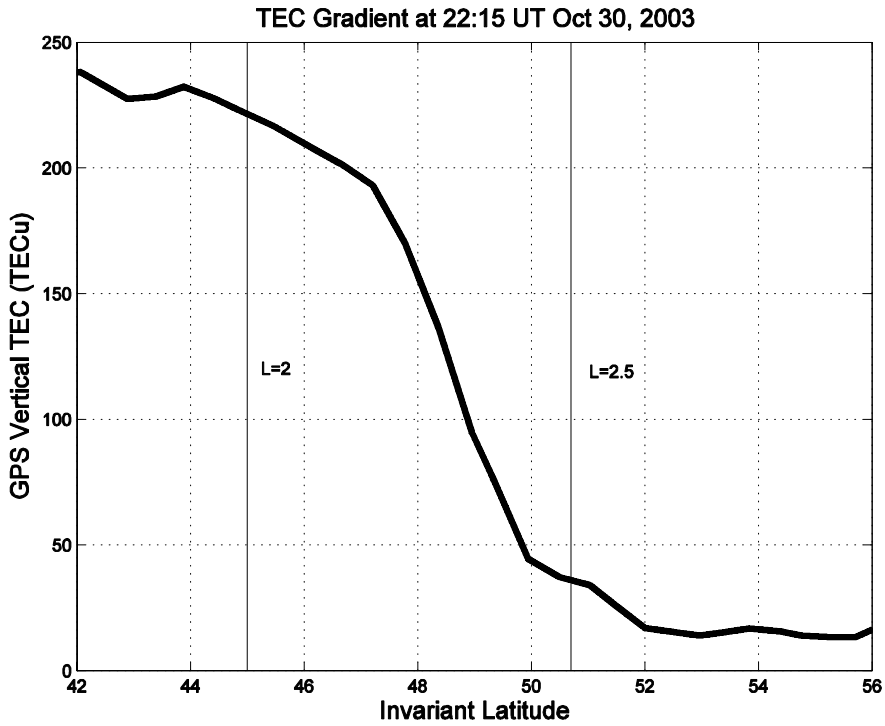

Figure 5-9: The TEC Gradient Across the Poleward Edge of the SED Plume Shown in Figure 5-8 is Presented. TEC in excess of 230 TECu is observed equatorward of the PBL gradients. The steep decrease in TEC with latitude across the PBL extends over ~ 3 deg of latitude with a characteristic gradient of -60 TECu per deg of latitude.

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5.2 IONOSPHERIC PROCESSES OF IMPORTANCE TO SEVERE SPACE WEATHER: A REVIEW[1]

(Mike Kelley, Cornell University)

5.2.1 Introduction

Fifty years into the Space Age, technical societies now are deeply committed to utilizing space. For the military, space is the ultimate high ground from which a variety of surveillance, communications, and navigation systems operate. For industry, the communications and positional/navigational opportunities

[1] Adapted from *Kelley et al*. [2006]. Reproduced with permission of the American Geophysical Union.

for using space-based systems are virtually unlimited. However, when plasma between the satellite and the receiver is turbulent, satellite signals scintillate, similar to the twinkling of starlight as it traverses the turbulent atmosphere, and communications and navigation systems can be seriously affected. Additionally, when steep gradients in the plasma content occur, navigation solutions are very difficult to achieve.

The natural assumption is that these problems maximize in the auroral zone where the energy input from the solar wind is at its peak. However, the most severe ionospheric weather occurs within ±20º of the geomagnetic equator where stored gravitational energy sometimes is released after sunset [1]. Depending on the condition of the equatorial ionosphere at that time, a null or modest event may occur or, more problematically, vast convective plumes of turbulent plasma can erupt, devastating communications from HF to GHz frequencies [2,3]. The plumes rise rapidly in a manner analogous to thunderstorm convection and, due to their electrical properties, are transmitted rapidly for vast distances north and south along the earth's magnetic field. Termed Convective Ionospheric Storms (CIS) to emphasize the analogy of the ionospheric process to thunderstorms, these plumes are caught up in the high-speed eastward plasma drift and often last until well after midnight, meaning that a single structure can affect a very large area of the earth in its lifetime [4].

Another surprising and more recent result is that very sharp horizontal gradients can develop at middle latitudes at night and sometimes even in the daytime [5]. Most of the ones observed to date developed over the Caribbean and erupted over CONUS, but they have also been seen in the European sector. These gradients can seriously affect systems such as the Wide Area Augmentation System (WAAS), which is based on GPS [6].

The physics behind these two phenomena are discussed next.

5.2.2 Convective Ionospheric Storms

The morphology of the equatorial ionosphere is quite different from that at other latitudes because the magnetic field is nearly parallel to the earth's surface. During the daytime, the plasma drifts upward under the influence of an eastward-directed electric field. The uplifted plasma then moves along the magnetic field in response to gravity and pressure-gradient forces, producing a fountain effect in which plasma moves upward close to the equator and then slides down the field line on the north and south sides. Two ionization maxima are formed on either side of the equator – the so-called equatorial Appleton anomalies, which create particularly dense plasma, ripe for disturbing satellite signals. The two crests are approximately ±15º from the magnetic equator [2].

The equatorial electric field is westward (eastward) during the night (day) and the plasma drifts downward (upward) in a diurnal pattern. However, just before this electric field reversal takes place, the upward drift increases suddenly, driving the main dense ionosphere, called the F layer, to high altitudes. In addition, production of ions by sunlight ceases after sunset and the conductivity of the lower ionosphere decreases dramatically, reducing its capability for "shorting out" the electrical potential. This large upward drift, combined with gravity, a decreasing neutral atmospheric density, and a vertical plasma-density gradient in the bottomside of the F layer, creates an unstable configuration. If the ionosphere is low in altitude on a given night, the event usually fades out. But if the post-sunset, upward-surging plasma layer is high enough (at or above 350 km), the stored energy can be released explosively, forming the low density, highly turbulent features that surge upward [7].

Like a thunderstorm, CIS releases gravitational energy stored in the height of the nighttime ionosphere, making altitude an important factor in the strength of the CIS – the higher the post-sunset ionosphere, the more gravitational potential it accumulates and the more likely the storm will be severe. The events usually die out by midnight but occasionally regenerate later, an occurrence that is associated with high geomagnetic activity [2].

During a severe event, the electric fields generated in the low density regions drive plumes of turbulent, low density plasma upward to heights of over 2000 km at the equator. Due to the high conductivity of plasma parallel to the magnetic field, these equatorial structures connect electrically to the plasma over good viewing sites such as Hawaii and Cerro Tololo, Chile to form mirroring features by CCD cameras [8]. In this manner, airglow emissions are used to trace the development of the event over vast distances from these sites and similar locations around the world. These features are now detectable from on-orbit systems such as the one flown on the TIMED satellite, a development that eventually could lead to a space weather observatory at geosynchronous orbit [9].

In the near future, a joint project between the Air Force Research Laboratory and the DOD Space Test Program, called the Communications/Navigation Outage Forecasting System (C/NOFS), has the mission goal of predicting CIS and soon will provide detailed, three-dimensional images of these storms [3]. To accomplish this task, the project will gather the most complete set of in situ and ground-based data ever attempted. These data sets include on-orbit and/or ground-based measurements of electric and magnetic fields, neutral winds, photon emissions, Doppler radar images, GPS and lower frequency observations of scintillations, GPS occultation observations, tomographic maps of the ionosphere, plasma density and its fluctuations, and total electron content. These data will be assimilated into predictive physics-based models with the goal of predicting scintillation for Air Force systems [3].

However, although space weather scientists have a solid grasp of the underlying physics of CIS, understanding the day-to-day variability of this phenomenon has proven difficult. The major challenge is to understand the physical processes leading to the formation of plasma irregularities in the ionosphere and to identify the mechanisms triggering or inhibiting plasma instability. Meeting this challenge requires accurate modeling of the parameters that are part of the instability growth rate. The electric field, whether caused by neutral wind (the dynamo electric field) or by magnetospheric phenomena, is probably the most important of these parameters [7]. Since the height of the ionosphere immediately after sunset is a major factor in determining whether or not CIS will occur, knowing the eastward electric field component driving the upward plasma motion is vital to our predictive capability. The electric field measurements obtained by the C/NOFS satellite will provide crucial information on this key parameter.

Other, more vexing issues involve lower atmospheric tides and waves that create initial disturbances [10] and the electrical conductivity of the low latitude ionosphere in contact with the rising ionosphere at sunset [11], which may or may not short-circuit the electric fields. The collisional Kelvin-Helmholtz instability also can seed CIS [12]. The physics-based modeling of plasma bubbles – how they are born, how they evolve in time and space, and how they die – also needs considerable improvement.

5.2.3 Steep Mid-Latitude Gradients

The problems associated with mid-latitude gradients are also severe and were even more unexpected than those associated with CIS [6]. One source is the development of mesoscale Travelling Ionospheric Disturbances (TIDs), which draw energy from either neutral winds or solar wind-related penetrating electric fields [13,14]. The initial TIDs then deepen and, concurrently, one edge steepens to form sharp gradients while the other edge becomes turbulent. For example, one such event was associated with a 15 Total Electron Content (TEC) unit difference as measured by two separated receivers looking at the same puncture point in the ionosphere [15].

Other substantial mid-latitude events seem to be related to intense magnetic storms and are referred to as Storm-Enhanced Densities (SED) [5]. The origin of the very dense plasma seems to be the equatorial daytime ionosphere, which can create copious amounts of plasma under full sunlight that is then continuously pumped up into the equatorial fountain and expands over the middle latitudes. These regions also steepen and exhibit the highest TEC values ever recorded, about 200 TEC units. The storm seems to generate a variety of electrical changes related to the SED events [16]. First, penetrating electric fields of

solar wind origin reach the magnetic equator with an eastward zonal component as the region 1 currents (highest latitude field-aligned currents) intensify, causing the storm time fountain effect mentioned above [17]. Then penetrating meridional electric fields drive the anomaly plasma into the daytime region where it is caught up in the classic convection pattern, established by then deep into the plasmasphere. The plume of high TEC plasma eventually flows anti-sunward into the polar cap [5].

5.2.4 Other Topical Research Areas

Global Thermospheric Winds During Storms. Studies of neutral atmospheric changes due to high latitude heating and momentum transfer have not been as successful as expected over the years. Current thinking is that small scale structure in the electric field contributes as much Joule heating as the average field because the fluctuating component is comparable to the average [2]. With the recent deployment of the Advanced Modular Incoherent Scatter Radar (AMISR) in Alaska and the rocket projects aimed at understanding this problem, we should soon have a better understanding of this important coupling issue. The thermospheric circulation changes so drastically that the worldwide electric field distribution is also affected. This is called the disturbance dynamo and penetrates all the way to the magnetic equator [18]. Once there, this phenomenon can also affect CIS development.

Development of Physics-Based Assimilative Models. Today, space weather scientists are building assimilative physics-based models like those used in weather forecasting, but currently the models are starved for data. The meteorological community uses hundreds of balloon soundings, made twice daily around the world, in their assimilative models. The ever-growing numbers of GPS receiving stations on the ground and on orbiting spacecraft are beginning to provide ionospheric data similar in density to the balloon soundings in meteorology. For example, the two GPS signals transmitted on every satellite can be combined to measure the total number of electrons between the satellite and the receiver. TEC information will be one of the key data streams assimilated in the models now being developed for predicting severe space weather [19]. In addition, with the help of a U.S. firm, Taiwan has just developed and launched six satellites in a system called COSMIC that is capable of over 2500 observations of GPS satellite occultations each day and potentially will provide plasma density profiles as inputs for data assimilation models for Space Weather, models that are analogous to meteorological models [20].

Active Experiments in the Ionosphere. High power radiowave systems, such as the one at the heart of the High-frequency Active Auroral Research Program (HAARP), continue to be of great interest. For the first time, E-region emissions have been generated at both low and high latitudes [20,21]. The latter was so intense that it reached levels visible to the naked eye, although at this point still too small (<1 km) to be seen [23]. Bright spots have also been produced in the F region when the beam is nearly parallel to the magnetic field. Research into generating ELF and VLF signals continues. The latter is of interest for possible radiation belt control in an emergency. Space Shuttle burns, which create significant depletions in the ionosphere, are planned over ground sites in the near future [24]. A near kiloton explosion is also being considered to determine detectability using ionospheric sensors (W. Junior, personal communication, 2006).

5.2.5 Conclusions

Ionospheric research continues to be scientifically rich and has increasing relevance in using space for commercial and military systems. The exploratory era is nearing its end, although certainly new results are reported frequently, and a new emphasis on prediction is underway. The Communications/Navigation Outage Forecast System is a prime example and, with the associated satellite launch in 2008, will play a major role in testing these waters. Building partnerships with countries that are developing strong space science programs is crucial. Japan has played a major role in Solar X-ray studies; rocket, airglow, and radar studies at mid-latitudes; and, of course, the International Space Station. Taiwan has also been very active with the ROCSAT 1 ionospheric sensor package and the recent COSMIC constellation.

One crucial area that may require similar cooperation is solar wind monitoring. If NASA does not continue this crucial role, much of our progress in Space Weather may grind to a halt.

5.2.6 Acknowledgments

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5.2.7 References

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5.3 TECHNOLOGY AND SECURITY AFFECTED BY SPACE WEATHER

(Frank Jansen, 1A – First Applications on Space Weather Service Greifswald & Space Weather Observatory Greifswald, 17498 Greifswald – Groß Karrendorf, Germany)

Abstract

This report describes the background of space weather development in the U.S.A., in Europe (EU and ESA) and highlights of the developments (Introduction of this section). The second section contains an overview and conclusions for each known affected technology branch. The third section describes several security aspects, latest developments and conclusions related to space weather.

5.3.1 Introduction

Several space weather effects related to technology, important for society, have been reported in the last decade ([1] and [2]).

Specific funding of space weather observations started in the U.S.A. in the early 1990s. These activities were partially a result of the superstorm and power blackout on 13 March 1989, as well as several satellite failures and communication problems. The National Space Weather Program (NSWP, under www.nswp.gov) started in 1994 instigated by several U.S. government agencies to guard against space weather effects. The overall goal of the NSWP is to achieve an active, synergistic, interagency system to deliver timely, accurate and reliable space weather warnings, observations, specifications and forecast. The following U.S. organizations contribute to NSWP: NSF, NASA, DoD, DoC, DoE, DoI and DoT. The second edition of the NSWP implementation plan of July 2000 describes in detail the direction for research, operations, education, training and program management to achieve the goals of NSWP until the end of the first decade of the 21st century.

In Europe space weather activities started in the second half of the 1990s. The first workshop on space weather was organized by ESA in 1998 [3]. It had sessions on effects and users, physical processes, models and data. Various worldwide space weather initiatives resulted from deliberations and discussions. There was general support for the idea of a European Space Weather Program (ESWP). Two parallel ESA space weather feasibility studies were carried out between 1999 and 2001 by the Alcatel Space Industry (France) and Rutherford Appleton Laboratories (RAL, UK) consortia.

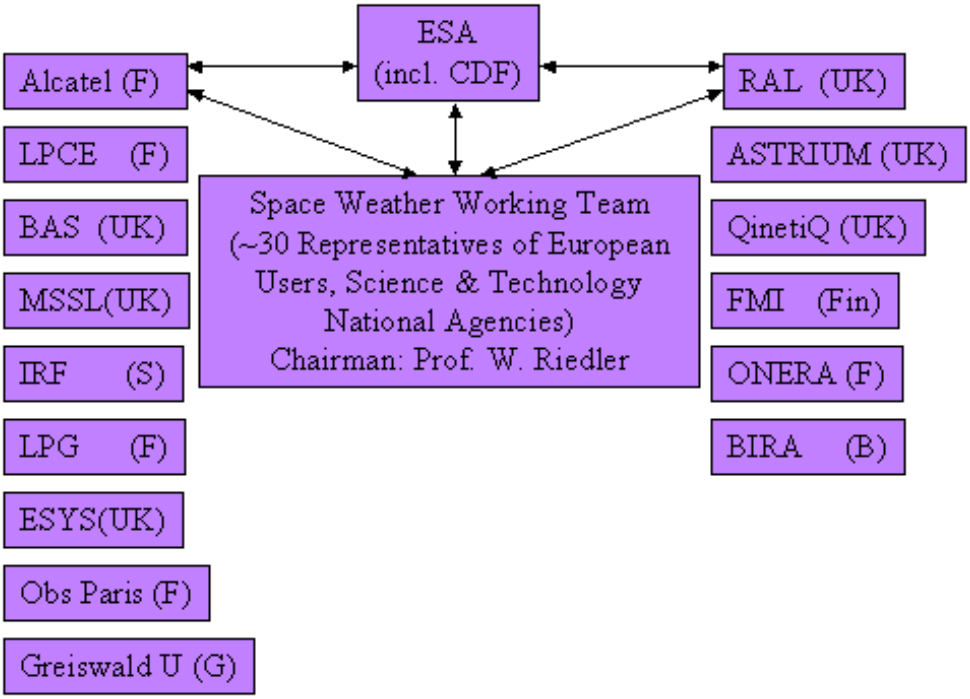

Figure 5-10: Main Bodies of Early Space Weather Activity in Europe: ESA, members of the Alcatel and RAL teams, Space Weather Working Team (SWWT) and ESA's Concurrent Design Facility (CDF).

The studies included for example:

1) The benefits, detailed rationale and details of an ESWP, including space and ground segment and prototyping of services;

2) The definition of structures that must be implemented by ESA and its member states; and
3) A draft programme, cost and risks.

The available ground-based and space-based instruments in Europe and the necessary capabilities for information about the Sun, interplanetary space, the magnetosphere, the ionosphere and the thermosphere were reviewed. For example, the status of ionospheric tools such as SuperDARN coherent radars, ionosondes, incoherent scatter radars were judged as in research status, but positional receivers were seen to be operational for GPS applications. In addition a cosmic ray muon telescope – required in the study of the Alcatel team – for the European region was also proposed to forecast the onset of disturbances in the magnetosphere/ionosphere. MuSTAnG (Muon Spaceweather Telescope for Anisotropies at Greifswald) was submitted for funding by ESA and DLR [4] and constructed from 2005 to 2006. It is currently in a test phase and will measure in real time the propagation of interplanetary Coronal Mass Ejections (CME) and forecast their arrival time at Earth.

Figure 5-11 shows the first European space weather telescope MuSTAnG (Muon Spaceweather Telescope for Anisotropy at Greifswald) which will assist in forecasting space weather storms.

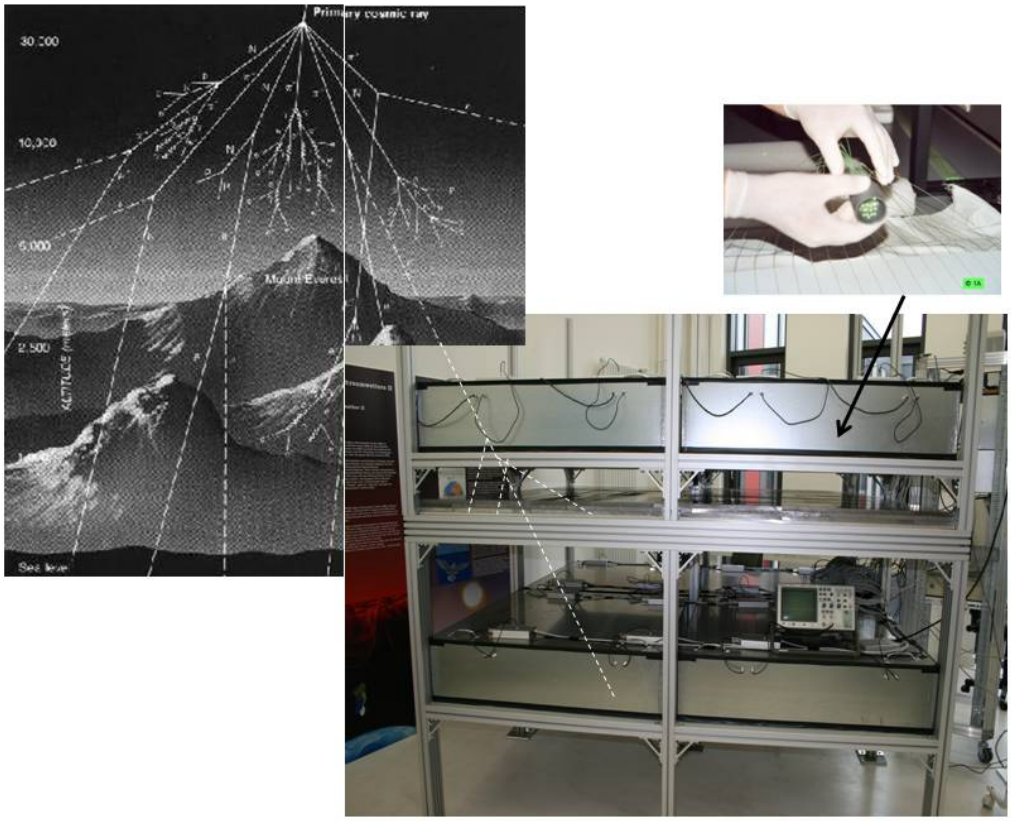

Figure 5-11: The Muon Space Weather Telescope for Anisotropy at Greifswald (MuSTAnG).

White lines signify cosmic rays in the Earth atmosphere and the MuSTanG telescope. Only muons reach the upper and lower detector layer. Other particles are stopped in a lead layer. Muons create flashes of green light in the Mustang telescope scintillator plates. The plates and fibres are mounted inside light-tight metal boxes (image: F. Jansen, 1A).

For the space-based segment an entire fleet of spacecraft and satellites including instrumentation, orbits and communication links are proposed finally by the two study consortia Alcatel and RAL to ESA.

Documents about space and ground segment, space weather effects and parameters, user requirements and market analysis as well as about the rationale and recommendations for the ESWP are available online at: http://esa-spaceweather.net/spweather/esa_initiatives/spweatherstudies/public_doc.html. In addition, the Space Weather Working Team (SWWT) was created, with about 30 European experts in a variety of both scientific and application-oriented fields relating to space weather. The team members also evaluated the primary scientific orientated results of both consortia. The consortia proposed many interesting options for a space weather system (see also Figure 5-12 and Figure 5-13 below). ESA's Concurrent Design Facility (CDF) further analysed these options to establish their feasibility and costs.

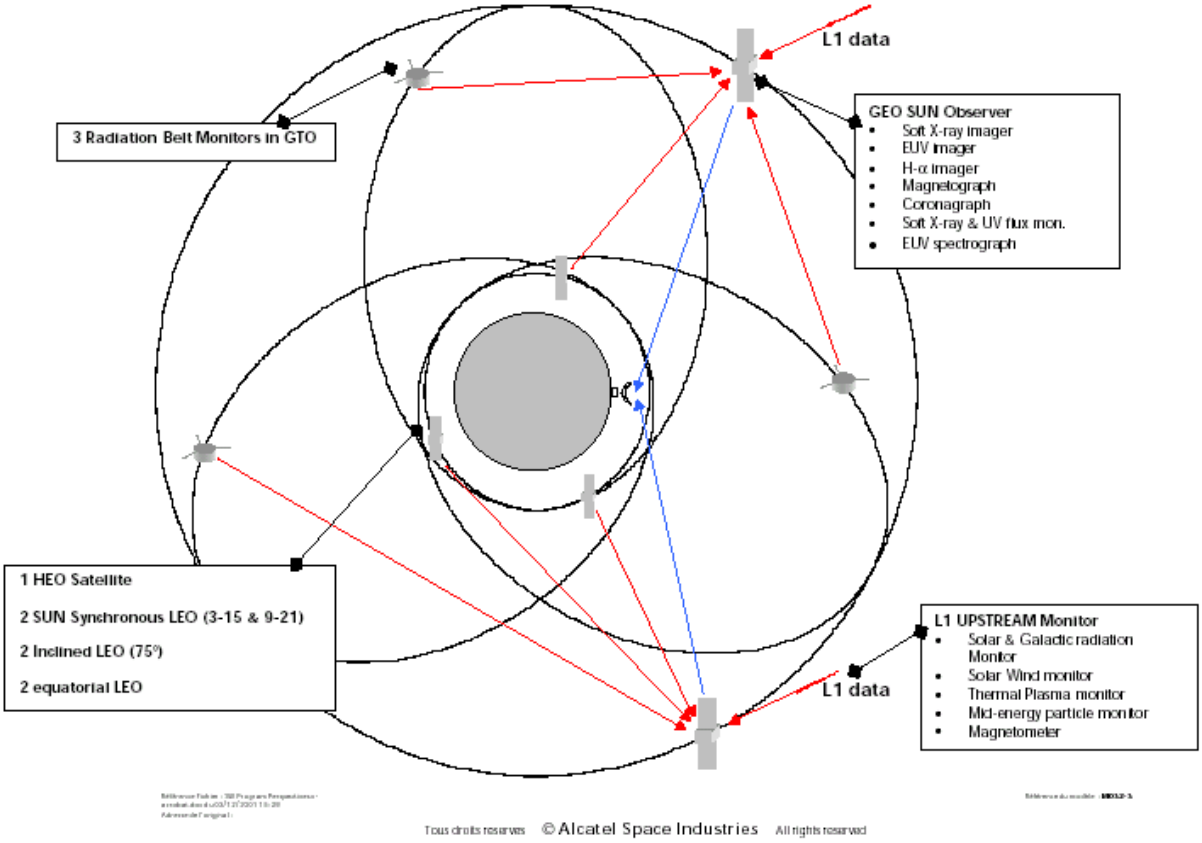

Figure 5-12: Full Space-Based Scenario by the Alcatel Space Industry Consortium with Global Data Communication Consisting of: Sun Observer and Upstream Monitor at L1, Three Radiation Belt Monitors in Geostationary Transfer Orbit (GTO) and Seven Additional Satellites in High Eccentric Orbit (HEO) and Low Earth Orbit (LEO).

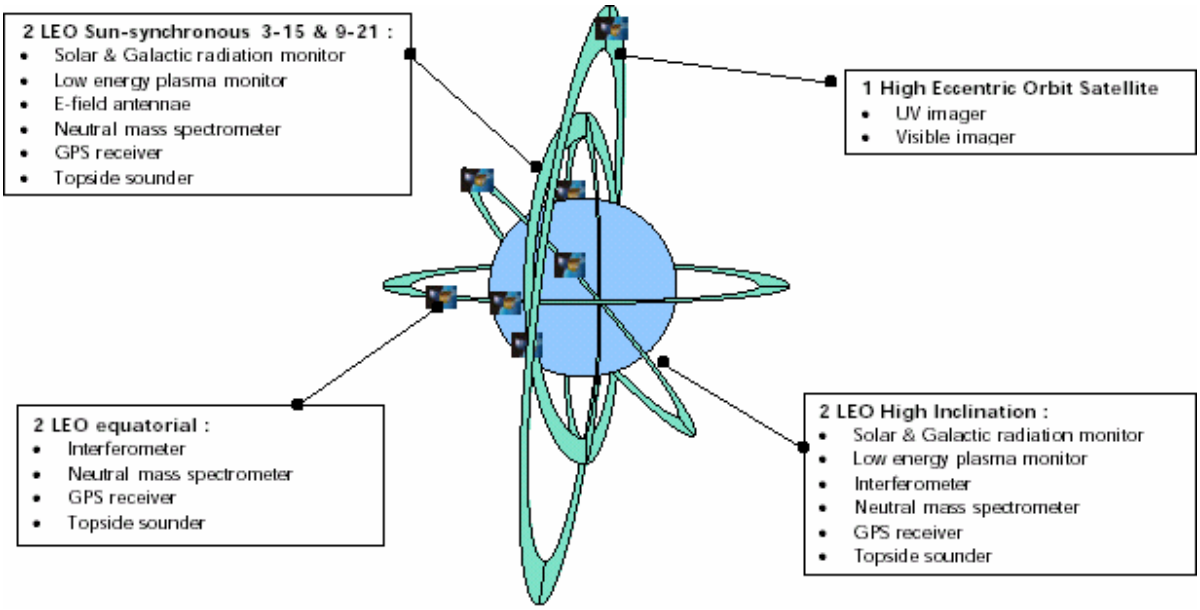

Figure 5-13: The Alcatel Space Industry Consortium Proposed this Space-Based Full Scenario of Satellites and Instruments in HEO and LEO; in Sun-Synchronous, Equatorial and High Inclination Orbits in the Ionosphere and Thermosphere.

On the European level several workshop proceedings, books and DVDs were published related to space weather: "Space Storms & Space Weather Hazards" in Greece [5] in 2000, and the SOLSPA Euroconference "Solar Cycle and Space Weather" in Italy [6] in 2001. After 1998, the year of the first workshop on space weather in Europe, ESA has organised space weather workshops each year. There was a workshop on the topic of the utilization of a future European space weather service [7] in 2000. The 2001 workshop looked towards a future European space weather programme [8]. In 2002 a potential space weather applications pilot project came into discussion [9]. In 2003 the workshop was orientated towards developments of a European space weather service network [10]. In 2002 the European Commission funded European Science Week, which carried out the project SWE (Space Weather and Europe) to promote societal and public awareness aspects of space weather all over Europe: SWE organised a public space weather forum in Berlin including a real-time video link to the International Space Station for about 300 politicians and representatives from industry and the media. The first interactive space weather CD-Rom worldwide was published by the SWE project in English, French and German [11]. A new level of space weather activities started with the European Space Weather Weeks in 2004 [12] and 2005 [13] at ESA/ESTEC in the Netherlands. To promote space weather aspects for the European Commission the space weather weeks in 2006 and 2007 were organised in Brussels. The first European space weather fair was a part of the second public space weather forum in Schwerin during the European Science Week in 2007. It was organised within the EU-funded SWEETS project (Space Weather and Europe – an Educational Tool with the Sun, see under www.sweets2007.eu), a successor of SWE. SWEETS published a new, educational space weather DVD in 8 languages [2].

Moreover, the European Commission and ESA published an action plan for implementing the European Space Policy in 2003 [14]. This White Paper underlined specific efforts to ensure that Europe has the capacity to supply to the different users critical information on space weather predictions.

In 2003 the European Science Foundation started the 'Action 724 on the European Cooperation in the field of Scientific and Technical Research (COST)'. This developed the scientific basis for monitoring, modelling and predicting space weather. The main aims of the action were:

1) To coordinate European research into modelling and prediction of space weather;
2) To promote new instrument deployment to satisfy data requirements and development of new models; and
3) To educate potential users.

The main benefit of this concerted space weather action towards an ESWP is that organisations will have a resource which will enable them to manage space weather risks. Especially the development of a coordinated European space weather network relevant to data, models, prediction and public outreach and education is foreseen. An international advanced school on space weather was initiated by the COST 724 action and realized in 2006 at the Abdus Salam International Centre for Theoretical Physics in Trieste [16]. The COST 724 action objectives described as tasks of the four working groups "Monitoring and predicting solar activity for space weather", "The radiation environment of the Earth", "Interaction of solar wind disturbances with the Earth" and "Space Weather Observations and Services". These objectives are:

1) The use of solar observations (extreme ultraviolet images, X-ray observations, radio emissions) and models (magneto-hydrodynamic models of flux tubes) for predicting energetic particle events;
2) The use of solar observations and models for predicting coronal mass ejections (CMEs);
3) To develop a quantitative model of the interaction of solar energetic particle events with the Earth's magnetosphere;
4) To develop a quantitative model of the development of trapped radiation in the Earth's magnetosphere during geomagnetic storms;
5) To develop a quantitative model of the variation of galactic cosmic radiation in response to solar activity;
6) To study how electronic technology in satellites, launchers and aircraft is affected by the Earth's radiation environment;
7) To study how humans (astronauts, aircrew, air passengers) are affected by solar and cosmic radiation in different activities;
8) To develop a quantitative model of the propagation of CME through the interplanetary medium to predict their arrival at Earth; and
9) To develop a quantitative model to predict geomagnetic storms and ionospheric current systems.

In 2007, the COST 724 action established the European space weather network 'European space weather web portal on-line' (see under http://gauss.oma.be/COST724/ESWWS/). The COST 724 action intensively cooperates with the COST action 296 "Mitigation of Ionospheric Effects on Radio Systems (MIERS)" [17].

A further European space weather related activity is DIAS (The Digital upper Atmosphere Server). DIAS is co-funded by the e-content programme of the EU and uses real-time information provided by seven operating digital ionospheric stations (ionosondes). DIAS is also based on historical data collections and has developed a pan-European digital data collection on the state of the upper atmosphere over Europe. The first release of the DIAS server prototype is now active on http://www.iono.noa.gr/dias/.

Regional Warning Centres (RWCs) of "The International Space Environment Service" (ISES) deliver tailored space weather forecasts within their own regions [18]. At present there exist seven RWCs, associated RWCs and collaborative expert centres in Europe. These centres are located in the following countries – in Belgium (Brussels), Czech Republic (Prague), France (Toulouse) , Netherlands (Noordwijk, ESA), Russia (Moscow), Poland (Warsaw) and Sweden (Lund). RWC Warsaw and partially RWC Prague inform users about ionospheric forecasts. The Space Weather Application Center – Ionosphere (SWACI)

is a research project at DLR in Germany, which provides nowcasts and forecasts of the ionospheric state to improve the accuracy and reliability of impacted communication and navigation systems for the European user community on a routine basis [19].

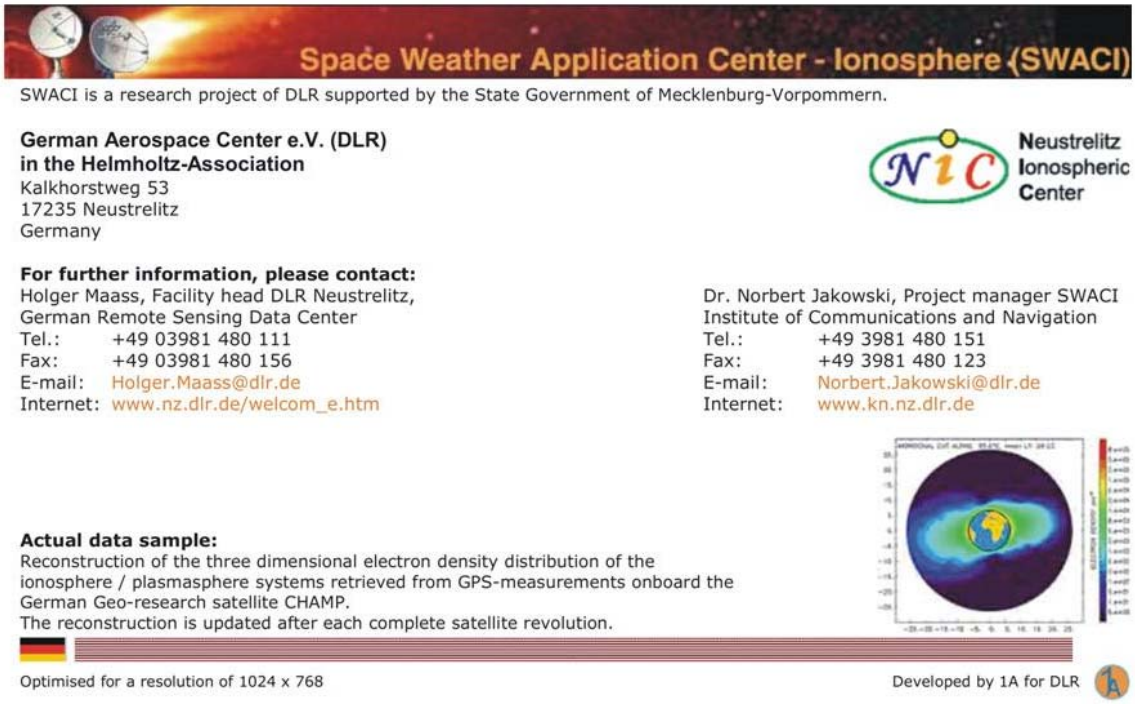

Figure 5-14: SWACI has 10 Partners from Industry (Allsat Hannover, 1A Greifswald), Governmental (like the Federal Agency for Cartography and Geodesy and others) and Scientific Organisations and Institutes (like ESA (SWENET), Space Environmental Center (SEC) Boulder, GFZ (Potsdam and others)).

On a different level several meetings, workshops and conferences took place, for instance in Armenia, Belgium, Denmark, Finland, France, Germany, Italy, Sweden, UK and other countries. For example in Germany two workshops were organised in 2000 [20] and 2005 [21]. The first workshop delivered a space weather recommendation to industry and organisation in Germany. At the 2005 workshop the space weather community in Germany proposed activities to German authority for a space weather satellite with international cooperation. Discussions on the equipment are directed towards a space weather service related to users from satellite navigation, telecommunication and aviation industry. Especially during the Solar Energetic Particle (SEP) conference in Armenia (2005) American, Armenian, European and Russian space weather experts discussed the important role of cosmic rays for a forecast and nowcast space weather service [22].

5.3.2 Technology, Infrastructure and Space Weather

Parts of many technological systems and infrastructure are strongly influenced by space weather. This is the case for civilian as well as for military systems. Space weather effects are known from the following technological and infrastructure branches:

5.3.2.1 Space and Spacecraft

All spacecraft, both military and civilian, for communications, navigation, remote sensing or research can be affected by the space environment which depends on space weather conditions. The environment a

spacecraft encounters depends on its orbit. For instance, high orbiting GPS and Galileo satellites can be disturbed by rapidly changing conditions in the nearby interplanetary space – by bursts of energetic particles from the Sun (so-called solar particle events SPE with up to several billions of electron-Volts) or Earth orbiting spacecraft may travel through the energetic particles of the Earth's radiation belts or the ionised gases of the upper atmosphere. SPE can have serious consequences for the spacecraft systems for instance:

1) Damage to sensitive spacecraft electronics;
2) Severe degradation of solar panels, thus reducing the area available to collect energy; and
3) Degradation of IR, optical and UV detectors, making them less efficient over time.

Onboard systems can be strongly affected during the solar cycle, especially long-lived satellites. Short-term effects due to space weather storms can trigger communication problems as well as memory malfunctions and data loss. In extreme cases as observed in the 1990s entire satellites were lost.

Strong solar flares trigger geomagnetic storms, which cause heating of the upper atmosphere. Heating of the upper atmosphere causes spacecraft in low Earth orbits to suffer increased drag. In those cases satellite operators have to make corrections for increased atmospheric drag in a timely fashion to avoid loss of the satellite. Contact was lost with the Japanese satellite ADEOS-2 during the intense space weather storm on 24 October 2003 (indirectly by strong enhanced drag). The US Skylab station crashed spectacularly in the southern hemisphere during July 1979 after increasing solar activity caused the atmospheric drag to become stronger than originally expected.

Man-made space debris as an artificial space environment effect is already monitored from US and European organizations. Satellites on low Earth orbits came into contact with rocket stage breaks up in size between microns and meters. The smallest particles frequently impact spacecraft causing damage such as solar cell degradation. Just during the retrieval of LDEF satellite in January 1990 a baseball-size piece of debris flew between LDEF and the space shuttle.

High energy particle radiation is a threat to electronics and other systems. This particle radiation plus high energy electromagnetic X-rays and gamma rays potentially have the ability to break DNA and cause lasting damage to astronauts. Higher levels of shielding in the ISS, or cancelling of extra-vehicular activities helps to minimize radiation exposure to astronauts, but during interplanetary manned missions prolonged exposure leads to large radiation doses and risk of cancer.

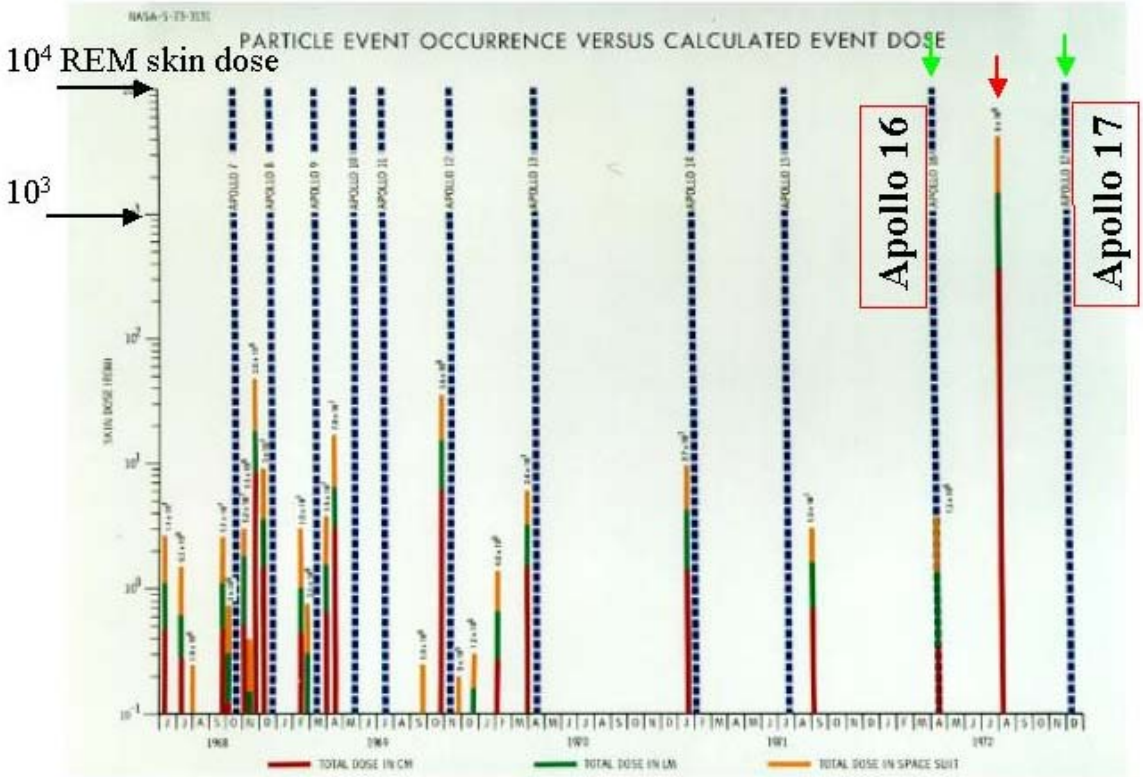

Figure 5-15: SPEs between 1968 and 1973.

It was fortuitous that the large SPE events did not occur whilst the astronauts were travelling to the moon. Had the astronauts been travelling to the moon during an SPE, they may have experienced severe health problems.

Conclusions: Damage to unmanned spacecraft by space weather is not completely avoidable, but plays an important role for high technology networks of infrastructure. Related risks must be recognised, analysed and quantified. Avoidance measures employed by the manufacturers and operators must be closely scrutinised.

5.3.2.2 Satellite Navigation and Telecommunication

Space-based Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS and GALILEO consist of fleets up to 30 satellites. The orbits cross the outer Earth radiation belt at a distance of about 20000 km. In addition to cosmic radiation damages, the most important space weather effect is the degradation of the signal quality, which causes positioning errors making the GNSS less reliable. GPS (U.S. system operational since 1995) and GLONASS (Russian system operational since 1996) were primary military systems, but later partially opened for civil purposes. Space weather storms already impacted the navigation capabilities of both GNSS by:

1) Interference of GNSS signal strength due to strongly enhanced solar radio emission (MHz and GHz frequency range); and

2) Delayed signal propagation and degradation of signal performance due to the dynamic behaviour of the ionosphere during space weather storms.

The Galileo satellites will be equipped with radiation monitors.

Solar radio waves and signals of GNSS satellites have frequencies above 30 MHz and are both modified in phase, amplitude and polarization during their ionospheric propagation by fluctuations of the total electron content and other charged particles in its phase, amplitude and polarisation. The resulting range, phase and signal strength errors cause difficulties in the reception of satellite signals for civil and security applications.

Applications such as the detection of minefields, search for mineral resources and oil and gas exploration by means of magnetically guided drilling are partly based on aeromagnetic surveys to map magnetostatic anomalies and rely on an undisturbed geomagnetic field. In addition they often rely on exact positioning by satellite navigation systems. The delivery of high quality data from weather satellites undisturbed by space weather played a major role during Desert Storm in 1991. Measurements and data collecting made during disturbed space weather stormy times result in low-quality results. They must either be repeated or result in missing the target.

Aspects of civil and military telecommunication related to space weather are:

1) The sensitivity and range of radar signals because of changing reflection characteristics in the ionosphere;
2) Ionospheric effects can lead to interference, i.e. signal degradation and delayed echoes;
3) Interference of mobile phone radio waves with solar radio waves in case of solar radio bursts leads to a minimum of failure rate of about 8 % of the calls; and
4) Telecommunication mobile networks working with high capacity are overloaded by extraordinary additional requests of users under space weather storm conditions.

Conclusions: Functioning satellite navigation and telecommunication systems not only represent several billion Euro in investment, but also the potential for damage to the operator's and western society reputations in the event of a failure. Many parts of western society depend on precise satellite navigation and reliable telecommunications. Therefore those service providers must introduce space weather forecast and nowcast information to reduce the navigation and communication problems.

5.3.2.3 Aircraft and Air Traffic

Secondary cosmic rays are produced in the Earth's atmosphere by galactic and solar cosmic rays and directly expose aircrew, passengers and electronics. Flight route, time of flight and aircraft type all influence the radiation exposure. During a flight between the U.S.A. and the Middle East under quiet space weather conditions pilots and military staffs obtain the equivalent of two chest x-rays as an additional effective dose. US and European studies carried out in commercial aircraft found effective dose rates experienced by aircrew between 1 and 15 µSv/h. For military jets and troop carriers similar magnitudes can be adopted or assumed as criteria. A flight on the same route during a SEP can increase the effective dose by an order of magnitude. Space weather effects by galactic cosmic radiation on civil aircrew have been the subject of European Union legislation since 2000. This EU regulation recommend that the annual radiation dose received by aircrew should fall within the 1 – 6 mSv range and that pregnant female aircrew should not be exposed to more than 1 mSv per year. On the other side during large SPEs, cosmic ray dose rates in the nearby Earth environment can increase by a factor of between 100 to 1000! SPE originated radiation dose on cruising altitude of aircraft are: 2.27 mSv (23 February 1956), 1.28 mSv (29 September 1989) and 0.078 mSv (15 April 2001) are much higher dose than about 0.05 mSv from galactic cosmic rays.

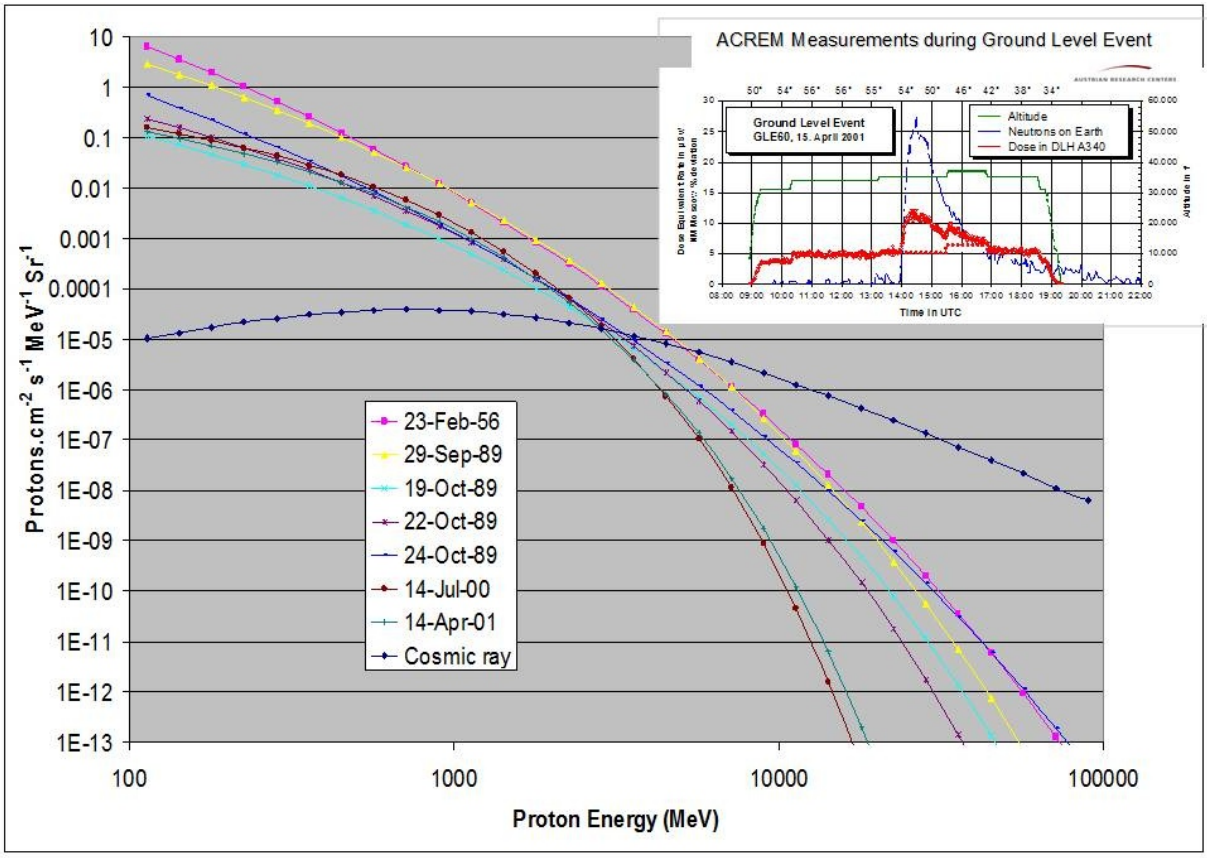

Figure 5-16: Cosmic Ray Spectra During Major SPEs (C. Dyer, QinetiQ) and Detection of an SPE on a Cruising Plan (P. Beck, ARCS).

SPEs let increase the dose rate during a North Atlantic flight to an amount of the same order of magnitude as that allowed for an entire year in Europe. In the U.S.A. the DOT / FAA has also developed cosmic radiation protection standards for air carrier crew members. In principle European and US civil radiation protection recommendations and standards are applicable to military flights. Shielding for sensitive parts and components is not a solution. Any additional shielding increases the mass of the aircraft. Re-routing the flights to lower altitude or to lower latitudes during space weather storms would decrease the cosmic ray exposure, but may be difficult due to logistic reasons and would also increase the costs of flights.

In addition to the dramatic increases seen during SPEs, average cosmic ray doses vary with the solar cycle, because more galactic cosmic rays are able to reach Earth during periods of low solar activity. At the solar minimum between 2007 and 2008, the hourly dose rate was expected to increase by a factor of between 10 % to 50 % compared to solar maximum conditions.

Another critical aspect is secondary cosmic rays potentially interfering with many aspects of the air traffic management system, including communication, navigation and avionics systems in military and civil aircraft. All modern aircraft have onboard electronics that contain microchips operating at very low voltages. Cosmic ray particles can deposit charge in these microchips leading to unexpected changes in the state of memory cells. This can result in unexpected commands or false readings. This type of error is called a single event upset. Software failures and ensuing hardware failures in aircraft systems are documented in scientific journals. Research into the effects of cosmic rays on microchips as well as meetings with pilots have shown that the effects of cosmic rays can be seen as frequently as every two hours at aircraft altitudes. Although the detection of a single cosmic ray is unlikely to result in failure of

any system, this highlights the need for redundancy in those systems (twofold) that are critical for safety, especially for combat zone transport aircraft and jet fighters in operation. Upsets occurred in airplanes of different scale and types – in Boeing, Airbus, private Learjets or others.

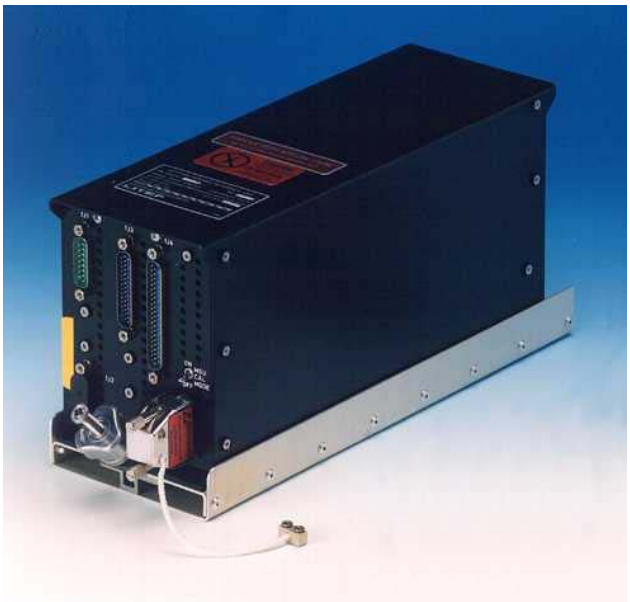

Figure 5-17: The LCR 93 System is in Use for Altitude Information in CESSNA EXEL and LearJet Planes. After cosmic ray induced software failures, new software was developed to compensate for space weather effects (Image: LITEF).

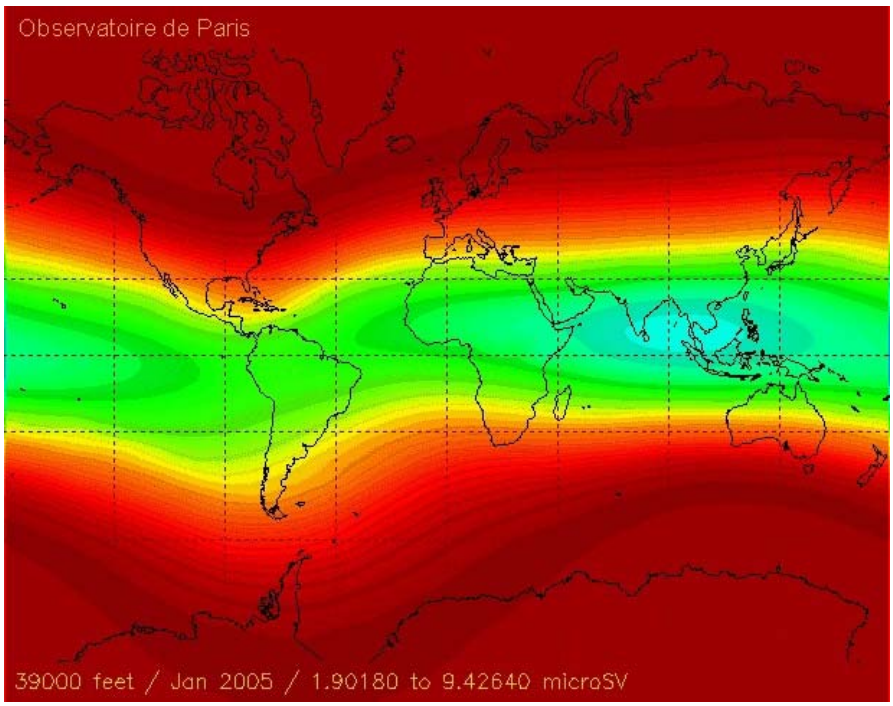

Figure 5-18: Worldwide Map of Estimated Dose Rate (Paris Observatory) during a Solar Particle Storm: Flights near the equator are well protected (white and light green); the maximum dose is obtained near the poles (red).

A third critical aspect is the aircraft communication during space weather events. Solar x-ray flares or energetic particles precipitating from the solar wind modify the lower part of the ionosphere thus changing the propagation conditions for radio waves. This strong sensitivity makes HF communication unreliable in particular at high latitudes. International operations must be aware about risks during high latitude (>50°N) flights.

One advantage aviation has over space flight is that faulty components on a plane can be replaced on the ground and cockpit crews are trained in managing emergency situations.

Conclusions: For security applications the most important potential failures due to space weather are effects on aircraft electronics and communication quality. Regulations for protection of civil aircrew against cosmic radiation exposure became standards in Europe and the U.S.A., however for military flight personnel it has to be studied. Especially in the case when military flight personnel changes to crewmembers of civil airlines the total personal dose has to be known – including radiation dose obtained during flight hours.

5.3.2.4 Power, Oil and Gas Pipeline Supply

Time variations of magnetospheric and ionospheric currents (caused by space weather storms) are seen as geomagnetic variations or disturbances at the Earth's surface. Geomagnetic variations are accompanied by geoelectric fields on the ground. The geoelectric field drives currents in conductors at the Earth's surface, for instance in electric power transmission systems. This current is known as a Geomagnetically Induced Current (GIC). Usually GIC vary much from site to site in a power system. In general, transformers located at corners and ends of a power system suffer from large GIC values and tend to heat up. Long transmission lines also carry larger GIC. How GICs affect the transformer and the whole power system depends on the transformer type, on the structural details of the network and its equipment, on the load and capacity of the power system. GIC are not only a high-latitude problem, although most of the studies performed for power systems in North America and Scandinavia. GIC studies have also been conducted in mid-latitude and equatorial countries, such as South Africa, Brazil and Vietnam.

The largest GIC event so far was experienced on 13 March 1989: A collapse of the Canadian Hydro-Québec power systems left six million people without power for nine hours in winter. The collapse time of Hydro-Québec was only 90 seconds! The absolute value of the changing magnetic field was 400 nT/min. In Minnesota the value was 865 nT/min. The total costs of the Hydro-Québec event were estimated at about 13.2 million Canadian dollars. During the same geomagnetic storm, a high-voltage transformer was completely destroyed in New Jersey. According to Metatech company, the U.S.A. were close to a total power blackout due to cascade effects originating from this super storm. The super storm influenced six 130-kV power lines in Sweden. GICs measured in Finnish power lines had about 130 amps. During the Halloween storm in October and November 2003 power supply failures occurred in South Africa and in Malmö / Sweden: A meltdown of a transformer was attributed due to the intense solar storm induced GIC in South Africa and a hour-long power outage occurred for 20000 inhabitants in Malmö. These and other, nuclear power plants in the U.S.A. and Sweden were discussed in the Department of Homeland Security Infrastructure Report [25] and in the DoC report on Halloween storms in 2003 [26]. The great power black outs in summer 2003 in New York, London and Rome were not caused by space weather storms, but showed how infrastructure systems and millions of people depend on a stable energy production!

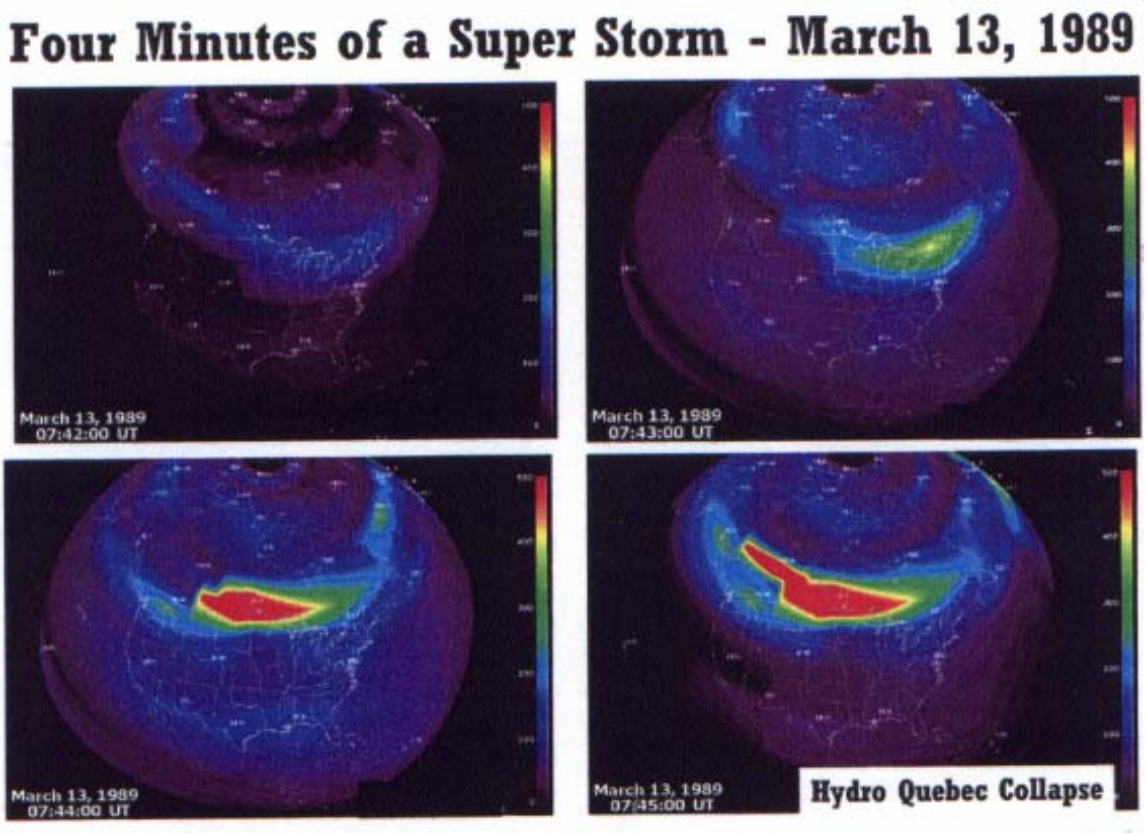

Figure 5-19: March 1989 – The Super Space Weather Storm Arrived at the US East Coast and Moved to the West Coast Within Four Minutes.

Figure 5-20: High-Voltage Power Transformer in New Jersey, USA, Before and After the Geomagnetic Super Storm (first and second image) on the 13th March 1989 and the Transformer Windings were Permanently Damaged in New Jersey, USA, During the March 1989 Geomagnetic Storm. Third image: destroyed transformer in South Africa in October 2003.

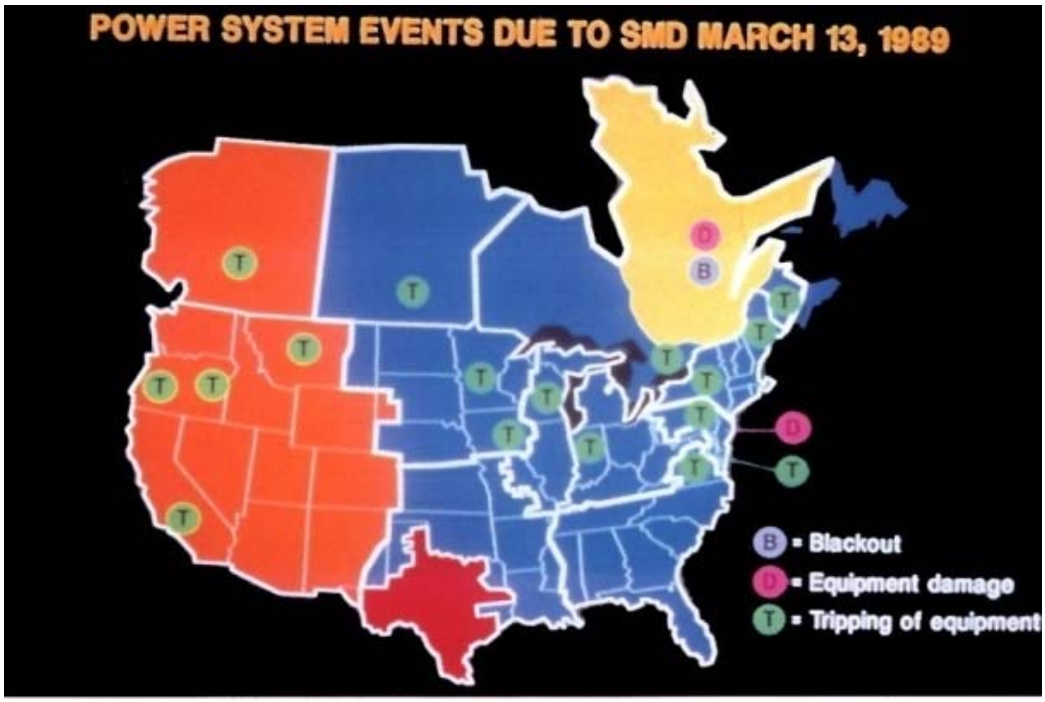

Figure 5-21: Map Showing Many Problems Caused by the March 1989 Geomagnetic Storm in North American Power Systems.

Besides power grids, GIC also flow in oil and gas pipelines. To avoid corrosion, pipelines are covered by an insulating coating and equipped with a cathodic protection system to prevent electric currents from the pipeline. Amplitudes of pipe-to-soil voltages related to GIC can easily exceed the cathodic protection potential thus removing the protection. It is unknown how strongly GIC effects increase the corrosion rate of a pipeline, because space weather risk has not been investigated as much in pipelines as in power systems. However GIC studies and GIC induced measurements on pipelines have been carried out in Alaska, Canada, Finland, Germany and Sweden.

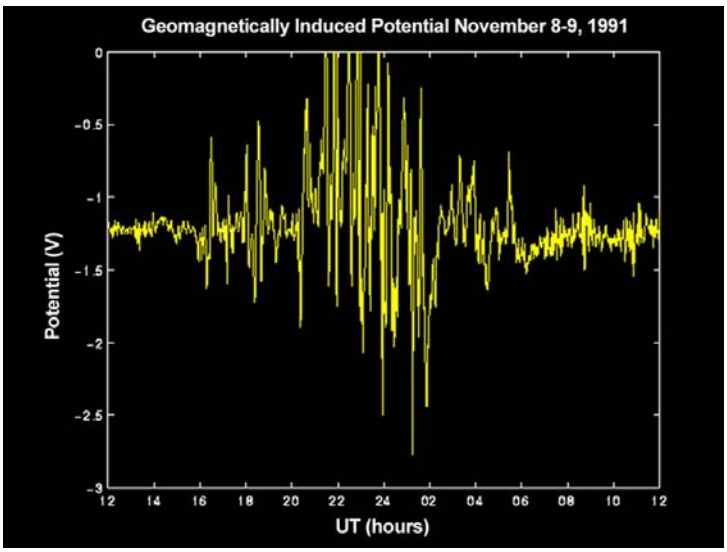

Figure 5-22: GIC-Related Pipe-to-Soil Voltage Variations Measured in the Swedish Pipeline on 8-9 November 1991. Note that the zero level is about -1.2 V indicating the value of the cathodic protection voltage.

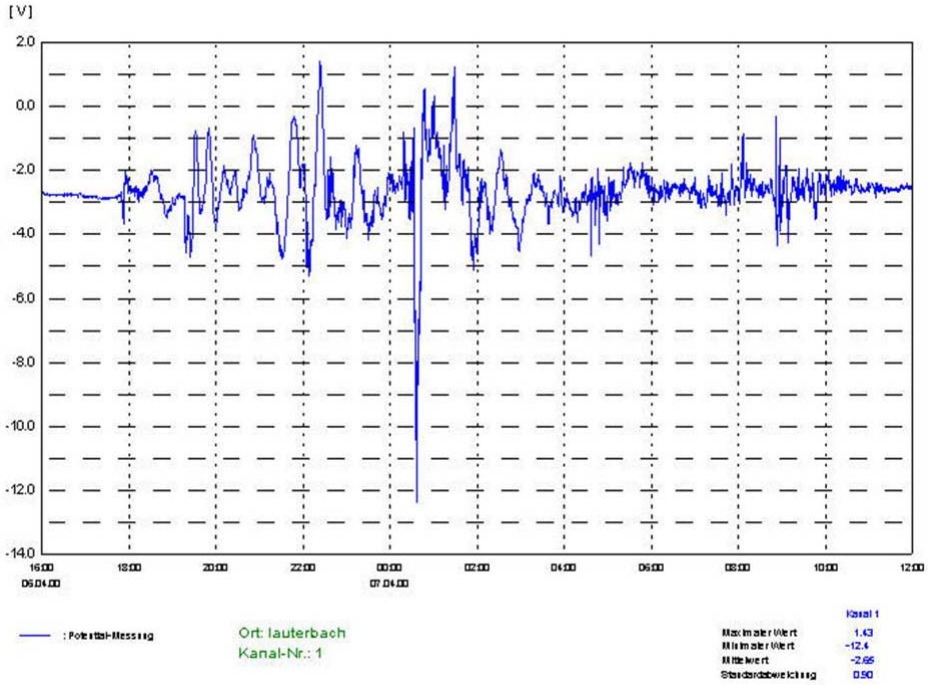

Figure 5-23: The Ruhrgas Pipeline in Germany is a Good 'Detector' of GIC – 6-7 April 2000.

Conclusions: Space weather storms have induced power cuts in the U.S.A., Europe and South Africa. Such events demand a regional and global risk analysis, a risk strategy and risk control in case of big solar storms.

5.3.2.5 Telecommunication Cables, Railway Equipment and Electronics

GIC also flow in other technological networks, such as telecommunication cables and railway power lines and traffic equipment, causing problems to the normal operation of the systems affected. The use of electrical telecommunication cables is decreasing in the developed countries. However these cables are still affected by GICs during space weather storms. Space weather has disrupted electric lines, railway signalling systems and engine drives as reported below. The first know example was a disruption of railway traffic in New York City on 15 May 1921.

In July 1982 railway signals switched from green to red light and vice versa due to strong geomagnetic activity near Stockholm in Sweden. In the 1990s the German high speed train ICE was equipped with high power semiconductors (GTO) in the engine drive. About 50% of all trains were affected by space weather. Cosmic ray particles produced electron bursts in layers of the semiconductors, completely destroying the layers. Therefore ICEs were driven with much smaller speed than the nominal 250 km/s during cosmic ray bursts. Later ICE equipment – so-called IGBTs – seems to be less affected. IGBT are also used in subways and trams. Significant links between geomagnetic disturbances and anomalies in the operation of railway automatics and disturbances occurred in 2004 / 2005 in the East Siberian Railway.

Electronic components form a vital part of today's western societies. Everything from cars, trucks to a high-tech aircraft and spacecraft contain electronics. As technology advances, the components become smaller and smaller. This miniaturisation allows computers to operate at much lower voltages than before. As a result, circuits are more susceptible to additional currents created by the impact of cosmic ray particles. Energetic cosmic ray air shower particles, created through the interaction of cosmic rays with the Earth's atmosphere, are capable of disrupting electronic systems in space, air and on the ground. In 1978,

IBM experts first studied the effects of secondary cosmic rays on memory chips in PCs [27]. The software errors caused by the interaction of the particles with memory devices, however, should not affect the normal operation of a PC because the system is developed such that it can detect the error and compensate for it. However cosmic ray induced errors in critical car and truck electronics are discussed in the industry. For instance significant implications for mission-critical automotive applications that utilize a so-called SRAM-based FPGA seems to be established.

Conclusions: Several important infrastructure and transport systems failures due to space weather have been reported. Modern societies depend on electronics in transport systems, i.e., railways, subways, trams, cars, aircraft, spacecraft and ships. The security of those systems is a foundation of a reliable infrastructure in modern societies and must be safeguarded against space weather failures. Several other effects to similar technical systems may have already occurred, but the producers, owners or users are often not aware of the space weather background of failures. Further studies, education and development of special action plans to diminish the effects of failures are very good measures.

5.3.3 Insurance

Space industry insurance experts estimate that over USD 500 million of the total USD 4,000 million losses can be linked to space weather in the second half of the 1990s. Over 180 satellites were insured in the same period for USD 24,000 million. Another 200 were not insured. These were larger research satellites and military satellites. In the first decade of the 21st century 1,400 satellites with a value of USD 220,000 million are planned to be launched. Of those, 900 will be used for commercial purposes. Considering that safety measures on these satellites are kept to a minimum in order to keep costs down, potential losses will increase significantly by the next solar maximum after 2011.

Investment by civil and military spacecraft operators in space weather services could provide one way in which the amount of shielding required could be reduced without increasing the risk to the spacecraft.

Many more risk reduction measures can be implemented in aviation. Increasingly precise early warning or forecasting systems now make it possible to change flight paths, thereby reducing the exposure of passengers, crew and the plane's technological systems.

Satellites and airplanes usually have comprehensive insurance. However, those responsible for space flight and air travel must be aware of space weather phenomena, taking organisational and technical measures to protect flight personnel and electronics from excessive exposure to high levels of cosmic radiation.

A remark to ground-based effects: It is far easier to assume that a transformer was destroyed by a technical defect than to imagine that space weather might have caused the loss. From the perspective of the insurance industry as a whole, lengthening the chain of cause and effect is not difficult. For example, a transformer fire such as in New Jersey in March 1989, can cause property loss and also lead to business interruptions. Insurance policies do not generally distinguish between fires caused by lightning, technical failure or a GIC. Experts estimated the economic loss in the New Jersey case to be USD 3,000 to 6,000 million. Only a small fraction of this was insured. Technically, this consisted of losses incurred within the company following the transformer fire, and losses incurred by a third party, for example, as a result of the power cut.

The following general factors are important for space weather insurance aspects:

- Increasing interdependency, particularly in the area of electrical and electronic systems (e.g., communication);
- The marked increase in systems liable to fail (although a certain degree of risk is accepted in the interests of cost saving);

- The complex relationship between production and communication processes, whose interdependencies multiply in the event of a loss; and
- Air travel: the rapidly growing importance of polar flight paths, e.g. from the U.S. to Asia (the dose encountered during a New York – Hong Kong flight is some 0.2 milliSieverts).

Variability in space weather means that the probability and extent of losses which may be incurred by the various companies involved in space and air travel, electric power generation, telecommunications or oil and gas transport, are not necessarily comparable. For this reason, individual actuarial assessment must be performed for each insured company, so that the most appropriate insurance premium can be calculated.

It is the insurance industry's responsibility to provide information on and raise awareness of space weather. The challenge is to develop, adapt and bring to the market products to insure the diverse range of potential losses related to space weather (see in [28]).

Conclusions: It is the responsibility of the insured organization or persons to implement risk-mitigating measures. Therefore early warning systems capable of detecting extraordinary solar activity and space weather storms - accurately and in good time - will become crucial in the future for insurance industry and infrastructure systems. In order to retain insurance cover, individuals may be required to take cognisance of any forecasts.

5.3.4 Space Weather and Security Aspects

In addition to the directly affected space weather technology and infrastructure described in chapter 2, several studies have been carried out relating to security aspects. Examples for overlapping civil and security aspects were the nuclear power plant and power grid problems in October / November 2003 in the U.S.A. and in Sweden. These were discussed in the DoC and DHS reports ([25], [26]).

HF satellite communication can be interrupted between half an hour and several hours due to large solar flares. One dangerous example took place during the Gulf war in 1991 when requests for fire support were made by HF radio communications, which were disrupted.

Over the Horizon radars (OTH) utilises HF propagation of signals over very large distances up to thousands of kilometres. The waves propagate in a duct between the ionosphere and the ground. OTH radar propagation can be enhanced either naturally or artificially. Natural enhancement is the result of space weather storms by CMEs and the influence of magnetic storms. Artificial enhancement can be achieved by locally heating the ionosphere, thus increasing its conductivity at the reflection point. High energies are needed to achieve this. By heating the local ionosphere using strong radio power, space weather effects may even be imitated to disrupt the radio communication and navigation services of the enemy.

Figure 5-24: A High Power Antenna Field in Alaska (with a 'Dust Devil' in Background (image: F. Jansen)).

Military radio systems are sensitive to space weather events, mainly due to the ionospheric impact on radio signals. Radar systems may suffer from limitations caused by the variability of the ionosphere. This is especially true for the detection of low flying targets or moving ships. Here the detectability of the target is reached by summing successive echoes at each rotation of the radar antenna. Ionospheric effects can lead to interference, i.e. signal degradation and delayed echoes. Since military users need reliable communication and precise navigation, ionospheric space weather effects may cause serious problems in the detection of aircraft and ships. Studies with radars at the east cost of Canada and the north cost of Australia showed that ship detections is strongly depending on the status of the ionosphere.

The French Nostradamus is an over the horizon radar demonstrator, capable of detecting and locating an aircraft well behind the horizon – the limit for conventional radars. Emitting very low frequency waves (6-30MHz) that bounce off the ionosphere, Nostradamus can transmit and receive signals over a range of over 1000 km.

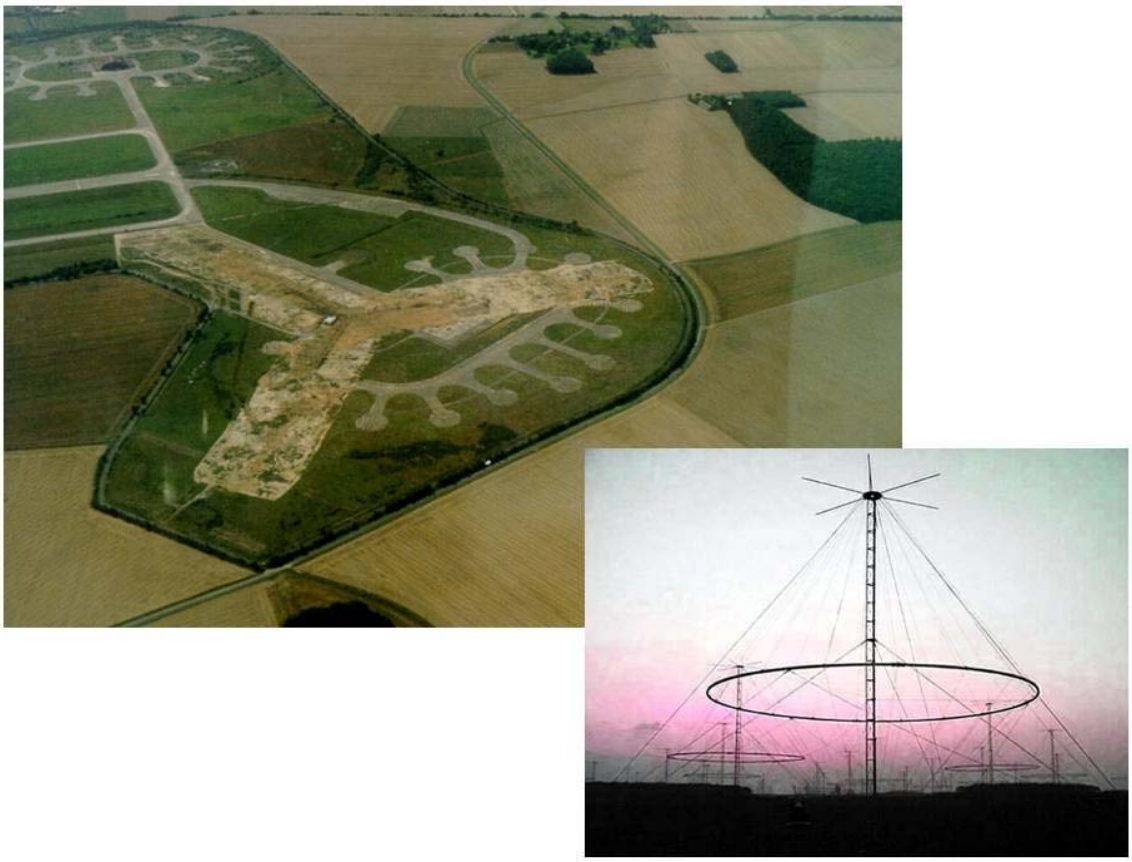

Figure 5-25: Aerial View and Antenna of the Nostradamus OTH Radar Located West of Paris. Each of its 3 arms stretches several hundred metres and comprise 100 antennas.

Different security-related activities of space weather in Europe have initiated or are in progress. Within the ESA space weather feasibility studies British and French Armed Forces were contacted by the Alcatel and RAL team members.

Later within the COST action 724, National Representatives contacted the German Bundeswehr, the Spanish Defence Ministry and the Swedish Defence Research Agency (FOI sponsored by the Swedish Armed Forces SWAF). The German Bundeswehr announced interest in the potential usage of MuSTAnG space weather telescope data, including access to the data from the international muon telescope network to predict 10 – 20 hours in advance the onset time of communication disturbances in the ionosphere. The German Bundeswehr is already using ionospheric data from Leibniz-Institute of Atmospheric Physics in northern Germany. FGAN – Research Establishment for Applied Sciences – in Wachtberg / Germany is carrying out space weather related ionospheric research, too. Activities include the correction of propagation-dependent bearing estimation errors of HF radio waves. The DG of INTA (Spanish acronym for National Institute of Aero-Space Technology www.inta.es) evaluate the national interest in the space weather topic and INTA would handle any future action. Members of the Swedish Defence Research Agency FOI attended US space weather week, discussed ESA space weather programs, EU COST action 724 and wrote a report. In the report it is recommended to create a unit within the Swedish Armed Forces to deliver space weather information to the divisions of the Armed Forces. FOI also recommend courses about space weather and effects for the Armed Forces in Sweden. According to Swedish National Representative it is very important for SWAF to have knowledge about space weather and its effects that are being used and owned by the SWAF during international operation.

A recent study done by SEA Ltd. / UK have shown the benefits of a 50/50 split between nowcast and forecast tools for a civil European Space Weather Service (ESWS). Furthermore, small initial investment will bring large benefits – to a civil as well as a security related space weather service.

A highlight of the European efforts will be a Space Situational Awareness (SSA) program, which is presently in preparation for adoption at the ESA Ministerial Conference in November 2008. It is foreseen that the optional SSA program will cover navigation, communications and reconnaissance activities. Especially it will focus on topics like space weather, near-Earth objects, as well as space debris. Main proposed deliverables are a radar array, and one to two LEO or GEO satellites. The SSA budget may reach about 500 million Euro from 2009 to 2019 and may be a cornerstone for security aspects.

Conclusions: At present and much more in future, civil and military daily life rely heavily on high technology. The idea that technological systems could be threatened by hazards originating beyond the atmosphere is not strange anymore for many organizations and people. Public, political and security awareness on space weather has rapidly increased.

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