2.3 TELECOMMUNICATION SYSTEM VULNERABILITIES TO SPACE-WEATHER EVENTS

John Michael Goodman[1]
Radio Propagation Services, Inc.
Alexandria, Virginia

1. INTRODUCTION

Many legacy telecommunication systems have intrinsic vulnerabilities, and modern systems that use the earth-space path can also suffer impairments as a result of variability in the distribution of ions and electrons within the ionosphere and plasmasphere. It has long been established that solar phenomena (e.g., flares, energetic particle events, coronal mass ejections, and related events) can play a significant role in the distribution of the free electron distribution, and this is critical in the propagation of radio waves, and the resultant performance of radio wave systems. With the growth in environmental monitoring and data assimilation technologies (i.e., GAIM), and with the improved speed of data access and timely dissemination of assessment and forecasting products, telecommunication systems can operate in an environment that may be characterized over several time regimes: present, near-term, and long-term. The accuracy of the characterizations is dependent upon the efficacy of the first-order models, the generic update schemes, as well as the accuracy of the data that drives the models. Certain adaptive telecommunication systems can respond to media variability through use of organic compensation schemes or systematic countermeasures (and these are usually referred to as self-contained robust systems), but often it is more cost effective to incorporate non-organic forecasting schemes to “steer” the system parameters so that optimal operation can be achieved. For the latter category of systems, space-weather monitoring and forecasting is not only useful, it is an imperative.

This paper starts with a general statement about telecommunication systems and their level of vulnerability to space-weather. Then, specific examples are given for specified geomagnetic storm periods encountered during the declining phase of the current solar cycle. A more general exposition can be found in a recent book by the author (Goodman, 2005). We discuss practical approaches for impairment mitigation in selected systems such as HF data link and voice communications used by commercial carriers and military air transport applications. Without some form of adaptive compensation, these systems may suffer significant performance impairment as the result of geomagnetic storms, and they also benefit the most from the incorporation of space-weather data for optimization of system parameters. We conclude with the benefits of space-weather information for a hierarchy of systems.

2. SPACE WEATHER DEFINED

What is space weather? The US Department of Defense, in its implementation plan (OSD, 2000), indicates, “Space weather refers to adverse conditions on the sun, the solar wind, and in the earth’s magnetosphere, the ionosphere, and the thermosphere.” Indeed this definition portrays those aspects of space weather that are generally of most concern, namely the more pathological elements. But space weather, and ionospheric weather, in particular, can be turbulent or benign. All aspects of space weather should be included in the definition. Indeed, from a telecommunications perspective, it can be safely stated that quiet conditions are not always good and disturbed conditions are not always bad. The National Space Weather Program (NSWP, 1995) has defined space weather as representing “conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems.” This definition is more appropriate. On the NOAA/SEC web site, it is indicated “Space Weather describes the conditions in space that effect Earth and its technological systems.” It

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[1] Corresponding author address: John M. Goodman, Radio Propagation Services, Inc., 8310 Lilac Lane, Alexandria, Virginia 22308-1943; e-mail: jm_good@cox.net

goes on to say, “Space Weather is a consequence of the behavior of the sun, the nature of Earth’s magnetic field and atmosphere, and our location in the solar system”. We like this definition as well.

In this paper, the vantage point of the telecommunications specialist drives our view of space-weather. Specifically we treat ionospheric and plasmaspheric weather as the most important from a nowcasting perspective. On the other hand, we treat the space weather generated within the magnetosphere and the extra-magnetosphere (and directly related to solar events) as primary in the context of forecasting and prediction services. We wish to emphasize this point, not only because the effects on various communication systems derive from near-space regions just above the troposphere, but because it identifies the hierarchy of very important terrestrial sensors that have played (and continue to play) a significant role in our knowledge of the ionosphere. These sensors are a major part of the space-weather remote sensing “network” and are basically ionospheric diagnostic instruments. Hunsucker (1991) has outlined many of these tools. However it is obvious that space-weather is the real driver of pertinent properties of the ionosphere. Hence a treatment of the hierarchy of effects on telecommunication systems is really a more general space-weather problem.

Space-Weather phenomena have been affecting legacy communication systems involving longwave and shortwave signaling since the dawn of the radio communication era. The impact of the ionosphere on radio transmission is well known through the consideration of the Appleton-Hartree expressions that detail the relationship between plasma and signals that propagate within that medium. Over the 20th Century, a wide range of telecommunication systems have been developed, and many have been fielded for operational use. While many of the systems received their impetus through military necessity, the utility of telecommunications is evident in virtually all aspects of human activity. Space-weather, a relatively new terminology, loosely defines the hierarchy of all phenomena within the earth-sun environment that may impact biology and systems that reside within that environment.

3. RADIO SYSTEM CATEGORIES

Radio Communication and broadcasting systems may be either controlled by the ionosphere, as in HF skywave systems, or simply influenced by it, as in transionospheric radio communication and navigation systems. In the former case, the ionosphere is actually an inexorable part of the system; while in the latter case, the ionosphere is fundamentally a nuisance. In both instances an account of the ionosphere is at least beneficial to system design and operation. In the case of HF skywave systems, the accounting may be a critical factor in system performance. What is not well understood is that radio communication systems that are affected by the ionospheric personality are not necessarily inferior to systems that are little influenced by the ionosphere. Intelligent use of space-weather information may lead to significant improvements in performance of adaptive HF systems. In fact, under some conditions, HF digital communication can be just as reliable as satellite communication. This may be surprising to some communication specialists, and it indicates the power of adaptive system design as powered by space-weather data. It is noteworthy that our emphasis is on *intelligent* exploitation of space-weather data as but part of an adaptive HF system incorporating sufficient levels of time, path and frequency diversity. We must be clear on that point. Space weather data incorporation is not a substitute for good system engineering.

The influence of the ionosphere on radio systems falls into two general categories. Category 1 involves those systems that depend upon the ionosphere (i.e., involve the ionosphere as part of the system); and Category 2 involves those systems for which the ionosphere is simply a nuisance. In addition to these categories, we may organize the various systems into three disciplines: communication navigation, and surveillance. From Table 1, we see that all three disciplines may be found in listings of category 1 and 2 systems. Figure 1 identifies the various space-weather interfaces involved for various telecommunication systems

In this paper we do not offer any new technical data regarding particular space-weather observables and communication system impairments, as the literature is already replete with such associations. Rather the goal is to offer some observations based upon many years of R&D experience within government and industry. The basis for these observations derives from early work at the Naval Research Laboratory supporting civilian and DoD communication and surveillance activities. Within the same time frame, we incorporated various methodologies for assessment and prediction of communication performance, including the ionospheric measurements using sounder systems and solar measurements using satellite platforms. Indeed, Navy specialists were the first to develop an approach for application of space-weather data in a near-real-time computer platform, PROPHET, which was quasi-operational (Rothmuller, 1978).

Table 1. Categories of Radio Systems in Terms of Ionospheric Dependence

Category 1	Category 2
VLF-LF Communication and Navigation	Satellite Communication
MF Communication	Satellite Navigation (e.g., GPS & GLONASS)
HF Communication	Space-based Radar & Imaging
HF Broadcasting (“shortwave” listening)	Terrestrial Radar Surveillance & Tracking
OTH Radar Surveillance	Meteor Burst Communications
HFDF and HF SIGINT	Any other system for which the ionosphere is not necessary for conveyance

Table 2. Sources of Ionospheric Disturbances

- Space-Weather
  - Solar flares (SIDs)
  - Magnetic storms (ionospheric storms)
  - Energetic Particle Events (PCAs)
- Instabilities & turbulence (scintillation)
- Atmospheric gravity waves (TIDs)
- Polar blobs, tongues, patches
- Large gradients associated with features
- Artificial Modification

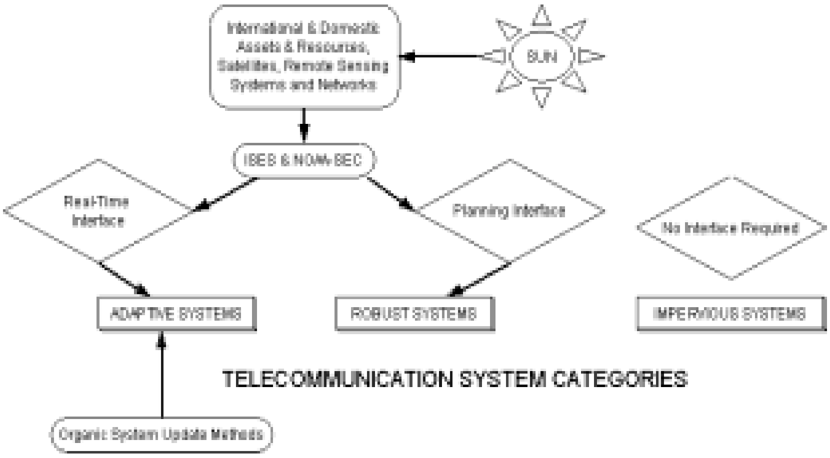

Figure 1: Well-designed Telecommunication systems, employing rigorous space-weather risk assessment, may be broken into three basic categories: adaptive, robust, impervious. A fourth major category (not depicted) includes systems that may not cope effectively with the environment, owing to the lack of space-weather risk assessment.

4. SYSTEM INFLUENCES UNRELATED TO SPACE-WEATHER

While space-weather is a term in vogue, it should be recognized that there are a number of external (environmental) factors that influence the performance of radio communication systems. While the energy that fuels variability of the ionosphere may ultimately derive from the sun, it is clear that secondary energy sources from below the ionosphere may also instrumental in the development of ionospheric irregularities. In some cases, the interaction between space-weather and the neutral atmosphere may be just as important as its interaction with the ionosphere and plasmasphere. Atmospheric gravity waves that produce traveling ionospheric disturbances (TID) come to mind. The process whereby space-weather influences the character of upper atmospheric winds is becoming understood, but the process of forecasting the direction, magnitude, and wavelength of TIDs has not been fully developed. Recently Rieger et al. (2005) have investigated mesoscale ionospheric anomalies not associated with space-weather events, but instead may be related to traveling ionospheric disturbances originating in the upper atmosphere. It is clear that atmospheric gravity waves (AGWs), and the TID patterns they generate, have many sources. While many of such sources may be fed by solar energy, AGWs can also be produced by natural and man-made events that we do not normally associate with the weather of space.

Radio communication systems operate at maximum efficiency in a high signal-to-noise environment. The community spends a great deal of time discussing the ionospheric (and space-weather) impact on the strength of radio signals, but very little time examining its impact on the atmospheric and cosmic noise components. The general radio noise environment has a climate of its own, and it is modulated by space-weather parameters. Existing models of radio noise are climatological in nature and are not amenable to update.

5. REQUIREMENTS

Practitioners of space weather disciplines are driven by a desire to improve upon the basic science and technology thereby enabling space weather effects to be better understood and predicted. The issue of user requirements is at the forefront of the current wave in space weather interest. Still, within the civilian sector, it is not well accepted that space weather is of vital importance to technological systems. This may be an education matter, but it is also true that commercial activities are not prone to honestly state the extent to which space weather may impact the performance of systems they are trying to market or protect. The extent of space weather data usage is probably best documented by "hits" on relevant web sites, even though such traffic does not generally distinguish between the curiosity seekers, scientist users, and operational users.

For systems in the VLF, LF, MF, and HF bands, such as long wave communication and navigation and short wave broadcasting, the need is obvious and the requirement for space weather assessment is not suppressed by the entities responsible for systems involved. But, for satellite systems, the space weather effects can sometimes be subtle. One thing is clear. Everyone agrees that there is a firm requirement for reliable and timely communication and navigation capability. Society depends upon these capabilities. However, some parties must be informed or reminded that these top-level system requirements depend upon a space environment that is not always cooperative. It would appear that the word is being heard judging from the worldwide interest in space weather.

Requirements are not always formally stated, but the military services generally provide the more complete descriptions of system vulnerabilities associated with ionospheric effects and space weather events. Goodman (2005) identifies many of these space-weather vulnerabilities, and one may derive a listing of system requirements, from both design and operations perspectives. The impact of space weather on short wave and long wave systems has been rather fully described in a number of texts (Goodman, 1992). Needless to say, the impact of space-weather is greatest on lower frequency radio systems.

System service requirements are generally well-defined for military systems and commercial systems alike. Such requirements are needed, and are usually based upon some a priori assumption about the medium within which the system must operate. System engineers may specify some standard model or characteristic as the basis of their calculations. There is a temptation to take climatological models of media (and its variability, if available) as a basis for media specification since such models are readily accessible, and generally easy to use. Many are in the public domain. Unfortunately, ease of use is not always a sound basis for judging the impact of space-weather effects on the propagation medium (or channel). Moreover, climatological models do not enable the user to assess the departure of the medium from its quiescent state at any given time. Estimates of average variability can be derived from some models, but this is not the same as reality, as the average variation may never arise, and can be irrelevant under a given set of circumstances.

This apparent need to address the actual medium has led to the development of so-called real-time models. Such models necessitate the continuous evaluation of the space-weather conditions and the media characteristics (i.e., the ionospheric conditions). To cope with variability in system reliability, we have seen the rapid development of quasi-adaptive systems, which may exploit real time data to change system parameters for service optimization. Sources of real-time data are far too numerous to enumerate in this paper. However, we can mention a few. They may derive from the system itself, using feedback or closed loop techniques such as channel equalization, or may be extracted from imbedded channel sounding (i.e., channel probes). As an alternative, system parameters from non-organic space-weather observables can be used. Examples include non-organic ionospheric sounding, and special software that validates and translates space-weather data into a data stream that can be readily and effectively assimilated by the system.

Much as we would like it, the engineer is certainly not going to invest in satellite systems that monitor the solar-terrestrial environment in order to get an estimate of media state specific to his specific system. An alternative approach is to subscribe to a service that transforms the hierarchy of solar-terrestrial and space-weather effects to system parameters, so that they could be used directly.

Another alternative requires a system design sufficiently robust to compensate for the most violent departures from climatology. This can be a costly proposition, and a robust engineering fix may limit the capability of the system itself.

For HF systems, the most important ionospheric properties are associated with the specified layers that are exploited for relatively long distance communication or surveillance. It is well-known that the climatology of these layers varies with time-of-day, season, geographical area, and sunspot number. However the real ionosphere, as opposed to its climatological proxy, is strongly modified by impulsive space-weather events. In recent years, accurate representation of the ionosphere has become the driving force behind many adaptive system improvements. This puts a premium on accuracy of nowcasts and forecasts. HF systems suffer from many space-weather events, and the most challenging ones are provided in Table 2.

It must be said that the most profound impact on satellite systems is the total elimination of system functionality. The investment in satellite systems, military and civilian, is enormous and growing. The demise of a satellite system represents not only a loss in capability, but a capital loss as well. While the direct cause of satellite malfunction may be unclear, there is no question that solar disturbances have led to the loss of a number of satellites. While the matter is important, it is not the focus of this paper. For the interested reader there is a general treatment of this subject by Carlowicz and Lopez (2002).

Table 2: HF Communication Systems and Space Weather Events: System Impacts

Space Weather Event	**Impacts**
Geomagnetic Storms	1. Large fluctuations in layer electron densities leading to coverage changes and, for negative ionospheric storms, reduction in the number of frequencies available for service. 2. TIDs leading to Direction-of-Arrival fluctuations and abnormal reflection effects.
Energetic Particle Events	Polar Cap Absorption causing long-term communication outages for arctic communications.
X-Ray Flares	Short Wave Fades (SWFs) on illuminated part of earth, especially near the sub-solar point, and at lower radio frequencies. These are often referred to as "blackouts".

The effect of the ionosphere on earth-space radio systems has been may be found in any number of publications, and will not be discussed in detail herein. Needless to say, an integrated "look" through the ionosphere leads us unmistakably to an awareness that the electron content (i.e., integrated electron density) is a key parameter. Table 3 gives a glimpse at the propagation effects that are related to the electron content of the ionosphere. Therefore measurements of the total electron content of the ionosphere, and global maps of TEC, are becoming important. GAIM technology has led to a growth in the number of investigators that are monitoring the TEC by exploiting the GPS constellation waveform.

Effects that are deemed to be of most significance in recent years are propagation disturbances associated with small-scale ionospheric structure causing scintillation of radio systems operating at UHF and above, and TEC effects that may impact performance of WAAS, DGPS, and single-frequency GPS sets. Magnetic storms appear to be the most important of the space-weather events that will give rise to the TEC effects, and one factor in high latitude scintillation is the growth in geomagnetic activity.

Table 3: Effects Related to the Electron Content

EFFECT	UNITS	FORMULAE
Faraday Rotation	Radians	$2.97 (10^{-2}) f^{-2} H_L (EC)$
Group Path Delay	Seconds	$\sim 1.34 (10^{-7}) f^{-2} (EC)$
Phase Path length	Meters	$-40.5 f^{-2} (EC)$
Group Path Length	Meters	$\sim 40.5 f^{-2} (EC)$
Phase Change	Radians	$-8.44 (10^{-7}) f^{-1} (EC)$
Doppler Shift	Hertz	$-1.34 (10^{-7}) f^{-1} d/dt (EC)$
Time Dispersion	Second/Hertz	$-2.68 (10^{-7}) f^{-3} (EC)$
Phase Dispersion	Radians/Hertz	$-8.44 (10^{-7}) f^{-2} (EC)$
Wedge Refraction	Radians	$40.5 f^{-2} d/dx (EC)$

Note: The units of EC are electrons/m^2, and H_L is that component of the geomagnetic field that lies along the ray path. The units are MKS (i.e., ampere-turns/meter). The Total Electron Content (TEC) is related to the EC by a secant factor. We have EC = TEC sec φ where φ is the ray zenith angle based upon a mean ionospheric height of ~ 400 km.

6. PREDICTION CONCEPTS

For those deeply involved in technological aspects of telecommunications, any variability in the propagation channel can represent a burden to be overcome. In general, measures that can be taken are either adaptive or robust. This author prefers to use the term *robust* to describe a system with a capability to operate satisfactorily, if not efficiently, in the benign environment but designed to provide sufficient margin or processing power to suffer the disturbed environment without further reduction in performance. These robust systems are designed to provide an even level of performance but not necessarily the best possible performance. The robust design approach is usually applied for strategic systems; typically low data rate communication systems. A robust system is designed not to fail, and for the communication systems, this may be at the expense of throughput. Some techniques utilized in robust system design include increases in transmitter power or antenna aperture, reduction in the symbol (information) rate, and various forms of diversity. Of course, these techniques can also be made adaptive. Another form of system architecture uses adaptively (i.e., parameter flexibility) explicitly. An *adaptive* system exploits knowledge of the propagation channel to adjust operational parameters actively so that they can best match the conditions and deliver the optimal performance under a given set of conditions. Long-term propagation predictions can be used in the design of both types of systems, but short-term predictions (i.e., forecasts or nowcasts) are required in the case of adaptive systems.

Predictions of telecommunications performance are an important guide for telecommunications requirements of military and commercial enterprises. Predictions may rely upon natural laws of physics—which are capable of being described in theoretical terms—or they may be founded upon the trends and patterns seen in stored data—in which case, the prediction method can lead to the development of quasi-empirical or climatological models.

Predictions have improved over recent years as a result of four factors: (a) high speed computers, (b) advanced computational methods, (c) data dissemination and access technology and (d) the development of advanced sensors.

The advent of communication satellites has prompted a significant advance in our global perspective, especially valuable in weather forecasting and its affect on telecommunications. Satellites have provided a unique collection of scientific data that has supplemented our basic understanding of cause and effect. Radio methods for earth-space and terrestrial skywave telecommunications are clearly influenced by ionospheric phenomena in a manner that is dependent upon the frequency used. HF systems are vulnerable to the widest range of ionospheric effects, and the magnitude of HF propagation effects provides a good index of intrinsic ionospheric variability. Moreover, since the HF medium is so sensitive to ionospheric effects, a major component of ionospheric remote sensing technology has been dominated by HF probes and sounding systems. This is now changing with the advent of satellite sensors and hybrid methods employing data assimilation techniques. Predictions, whether based upon HF sensors or other methods, allow one to cope with propagation variability.

One of the elements that can promote relatively accurate short-term predictions of system performance involves the process of model updating by incorporating live data from sensors that probe the temporal and spatial regions of the path of concern. In the context of HF skywave propagation, any sensor or probe, which permits ionospheric characterization of the critical portions of the path, can be a very useful. Under disturbed conditions, forecasts can lose significance in less than an hour (corresponding to the period of an atmospheric gravity wave) if probe information is less than complete or if the probe is not in close proximity to the so-called “control point” (*i.e.,* within a few hundred kilometers).

Other factors may similarly affect forecasts. For instance, the update data from the probe is subject to its own built-in errors in scaling and its own imprecision in converting raw data into useful information. Nevertheless, it is possible, in principle, to prepare forecasts that are accurate and useful.

The term *prediction* has a rather elusive meaning, depending upon the nature of the requirement for knowledge about the future. In the case of the ionosphere, a distinction is made between long-term predictions and short-term predictions. Long-term predictions of ionospheric behavior may be based upon climatological models developed from historical records for specified solar and/or magnetic activity levels, season, time of day, geographical area involved, etc. In many models the only space weather driver is the running mean sunspot number. Quasi-theoretical models based upon first-principles physics have also been developed, but these may also depend upon the specification of a number of constraints, boundary conditions, and driving parameters, some being similar to those used in the climatological models. The drivers used by both classes of models may themselves be stochastic. Thus, at least two sources of error occur in long-term predictions, one arising because of an imprecise estimate of the driving parameter, such as sunspot number, and the second arising from ionospheric variability, which cannot be properly accounted for in the model. Given these difficulties, it may appear surprising that the process can yield useful results, and yet it often does. Long-term predictions are necessary in HF broadcast planning and in other spectrum management activities where significant lead times are involved. They are also needed for both satellite and terrestrial systems when planning for operations in the future. For example, advanced knowledge of scintillation in a particular operational area will allow satellite communication managers to develop mitigation strategies or provide alternate methods for data retrieval

Short-term predictions involve time scales from minutes to days. The term *forecast* is sometimes used to describe those prediction schemes that are based on established cause-and-effect relationships, rather than upon simple tendencies based upon crude indices. In the limit, a short-term *forecast* becomes a real-time ionospheric assessment or a *nowcast.* In the context of HF communications, real-time-channel-evaluation (or RTCE) systems, such as oblique sounders, may be exercised to provide a *nowcast*. Such procedures are useful in adaptive HF communication systems. The term *hindcast* is sometimes used to describe an *after-the-fact* analysis of ionospherically dependent system disturbances. Solar control data are usually available for this purpose, and this may be augmented by ionospheric observation data.

The error associated with any prediction method is critically dependent upon the parameter being assessed, the lead-time for the prediction, and other factors. One of the most important parameters in the prediction of the propagation component of HF communication performance is the maximum electron density of the ionosphere, since this determines the communication coverage at a specified broadcast (or transmission) frequency. Thus, the ability to predict the maximum electron density of the ionosphere, N_{max}, is a necessary step in the prediction of HF system performance if skywave propagation is involved. For satellite systems, the ability to derive the distribution of ionospheric inhomogeneities is critical in any evaluation of scintillation at a specified frequency. In general, any space weather sensor that can be used as a driver for improved modeling or forecasting of the ionospheric state is important. For both skywave systems at HF and earth-space systems at VHF and above, predictions can be based upon climatology, quasi-theoretical models, or a combination of methods. Forecasts can start with a baseline prediction followed by timely updates using information extracted from non-organic space weather diagnostics or by information derived from the system under test. Nowcasts of system performance may be obtained by direct assessment of the system parameters.

7. USE OF SPACE-WEATHER DATA

The use of ionospheric measurements for development of accurate ionospheric maps has yet to be embraced by the civilian community in any significant way. This is true whether or not emergent Space-Weather data is actually applied for improved specifications (i.e., nowcasts and forecasts). There are a number of reasons for this, not the least of which is education. Education goes both ways. For example, the constituency of ionospheric specialists and Space-Weather advocates is not fully conversant with the problems of system architects and engineers. They don't know what is needed, and often offer solutions to the wrong problem. On the other hand, the community of system specialists has limited awareness of the growth of Space-Weather science and technology, and has no capacity to exploit the results. This has spawned a 3rd-party vendor community designed to fill the gap. Table 4 is a list of designated Space Weather Vendors. A number of them are members of the Commercial Space Weather Interest Group (CSWIG). This organization was spawned through with the support of NOAA-SEC, and group meetings are typically held at annual Space Weather Week workshops in Boulder, Colorado. We note that the emphasized vendors (i.e., boldface firms in Table 4) are commercial vendors that specifically offer space weather services or products for telecommunication systems. It should also be noted that the space weather community is global, and the European Community has inaugurated Space Weather activities similar to those organized in the USA.

Table 4: Partial Listing of Space Weather Vendors

Name of Vendor
Aerospace Corporation
ARINC
Metatech Corporation
Northwest Research Associates
Radio Propagation Services
Rockwell-Collins
Solar Terrestrial Dispatch
Space Environment Technologies/SpaceWx
Exploration Physics International
Community Alert Network
In-Flight Radiation Protection Services
High Altitude Radiation Monitoring Service
Federal Data Corporation
Electric Research & Management

There are a number of public sources of space-weather data on the Internet. Important sources include: (i) the NOAA-SEC family of sites, (ii) the various World Data Centers, and (iii) and sites affiliated with the International Space Environment Service (ISES). The Dynacast® service provided by RPSI makes use of these data sources. It should be noted that a number of organizations have published sites that incorporate similar information as may be mined from the NOAA-SEC URL.

8. Operational Terminals and Workstation Applications

We have mentioned earlier that the Naval Ocean Systems Center (now defunct) and the Naval Research Laboratory teamed in the development of a terminal concept for evaluation of system impairments introduced by ionospheric effects (Rothmuller, 1978). Space-weather data was provided by the SOLRAD satellite, and the terminal contained an imbedded set of simplified models that could be updated by the satellite data in real time. This was probably the first attempt to exploit space-weather data in an operational environment. Tests were successful but the program was eventually cancelled to fund other priorities.

A regional nowcasting and forecasting system for UHF and L-Band scintillation has been developed by the USAF and is currently being tested. This system, called SCINDA, utilizes data from terrestrial receivers to generate tailored products, and might be regarded as an intelligent scintillation detection and tracking system (Caton et al., 2002). The USAF has also developed an Operational Space Environment Network Display (OpSEND) that provides easy-to-visualize displays of space-weather effects on designated systems. Nowcast and forecast options are available (Bishop et al, 2002).

9. Strategies for Combating Space Weather Influences

From a communication vulnerability perspective, space-weather influence derives from two classes of data: (a) ionospheric (or *downstream*) data, and (b) exoionospheric (or *upstream*) data. The *upstream* space-weather information can have a significant operational impact on terrestrial HF and SATCOM systems only if accurate forecasting algorithms relating the *upstream* data to pertinent ionospheric disturbances (i.e., the *downstream* data) can be developed. Such information will aid in top-level resource management decisions.

In the context of short-term forecasting and nowcasting, near real-time assimilation of ionospheric data (e.g., GAIM technology) is preferred over methods based upon purely *upstream* data assimilation. However neither approach should proceed in a vacuum. Without meticulous assimilation of the upstream and downstream data, a real solution to the forecasting problem will not be obtained.

This solution is in fact a primary goal of the National Space Weather Program. It is encouraging to see that in the priority list showing the key physical parameters for the ionosphere and the thermosphere, the Space Weather Program Implementation Plan has the following listed as among the 1st priorities: *Ne* and its intrinsic variability and $\delta Ne/Ne$ (NSWP, 2000).

For certain communication systems, an accurate specification or forecast of the geoplasma distribution is a key ingredient to the improvement of performance. Robust systems have been developed, based upon the gloomy prospect that this “key ingredient” will never be available in a timely or with sufficient accuracy. But these robust approaches are more limited than should be necessary.

Some basic needs include the development of new and/or improved physical relationships between space-weather parameters (e.g., IMF characteristics) and the global distribution of Ne in the ionosphere and plasmasphere. In addition we need further development of sensors and/or techniques for the timely delivery of space-weather parameter. When it comes to specific systems, impairment that may arise from space weather events is a difficult issue to address. For most commercial system managers, there is a real disincentive to announce problems in a competitive environment. The government-run systems are typically more open when it comes to the identification of problems and the search for solutions. Disclosure is assisted when the problems are hard to hide, as in the case of various legacy systems, such as HF communications. It is certainly true that most people understand that systems operating at HF and below are constrained by the ionosphere, and that this constraint may become a hangman’s noose when strong space weather events occur. For satellite systems, the matter becomes less clear. The author spent many years trying to identify space weather issues to telecommunication managers, and to encourage the incorporation of available information into their thinking. The activity was not always successful, except at HF. One of the early HF success stories was the development of a system performance prediction platform, called PROPHET, which was developed by U.S. Navy engineers at Naval Ocean Systems Center, now SPAWAR, and the Naval Research Laboratory. It is felt that this forecasting terminal, described in Section 8 was of major significance in that it was the first system to exploit space weather data in real time for the benefit of the ultimate user, the naval communicator. This prediction system actually supplied tailored products based upon space weather data to the system operators, and they were delighted. There are now other systems that use a similar, but more advanced approach. Getting tailored information to the user is extremely important, especially if he can do something with it.

Everyone recognizes that HF communication systems have a bad reputation, and most feel this reputation is richly deserved. The HF radio band (i.e., 3-30 MHz) is extremely vulnerable to ionospheric effects under the best of circumstances. During disturbances caused by space weather conditions, individual circuits can be annihilated or rendered virtually useless. At other times predicted coverage patterns may become distorted by magnetic storms, and sporadic E phenomena may introduce deleterious screening effects. In short, the situation can be quite unpleasant for a communicator unless steps are taken to cope with the environment. As odd as it may seem, some circuits may actually be improved with respect to climatological projections. The secret to making adaptive HF systems perform optimally is to track the channel conditions. Optimal system performance for a given circuit is achieved if one can successfully match the system parameters to channel conditions. This matching process is not always possible, but there are successful methods for approaching the ideal situation. One method is to employ sounding. This is usually achieved with an imbedded sounder to derive channel properties, but it can involve nonorganic sounders as well. Modern ALE systems employ an imbedded channel probe to assist in organization of an optimal transmission frequency scan list. While there is some vulnerability to imbedded sounding, it is currently the method of choice. These methods have been described by Goodman [1992] and in the ALE Handbook [ITS, 1998]. In the final analysis, the best way for HF systems to cope with space weather events is to apply two principles of design and operation: diversity and adaptivity.

For satellite communication and navigation systems, the main problem without question is amplitude and phase scintillation. What role does the space weather community play in mitigation of this particular effect? To answer this, we need to understand the phenomenology of scintillation, and the main drivers. We must also be aware that climatological solutions are inadequate but they do provide guidance. There are several flavors to the solution, and they begin with a set of possible countermeasures that may be imposed by the system, given proper space weather data. Satellite communication systems typically operate at a fixed frequency, so that frequency management is not really an option. In any case, scintillation is correlated over a wide range of frequencies limiting any frequency management options that might exist. It goes without saying that satellite communication systems are designed to cope with a range of fading conditions, and they exploit time and space diversity to counter the generic problem. However no system can easily recover from severe scintillation events without some loss in throughput.

Outside the military arena, it is hard to find many telecommunication systems that take space weather into account as an integral component of the system. In the commercial world, designers typically use diversity to circumvent or mitigate against various forms of impairment. This process is not always successful even for systems that use frequencies at L-band and above. The GPS constellation is a case and point. As indicated above, scintillation can persist well into the GHz frequency regime. While GPS, like many satellite radiocommunication systems, can suffer scintillation in phase and amplitude, it has been designed to eliminate the impact of group-path delay errors associated with TEC. Two-frequency receivers can eliminate the ionospheric effect since the GPS L1 and L2 channels suffer different amounts of signal delay for a fixed level of TEC. By measuring the time delay (or phase path) difference between the two channels, one can solve for the TEC, and using this information, subtract the excess path delay due to the ionosphere. Unfortunately two-frequency GPS systems are expensive, and equipage is not widespread. However, engineers are not without imagination. For example, DGPS systems, used by the U.S. Coast Guard, among other organizations, exploit judiciously located (and fully equipped) reference stations that develop corrections for users within a certain correlation distance. The accuracy of DGPS systems is directly related to the separation between the reference station and user set. The FAA WAAS system uses a similar principle, but is far more sophisticated.

A number of forecasting schemes and systems exist. For the most part, the outputs (i.e., the forecasts) must be transmitted to system operators who use the data to modify system parameters or operational rules. In short, the forecasting systems are usually non-organic in nature. Non-organic strategies predominate because the alternative methods imply increased cost and complexity, but, sadly, lack of foresight is another reason. Of course, it makes no sense to invest in organic forecasting systems if the forecasts are not associated with a clear-cut mitigation strategy. Below we discuss a well-known and widely disseminated HF system that operates effectively in a dynamic, if not perturbed environment.

Automatic link establishment (ALE) is an HF system process that automates many labor-intensive operator manipulations. It also has the provision to use organic sounding to exploit the most appropriate propagating band from among those available. While the system is superior to conventional HF radio, it is still vulnerable to ionospheric effects. ALE systems could be designed to exploit space weather information, including real-time ionospheric data, but ALE processes do not include this option at present. To cope with ionospheric effects, ALE systems exploit diversity countermeasures without the benefit of space weather data to “steer” the system parameters. Under moderate disturbances ALE systems can perform quite well, and operators are generally well satisfied with ALE, certainly in comparison with the performance of plain vanilla HF radios. However, under highly disturbed conditions, an ALE network can spend an inordinate amount of time reorganizing itself for optimal operation. With space weather nowcasting and forecasting information, it might be possible to improve the efficiency of link establishment and link maintenance functions. It should be noted that such a suggestion is unlikely to gain much traction, since the ALE fairly is fairly efficient with its existing frequency management strategy, and non-organic improvements are likely to be an unwelcome expense. In any case, HF-ALE does *not* belong to the class of systems that have provisions for combating influences of space weather directly. But by virtue of its design it can perform adequately in the face of modest space weather effects. The key to an efficient HF-ALE network is the way the scan lists are developed and exploited.

There are at least two specific systems that exploit space weather directly. Like HF-ALE radio systems that are deeply rooted in the aviation community, these additional systems also support commercial and military aviation. They are: (i) the ARINC GLOBALink/HFDL system, and (ii) the FAA-WAAS system. In this paper we discuss only the ARINC system. More details are found in a recent book by Goodman (2005).

10. Motivation for Study

The Halloween storm period of October-November 2003 was a period of significant ionospheric effects. Large geomagnetic storms were evidenced, and Figures 2 and 3 show the progression of sunspots and estimated magnetic activity respectively. Table 5 is a sampling of system impacts that were compiled by Joe Kunches (2004).

From Table 5, we note that most of the reported telecommunication disturbances involved bands at HF and below. Exceptions include propagation disturbances on the GPS (i.e., L-band) system transmissions and on WAAS, a system that exploits GPS. Clearly there were many more satellite systems that were similarly afflicted by radio scintillation effects, especially VHF and UHF systems. Many of these are military systems and not faithfully reported in such a way as to be ingested into the NOAA or ISES catalogues of disturbances.

It is noteworthy that while HF systems are generally quite vulnerable, we note that the HFDL system is virtually unaffected by the Halloween storm. This may seem odd, but is an understandable consequence of the power of diversity. The most vulnerable HF systems involve individual communication links or non-cooperative propagation scenarios (i.e., DF nets and HF broadcasts). HF networks with full diversity can have limited vulnerability, if designed properly.

Table 5: Sampling of System Impacts during the 2003 Halloween Storm Period (October 19th – November 7th, 2003). Compilation due to Kunches (2004).

Aircraft communication systems at HF/VHF suffered severe degradation and periods of complete blackout (above 57 degrees N) during Polar Cap Absorption (PCA) events caused by radiation storms.
Terrestrial HF communication systems experienced outages during radiation storms (i.e., PCA) for arctic paths.
Trans-polar flights of a major U.S. carrier were re-routed (equatorward) from Polar-3 to Polar-4 routes to avoid radiation hazards associated with radiation storms (i.e., enhanced energetic flux).
There were difficulties with long-haul HF communication circuits associated with trans-Atlantic flights, requiring extra operational staff and the use of backup systems.
The United States Air Force experienced degraded HF communications for stations at San Francisco, Keflavik (Iceland), and Kodiak (Alaska).
The Voice of America (VOA) experienced outages and anomalies on HF broadcast programs during Short-Wave-Fades (SWFs) and magnetic storms.
HF communication systems encountered radio blackout conditions for solar-illuminated paths due to SWFs.
HF radio relay paths in Antarctica experienced over 130 hours of blackout during the Halloween storm period cited.
Loran-C experienced RFI problems.
The U.S. Navy Re-Locatable OTH Radar (ROTHR) had operational difficulties (unspecified)
Some features of the GPS-based WAAS system were interrupted in the continental USA. However, the system alerted appropriately, and no failure was reported.
GPS receiver outages occurred at high latitudes
The ARINC GLOBALink/HF (i.e., HFDL) system suffered minimal impairment, and the system operated as designed.

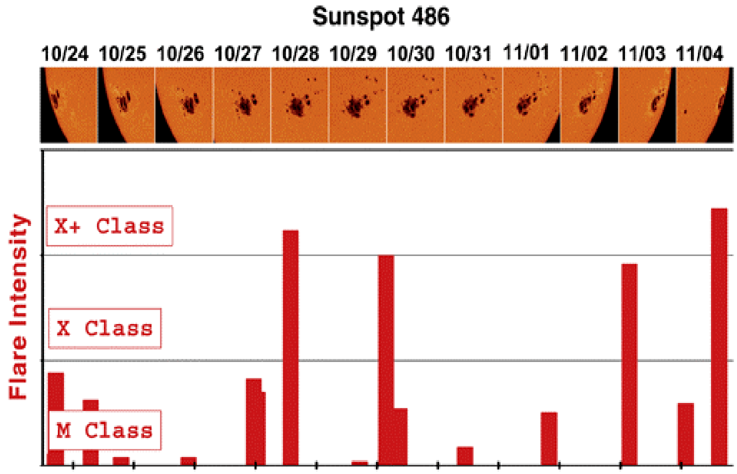

Figure 2: Progression of Active Region 486 during the period from 10-24-04 and 11-04-04. The figure is from Simpson (2003). The image is due to the NASA-SOHO program, the flare data is from NOAA, and the compilation is by Metatech Corporation.

Below we have provided a combined excerpt of NOAA-SEC *Advisory Outlook #03-44* and *Space Weather Advisory Bulletin #03-5.*

Summary for October 27-November 4, 2003:

Space weather during the past week reached extreme levels. The dynamic solar region, NOAA Active region 486, continues to produce high levels of solar activity. Region 486 produced a category R4 (severe) radio blackout on October 28 at 11:10 UTC. Associated with this flare was a category S4 (severe) solar radiation storm beginning at 0025 UTC on 29 October. A coronal mass ejection (CME) was also associated, and it produced a G5 (extreme) geomagnetic storm starting at 0613 UTC on 29 October. This persisted at the G3-G5 levels for 24 hours. Region 486 continued to produce solar activity with yet another major flare at 2049 UTC on 29 October, resulting in an R4 (severe) radio blackout. A CME was also associated with this flare. Moving at 5 million miles per hour, the CME impacted the earth's magnetic field at 1620 UTC on October 30th, and produced a category G5 (extreme) magnetic storm. Stormy conditions persisted for 24 hours. Region 486 grew to become the largest sunspot region of cycle 23.

Giant sunspot region 486 unleashed another intense solar flare on November 4th at 1950 UTC. The blast saturated sensors onboard GOES satellites. The last time that happened, in April 2001 (i.e., near the peak of the cycle), the flare that saturate the sensors was classified as an X20, the biggest ever recorded at that time. The November 4th flare appears to have been stronger. Because sunspot region 486 is near the sun's western limb, the blast was not directed toward earth.

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We have examined the impact on HFDL of the various phenomena observed during this period. We have found some impact on HFDL performance for the October 29-31 period, but it is manageably small in amplitude. While HFDL is based upon HF propagation, a medium known for its vulnerability to ionospheric variability, the system performance metric does not reflect this vulnerability to a significant degree. This is thought to be the result of the substantial amount of diversity built into the system, including a diverse network of ground stations, and adaptive frequency management system, Dynacast®, a system developed by RPSI. The adaptive frequency management system involves the use of active frequency tables (or AFTs) that are based upon space weather observables. During the stormy weeks of October and November, ARINC issued over seven changes to the AFTs used by every HFDL station. These changes helped the HFDL network to maintain a delivered message success rate of 97%. The paper outlines how this was accomplished. In that context, we examine the attributes of diversity in mitigating against the impact of large disturbances.

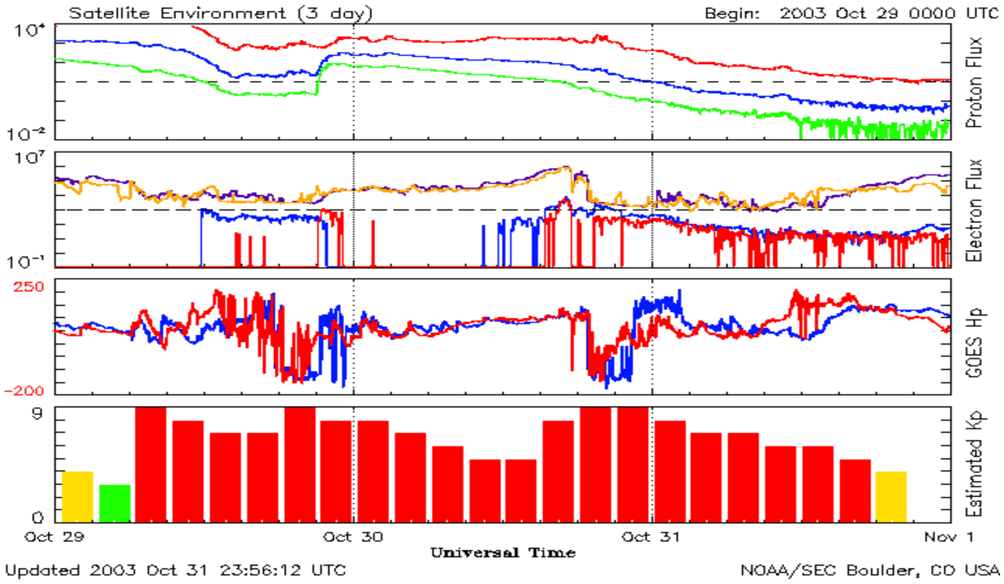

Figure 3: The Satellite Environment plot obtained from the NOAA-SEC "Today's Space Weather" web page. The top plate depicts the energetic particle flux (and potential PCA activity), while the bottom plate depicts the effective magnetic activity index Kp.

11. GLOBALink/HF Description

The GLOBALink/HF system, developed and managed by ARINC, is a global high frequency data link communications network providing service to commercial aviation worldwide. It consists of 14 ground stations located around the globe, and a network control center located in Annapolis. The system was designed to provide reliable aircraft communications through the use of multi-station accessibility, quasi-dynamic frequency management, and a robust time-diversity modem with equalization. Although HF (i.e., 3-30 MHz) signaling has a poor reputation when considering individual circuits, it has been shown that near-real time channel evaluation and/or adaptive frequency management can improve performance considerably. Moreover, multi-station network operation provides an additional form of diversity, which is probably the most valuable design strategy. Our paper briefly describes the system, but a major segment of the discussion will be about performance metrics derived during geomagnetic storms, and especially the Halloween storm period of 2003.

In the context of space weather, the GLOBALink/HF system counters pathological changes in the environment by selecting frequencies that are optimal for use under current conditions. This is achieved by continuously monitoring the environment through a Dynacast® system that delivers Active Frequency Listings (AFTs) to the network operations center in Annapolis, MD. In practice, the delivery cadence of these independent AFT listings is very slow, about once per week, if there are no storms involved. The AFTs in that instance simply reflect the normal daily variations of the global ionosphere. Storm times create the excitement and can drive sharp increases in the AFT delivery cadence.

High Frequency Data Link (HFDL) is certified and has industry approvals based upon findings of the International Civil Aviation Organization (ICAO), the Radio Technical Commission for Aeronautics (RTCA) and the Airline Electronic Engineering Committee (AEEC). ARINC is the sole provider of HFDL service (viz., GLOBALink/HF), which was inaugurated in 1995. The HFDL data transmission speed is governed adaptively by the prevailing radio propagation conditions. The rates are 300 – 1800 bps. These rates are relatively low but acceptable for the mission involved. There are 14 ground stations as listed in Table 6 to satisfy global coverage requirements, including polar coverage. Table 7 gives the general properties of the system.

Table 6: **Ground Network for HFDL System**

Station	Station Designation	Latitude	Longitude	Geomagnetic Latitude	Global Service	Polar Service
Dixon, CA, USA	H01	38.38 N	121.76 W	+44	Yes	Yes
Molokai, HI, USA	H02	21.18 N	157.18 W	+23	Yes	
Reykjavik, Iceland	H03	64.08 N	21.85 W	+65	Yes	Yes
Riverhead, NY, USA	H04	40.88 N	72.64 W	+52	Yes	Yes
Auckland, New Zealand	H05	37.02 S	174.81 E	-43	Yes	
Hat Yai, Thailand	H06	6.94 N	100.39 E	-7	Yes	
Shannon, Ireland	H07	52.73 N	8.93 W	+51	Yes	Yes
Johannesburg, SA	H08	26.13 S	28.21 E	-37	Yes	
Barrow, AK, USA	H09	71.30 N	156.78 W	+70	Yes	
Santa Cruz, Bolivia	H13	17.67 S	63.16 W	-9	Yes	
Krasnoyarsk, Russia	H14	56.17 N	92.51 E	+52	Yes	Yes
Al Muharraq, Bahrain	H15	26.27 N	50.64 E	+21	Yes	
Pulantant, Guam	H16	13.47 N	144.40E	+9	Yes	
Las Palmas, Canary Is.	H17	28.12 N	15.28 W	+18	Yes	

Of the 14 ground stations listed in Table 6, three of them are clearly within the equatorial region (viz.., Hat Yai, Santa Cruz, and Pulantant); three are near the crest of the equatorial anomaly (viz., Molokai, Al Muharraq, and Las Palmas); two would be classified as high latitude sites (viz., Reykjavik and Barrow), and the remainder would be considered midlatitude sites. Of the high latitude sites, Barrow is always poleward of the auroral oval and would be expected to represent polar cap conditions; whereas Reykjavik is typically a site that straddles the oval. Due to the fact that the auroral oval, a primary geophysical marker, can move decidedly equatorward under magnetic storm conditions, a number of stations could be considered transient high latitude sites (viz., Riverhead, Shannon, and Krasnoyarsk) when *Kp* indices are highly elevated.

Figure 4 is a map of the HFDL network of ground stations, and Figure 5 illustrates commercial air traffic for a given day. It is obvious that the traffic pattern is not a uniform distribution. Moreover the traffic patterns display well-known diurnal patterns and seasonal tendencies. Other factors such as world conditions (i.e., economy, war, calamity, etc.) can also drive the patterns askew. Figure 5 is a 24-hour representation for May 26th, 2004.

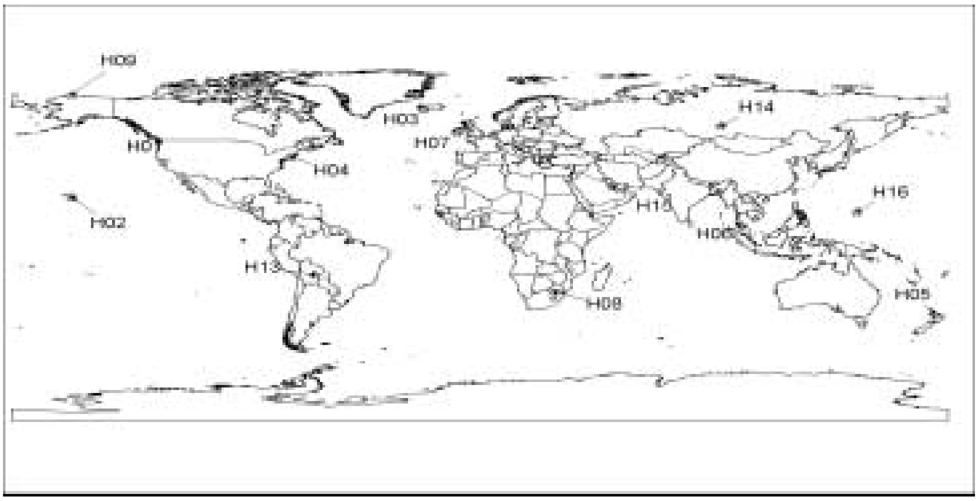

Figure 4: Map of the HFDL network (GLOBALink/HF). From ARINC, by permission.

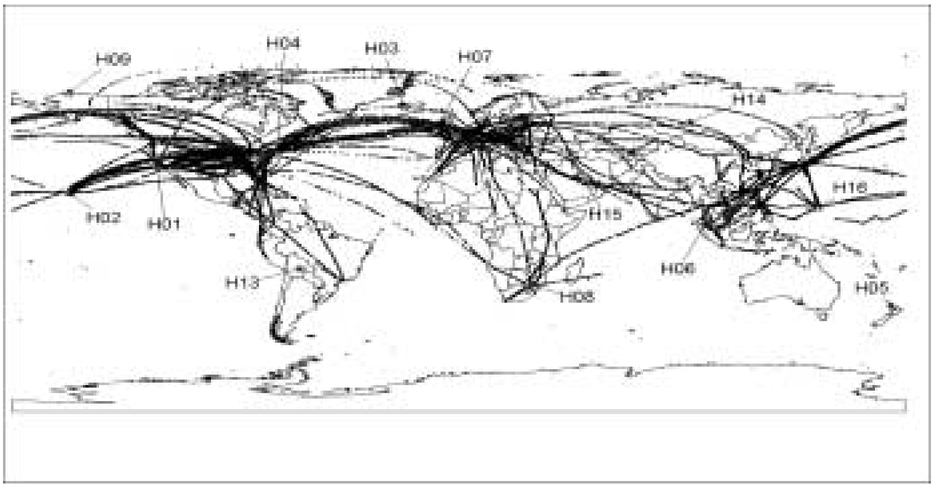

Figure 5: Map exhibiting aggregate commercial air traffic using HFDL for a representative day (i.e., May 26, 2004). There is no time information retained in such composite plots, but they show the general traffic patterns. There is obviously more traffic in the Northern Hemisphere, and there are certain corridors that dominate the commercial traffic. From space weather analysis perspective, the more dense traffic regions are the ones that demand the most attention

Table 7: Characteristics of the GLOBALink/HF system

- HF data radio (ground segment and aircraft)
    - Modem uses adaptive equalization for optimum receiver performance (decision feedback)
    - TDMA protocol for message collision avoidance
    - Unique Squitter message and format for system status for protocol control and timing information
- Constellation of 14 ground stations
    - Two transmitters per station
    - Interconnected network
- Network Control (Annapolis)
- Non-organic Frequency Management System (Dynacast®)
    - Weekly AFTs derived from climatology as updated by short-term forecasts of solar-terrestrial observations (e.g., space weather)
    - Emergency AFTs derived from nowcasts and short-term forecasts of the environment (i.e., current *Kp* time history, sounder data, etc.

The frequency management subsystem of GLOBALink/HF involves an appreciation of HF propagation (i.e., coverage patterns) for all propagating frequencies as well as airline traffic patterns. While knowledge of real-time ionospheric conditions is primary in an adaptive frequency management system, we need to derive a set of canonical coverage patterns over which frequency optimization is to be established. While purely dynamic considerations are possible in the pattern analysis, it was decided to convolve the seasonally-averaged traffic patterns with the standard HF coverage associated with each ground station, taking the system parameters into account (i.e., antenna, transmitter power, etc.). To first order, this is a modification of the plain vanilla model (i.e., VOACAP and/or ICEPAC). However, in this instance, the gridpoint population defining the desired coverage is weighted by the aircraft traffic patterns.

At any given time, an HFDL ground station is designed to activate two distinct frequencies. The challenge is to activate the best two bands for the desired coverage area for each ground station from among a limited group of available frequencies. This generally requires a real-time adjustment in the ionospheric model that is used to derive the propagation parameters. The data sets used as input to the modified ionosphere come from vertical sounders and oblique-incidence sounders. Other options include the use of global TEC maps suitable analyzed to derive an estimate of the near real time *foF2* values for insertion into the propagation model. The Dynacast program manages this process and provides an optimal pair of frequencies for each station, taking potential interference and other factors into account.

The frequency management product used by HFDL is called an Active Frequency Table (AFT), a computer file that specifies the active frequencies for each ground station over a 24-hour period. Under benign conditions, the Dynacast system submits weekly versions of the AFT; but Emergency AFTs are submitted to net control as required by space weather conditions. Emergency AFTs are needed during certain pathological conditions, with ionospheric storms and PCA events being prime examples. Emergency AFTs are also needed if certain system elements are changed (i.e., new frequencies added, etc.) Network control disseminates the AFT files to all ground stations for coordination and action. The GLOBALink/HF system includes the features given in Table 6.

The communication traffic for the HFDL system generally exceeds 400,000 messages per month and the average message success rate is greater than 97%. This is comparable to satellite availability and is far better than typical HF voice circuits, even under benign conditions. This clearly shows the benefit of (i) a multi-node network architecture (i.e., for path diversity), (ii) an adaptive HF data radio using (i.e., exploitation of time diversity and code diversity), and (iii) adaptive frequency management (i.e., frequency diversity).

12. Diversity Experiments as a Basis for HFDL (or “Why HFDL is effective”)

It has been shown [Goodman et al., 1997] that HFDL communications can be as reliable as satellite systems given the diversity attributes than can be applied. Frequency diversity is well established as a way to improve communications connectivity for point-to-point circuits. Since aircraft have multiple opportunities for connectivity (i.e., in terms of stations and frequencies), it should not be a surprise that HFDL can be successful. For example, if an aircraft has access to 8 bands per station and four stations within the calling area, there are potentially 32 independent circuits to choose from. In general there are fewer circuits than this, but the diversity is still substantial. By contrast, a satellite circuit, while advantaged in other ways, does not have the same diversity advantage (i.e., station and frequency diversity). It has been pointed out that a combination of satellite and HF data link can provide a very high level of connectivity. Since the failure mechanisms of HF and Satcom are likely to be different, an HF unavailability of 0.9 and a Satcom availability of 0.99 implies a composite availability of 0.999 or an unavailability ~ 9 hours/annum or ~ 1.5 minutes/day. Given this high system availability, what can we say about the distribution of residual system outages? As one would expect, there is a tendency for one class of residual outages to cluster in the temporal neighborhood of space weather disturbances. Other outages are systematic and unrelated to space weather.

A comprehensive study of HF propagation conditions was carried out between 1994-1997 using Chirpsounder® assets. Figure 6 depicts the geometry of the campaign. The SNRs for all frequency bands in the aeronautical spectrum were continuously monitored and archived for a substantial number of propagation paths in the Northern Hemisphere [Goodman et al., 1997]. From this database, it was possible to deduce the availability of communication for selected subnetworks. This experimental investigation was the basis for certain feasibility studies for HFDL during architecture and standards development. Four subnet clusters were examined, each having a four-pronged star configuration, meaning that each clusterhead, simulating an aircraft position, was always connected to four other nodes. The clusterheads for the star subnets, arranged in order of highest geomagnetic latitude to the lowest, were located at Churchill (Canada), Reykjavik (Iceland), St. Johns (Newfoundland), and Henrico (North Carolina). Figure 7 is an examination of stormy and quiet conditions. It is clear that stormy conditions can introduce significant (but not devastating) unavailability increases for the highest latitude networks (i.e., Churchill and Reykjavik). For the St. Johns clusterhead the effect was small, and for the Henrico clusterhead the effect of storms was virtually non-existent. It is noted that the communication availability is close to 95% even for high latitudes under the worst possible conditions. Naturally, one would not expect this for individual HF circuits. This was strong evidence that HFDL would be successful once implemented.

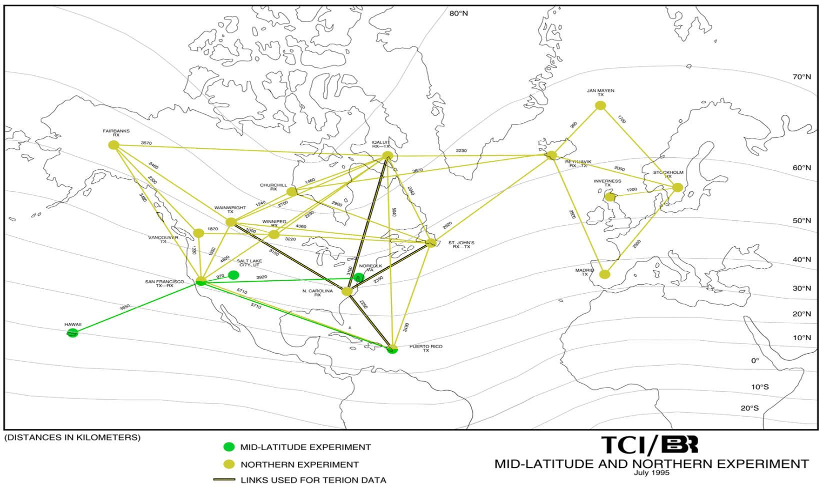

Figure 6: Geometry of the Northern Experiment directed by TCI/BR Communications. From Goodman et al. [1997].

13. Halloween Storm Impact on HFDL

As previously observed, the Halloween storm period of October-November 2003 was a period of significant ionospheric effects. Patterson [2004] of ARINC has examined the impact on HFDL of the various phenomena observed during this period, and has provided certain data shown in Table 7. It is a listing from October 19th – November 7th of a daily metric that is proportional to the performance of the global HFDL system. We have added the magnetic activity index *Ap* for comparison. We see that some impact on HFDL performance on October 29-31 may be arguably present, but it is minimal in amplitude. While HFDL is based upon HF propagation, a medium known for its vulnerability to ionospheric variability, the system performance metric does not reflect this vulnerability to a significant degree. Some of these results have been presented at AGU (Goodman and Patterson, 2004).

Table 7: **HFDL Performance during the Halloween Storm period (10/19/2003 to 11/07/2003). The metric selected is the uplink block success rate in percent. The Uplink Metric data is provided by Patterson (2004), courtesy of ARINC. The *Ap* data were obtained from NOAA-SEC.**

Date	Uplink Metric	Est *Ap*	Date	Uplink Metric	Est *Ap*
Oct.19	59	32	Oct.29	51	189
Oct.20	63	30	Oct.30	55	162
Oct.21	59	39	Oct.31	55	93
Oct.22	58	33	Nov.01	56	21
Oct.23	58	07	Nov.02	59	18
Oct.24	57	34	Nov.03	57	10
Oct.25	58	14	Nov.04	57	31
Oct.26	59	10	Nov.05	57	09
Oct.27	56	15	Nov.06	60	14
Oct.28	60	20	Nov.07	57	08

In Table 7 we are actually dealing with the uplink block success rate. The message success rate is much higher since there are typically several attempts made to send a block of data, and time diversity provides a sizable gain in most instances. The diversity gain can be significant if the tries are independent and if multiple tries are attempted within the allotted time span. For example, if the block success rate is 60%, and four tries are afforded, the maximum block delivery rate would be > 99%, using statistical arguments. More than four attempts can be made to attempt transmission of a given block. On the other hand, some messages may be larger than a block in length. So we see that time diversity and ARQ technology provides a significant diversity gain. Moreover, there are other connectivity and throughput "opportunities" afforded by path diversity and frequency diversity as previously stated.

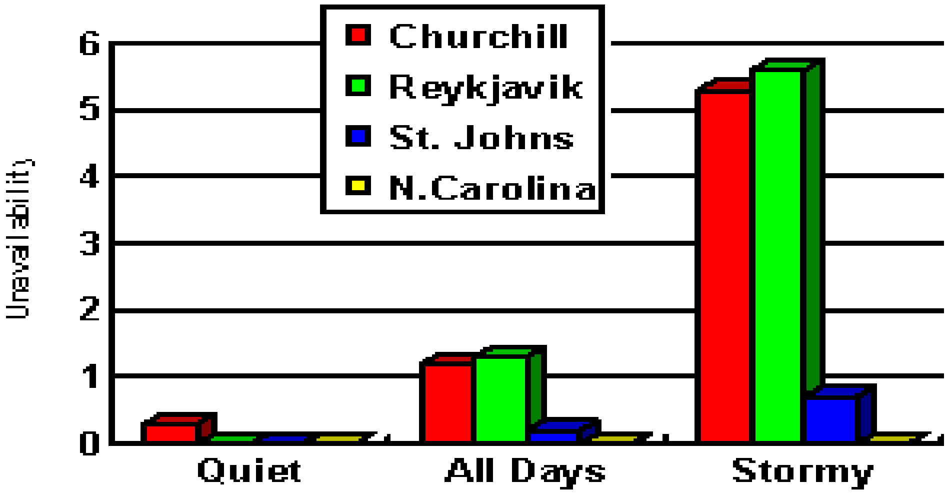

Figure 7: Simulation of the impact of storms on diversity networks such as HFDL. Real data from oblique sounders was used in the simulation. The conditions are for four star-net clusters during April of 1995, a period of wide-ranging *Ap* values. The clusterheads are at Churchill, Reykjavik, St. Johns, and northeastern North Carolina, and each cluster consists of four paths terminating at the clusterhead. Each star-net had access to one frequency in each of the eleven aeronautical-mobile bands, and these frequencies are shared between the four links of the cluster. The most stormy period was between 7-12 April when 22>*Ap*>100. From Goodman et al. [1997] and ITU-REC.F.1337.

It is evident from Table 7 that the three lowest reliability days, in terms of the uplink block success rate, are October 29-31. While this is interesting, a fully satisfactory interpretation is elusive. The globally-averaged block success rate (i.e., the specified metric) is minimally affected by magnetic activity for the period Oct. 29-31, when the super-storm activity occurred (viz., average *Ap* ~ 148), since a moderately suppressed metric value of ~ 54% was observed as three-day average. In fact, a moderately suppressed value of ~51% on the single day of largest Ap (i.e., October 29th when *Ap* =189). But there also some inconsistences in the results, which suggests that other phenomena or systematic problems may be masking the space-weather effects. Masking would be possible if the space weather effects are of the same order of magnitude as the systematic effects. These issues are being examined in greater detail in a paper appearing in an upcoming issue of Radio Science. (Goodman, 2005).

Patterson and Grogan [2004] remark that “ARINC engineers monitor the solar data coming from the NOAA satellites and issue frequency changes to the ground stations that will be impacted by the solar event.” They go on to say, “this is the heart and soul of the adaptive frequency management system of HFDL. During the stormy weeks of October and November, ARINC issued over seven changes to the Automatic Frequency Tables (i.e., AFTs) used by every HFDL station. These changes helped the HFDL network to maintain a delivered message success rate of 97%”. The adaptive frequency management system referred to by Patterson and Grogan is the RPSI Dynacast® system, discussed earlier.

14. Discussion of HFDL Response to Space-Weather Events

We have indicated that diversity is the secret to reliable communication for a network that is challenged by ionospheric variability. The HF band is thought to be the most seriously compromised part of the spectrum since HF systems rely upon the most pathological regions of the ionosphere to achieve coverage and connectivity. It cannot be avoided. While HF is known to be very unreliable under most conditions, we can design a communication network such that highly reliable performance can be achieved. While frequency diversity is an obvious advantage, the power of station diversity is of major significance. We have found that the network-wide throughput is generally acceptable even in the face of the largest of magnetic storm episodes. This is largely the result of the way the HFDL system accommodates to regional variabilities. While conventional wisdom suggests that aircraft communication is best when the ground stations are within one hop (i.e., nominally 4000 km), it is also true that longer paths can sometimes provide the highest signal-to-noise ratio; especially if the shorter paths traverse pathological regions (i.e., auroral oval, trough, etc.). Moreover higher frequencies, typically used at greater distances, will compete with a lower noise background since ambient noise (viz., man-made and atmospheric) decreases with increasing frequency. The protocol for HFDL allows for any aircraft to communicate with any ground station in the global network. In principle, any aircraft has up to 30 opportunities to interact with the HFDL network, as there are 12 two-channel and 2 three-channel ground stations distributed globally. In most instances, it is unlikely that all propagation paths from a given aircraft would be totally impaired.

It was noticed that communication traffic tends to “migrate” from one sector to another in response to regional propagation impairments. Given the remarks above, this discovery is reasonable. Even without comprehensive data examination, we would expect such a thing to happen. For example, we would expect high latitude stations to carry less traffic during the early phases of a magnetic storm, leading to more traffic being supported by midlatitude stations. This, in turn, should lead to more competition for use of midlatitude stations, and some migration toward equatorward stations.

During x-ray flares, we would expect lower bands near the sub-solar point to be preferentially disturbed. Thus longer paths (and higher frequencies) will be exploited, along with paths for which the D-region intercept points are associated with higher solar zenith angles. The migration effect in this case would tend to be in the poleward direction and toward the hemisphere not illuminated by the sun. The traffic migration phenomenon, if borne out by more detailed analyses, is a major factor in the relatively healthy performance of HFDL during disturbances. It is our intent to explore this matter more extensively.

In summary, we have found that the HFDL network is remarkably resilient, even in the face of strong magnetic storms that effect the ionosphere adversely. For the Halloween storm period of 2003, the aggregate throughput efficiency was of the order of 97%, good by most standards. The relationship between the aggregate global performance metric and *Ap* index was not precise, but only the most elevated levels of *Ap* appeared to reduce the message delivery efficiency noticeably. Still the overall performance was generally acceptable. There are still ways to improve the HFDL performance, through invocation of improved ionospheric specification as the driver for Dynacast predictions, and we are actively exploring data-driven assimilation models such as GAIM for this purpose. Other improvements include access to additional frequencies (and transmitters) in areas where coverage is sparse. From a system perspective, the traffic migration effect is being examined as another factor in Active Frequency Table revisions as a function of storm time.

15. Conclusions

There is certainly a growing awareness of space weather. There are a variety of space weather programs sponsored by government agencies, and there are periodic symposia that emphasize space weather initiatives and research. There are several new books on the market (e.g., Goodman, 2005; Hanslmeier, 2002) that examine space weather in light of the impressive growth in global monitoring capability and data assimilation technology. McCoy (2001) has noted that our "ability to model and forecast the global ionosphere lags significantly behind current capabilities to model and forecast global (tropospheric) weather". But McCoy points out that the situation is steadily improving, with the advent of new monitoring systems, and with the likely success of GAIM technology. With all this activity as a backdrop, our paper examines various system vulnerabilities.

We have examined the vulnerabilities of telecommunication systems as a function of space-weather. While generalizations are dangerous, for the most part we are concerned with the ionosphere, where nowcasting or short-term forecasting of the propagation medium assumes a primary role. Traditional space-weather observables, augmented by ionospheric parameters derived from soundings and TEC measurements developed from GPS technology, are gaining increased significance as data assimilation and specification systems achieve a degree of maturity. We find that there is a logical distinction of telecommunication systems based upon whether or not the ionosphere is required to satisfy their requirements, or whether the ionosphere is simply a nuisance. We have concluded that the major space-weather impacts arise for systems in the HF band or below. This is hardly a surprise for anyone familiar with the Appleton-Hartree equation. What is surprising is that HF systems, the most precarious of the systems examined, can be designed to achieve performance reliabilities that rival satellite communication systems. We look at several HF systems that use space-weather data, and discuss the ARINC GLOBALink/HF system in some detail. The reader should come away with the lesson that diversity schemes and good engineering can transform a previously vulnerable HF system into a relatively robust one. If diversity measures are made adaptive with the incorporation of real-time representations of the ionosphere, and space weather forecasts, the situation will improve even more.

Not all telecommunication systems are impaired by space-weather events. There are also some systems that suffer impairments that are unrelated to space weather. If space weather is effective, then the gross effects are limited to systems using radio frequency bands below a few GHz, The two effects of most concern to operational space systems are radiowave scintillation arising from ionospheric inhomogeneities, and group path delay abnormalities typically associated with ionospheric storms. The Air Force and the FAA are two organizations that are vigorously combating these potential impairments using system approaches.

We have gone through some of the history of real-time forecasting, and specifically forecasting terminal concepts. Early work was done by the U.S. Navy (i.e., PROPHET), but recent advancements have been made by the U.S. Air Force (e.g., OpSEND). We have also noted the emergence of a 3rd party vendor group (i.e., CSWIG), some of whom provide tailored forecasts for individual customers. Most scientists and government specialists still use the generic services and products of organizations like NOAA-SEC, and international counterparts. The internet is a vast reservoir of space weather data, and is becoming indispensable not only for data mining, but also as a conveyance for quasi-real-time data streams used in operational systems or in forecasting modules serving such systems.

The provision of definitive forecasts and relevant space weather data sets can benefit the telecommunications system manager in the following ways:

1. Space weather data can be incorporated in general advisories supplied to high-level policy makers and military tacticians.
2. Space weather data can be utilized by top-level system managers to develop resource management decisions (e.g., mixed-media communications).
3. Space weather data can be used to develop tailored advisories and alerts for use by engineers of specific telecommunication systems. This information allows the system manager to orchestrate system-wide decisions concerning traffic flow control based upon message priority.

4. Space weather data can be utilized to assist the military planner in the area of propagation tactics, for purposes of exploitation, electronic warfare, and surveillance.
5. Space weather data can be used by 3rd party vendors that offer real-time applications supporting telecommunications.
6. Specified space weather data streams can be fed directly to telecommunication system controllers (i.e., system computers) to alter system operational procedures and parameters in near real time.
7. Space weather data can be used to evaluate prior events for: (i) assignment of cause related to impairment and (ii) for the development of mitigation measures.

Finally, it is recommended that all telecommunication system architects be encouraged to fill out a space-weather impact statement before the system is fully designed, and that all prototype hardware or software proxies be tested in the field or in connection with an appropriate space-weather simulator. This would surely require the development of fully sanctioned (and standardized) set of space-weather models, and could energize the space weather community even more than it currently is. The most important outcome would be the fielding of systems that should not fail catastrophically in the face of space weather events or super storms. It would also force system developers and space weather practitioners to engage in meaningful dialogue. Such a step could easily be written into procurement documents to make the process legally binding.

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