

## REPORT 727-3

**SHORT-TERM PREDICTION OF SOLAR-INDUCED VARIATIONS OF  
OPERATIONAL PARAMETERS FOR IONOSPHERIC PROPAGATION**

(Study Programme 27A/6)

(1978-1982-1986-1990)

**1. Introduction**

This Report considers the short-term prediction of solar activity and prediction of magnetic, ionospheric and radiocommunications disturbances which follow certain kinds of solar activity. It then references available short-term prediction services. The prediction of day-to-day variations in ionospheric parameters (mainly foF2 and total electron content) is considered in Report 888.

**2. Solar-terrestrial relations: Background and sources**

The literature in this field is mainly to be found in two independent series of publications: those of the Special Committee on Solar-Terrestrial Physics (SCOSTEP) which, in cooperation with the Committee on Space Research (COSPAR), organizes every four years symposia on the subject, and those of the International Ursigram and World Days Service (IUWDS) which has initiated a series of periodic workshops devoted more especially to techniques for predicting solar-terrestrial relationships [Simon *et al.*, 1986; Donnelly, 1979].

**3. Short-term prediction of solar activity**

Prediction of solar activity has three applications to short-term prediction of ionospheric parameters: firstly, as an indicator of the likelihood of solar flares causing increased D-region absorption; secondly, as an indicator of possible occurrence of those solar events and situations likely to be followed by magnetic/ionospheric disturbances, and thirdly as an indicator of short-term changes in the sun's ionizing radiation leading to variations in ionospheric critical frequencies and basic MUFs.

There is also the need, for scientific and other purposes, to recognize the active regions likely to produce proton flares, as well as to identify proton flares in their early stages.

The optical, radio and X-ray emission from the Sun is assessed each day at the IUWDS Regional Centres [IUWDS, 1973]. The observations made at and received at these centres are used in the prediction of solar activity and the associated effects on radiocommunication system performance.

Solar observations can be used to indicate, a few hours to a few days in advance, the regions on the solar disk which produce flares observed in the H $\alpha$  line and the likely effects of such flares. The basic data for the predictions are solar spectro-heliograms (H $\alpha$ , calcium), solar magnetograms, radio maps in millimetric and centimetric wavelengths and daily reports of the flares observed in the H $\alpha$  line [Simon *et al.*, 1969; Martres *et al.*, 1973; Bleiweiss *et al.*, 1977; Stasiewicz *et al.*, 1979; Severny *et al.*, 1979; Cook and Davies, 1979; Heckman, 1979]. Solar active regions that are likely to produce flares are marked by magnetic complexity, including high magnetic gradients and shears [Sawyer *et al.*, 1986].

Some of the data on H $\alpha$  flares are such that one can predict the onset of a polar cap absorption event (PCA) a few tens of minutes in advance. These data are the position of the flare on the solar disk relative to the position of the sunspots, centimetric bursts, spectral radio bursts and hard X-ray bursts [Croom, 1971; Lange-Hesse and Rinnert, 1970; Tanaka and Enome, 1975; Cook and Davies, 1979; Heckman, 1979; Smart and Shea, 1979].

The prediction of short-term solar activity is largely subjective and is based usually on the behaviour of previous active regions with similar characteristics [Heckman, 1979]. Objective techniques are being developed [Hirman, *et al.*, 1980] but with limited success. Sources of information dealing with the subject of the prediction of solar activity and solar flares are given by McIntosh and Dryer [1972], Cook and McCue [1975] and Sawyer *et al.* [1986].

#### 4. Short-term prediction of magnetic and ionospheric disturbances

The short-term prediction of magnetic and ionospheric disturbances is closely related to observing those solar and geophysical phenomena that relate to these disturbances and to forwarding warnings to regional centres.

Such observations include:

- satellite and ground-based measurements of X-ray, optical, and radio signatures of significant solar flares [Heckman, 1979; Cook and Davies, 1979];
- ground-based optical and radio measurements of solar coronal holes [Heckman, 1979; Cook and Davies, 1979; Marubashi *et al.*, 1979];
- satellite and ground-based measurements of proton fluxes at energies greater than 10 MeV [Bailey, 1964; Larsen, 1979];
- measurements of inter-planetary scintillations of radio sources to identify disturbances propagating through the inter-planetary medium [Hewish, 1972; Coles *et al.*, 1974; Cronyn *et al.*, 1975];
- spacecraft measurements of solar wind plasma and magnetic field data. This specifically includes the magnitude of the southward component of the inter-planetary field and the general strength and direction of the field (either toward or away from the sun) [Akasofu *et al.*, 1973; Foster *et al.*, 1971; Svalgaard, 1975; Russell *et al.*, 1975; Tsurutani, 1979].

##### 4.1 Sudden ionospheric disturbances (SID)

The enhanced flux of X-ray radiation accompanying large flares may cause sudden ionospheric disturbances (SID). Two of these solar flare effects are the immediate increase in ionization densities throughout the D region and the lowering of the base of that region. The increased ionization density results in increased absorption of radio waves, which causes short-wave fade-outs (SWF). The lowering of the layer, on the other hand, is not significant at HF, but causes sudden phase anomalies (SPA) on VLF circuits. Other immediate effects are sudden absorption of cosmic noise (SCNA), sudden enhancement of atmospherics (SEA) on very low frequencies, sudden increases in total electron content and sudden changes in field strength at long wavelength [Mitra and Goyal, 1984]. The subject has been reviewed by Larsen [1979]. A simple expression for the probability of an SWF within a 24-hour period is given by Milsom [1985].

Forecasting the quantitative aspects of the SID arising from a given flare can be done with some success using models of the D region which consider in detail the ionization changes induced by X-rays of given amplitude and spectral distribution. Once the modified D-region electron density profile has been calculated, it is a relatively straight-forward matter to determine the effects on selected communication circuits. Such methods are described by Kjos and Stasiewicz [1979] and by Argo and Rothmuller [1979].

The increase in the lowest observed frequency (LOF) following a solar flare has been found to be proportional to X-ray enhancement and solar zenith angle [Rose *et al.*, 1974]. Real-time measurements of X-ray flux between 1 and 8 Å have been used to predict the duration of HF spectrum outage due to a short-wave fade-out [Argo *et al.*, 1978a]. By use of event rise characteristics, the outage time of short-wave fade events was directly related to the peak of the solar X-ray event. The decay slope was accurately depicted as having one of four exponential time constants, the chosen constant being associated with the ratio of the flux change to the rise time.

#### 4.2 Polar cap absorption (PCA) and solar proton events

Solar proton events can cause polar cap absorption events (PCA) which lead to complete radiocommunications blackouts at high latitudes due to greatly increased absorption. The so-called proton flares have distinctive characteristics which allow reasonable success in forecasting their eruption and consequent terrestrial effects [Cook and Davies, 1979; Heckman, 1979; Smart and Shea, 1979].

Using observations of radio frequency solar noise and *in situ* measurements of high energy protons, it is now possible to predict:

- whether or not polar cap absorption can be expected from a particular solar flare-burst and
- the maximum absorption to be expected from a particular solar storm [Castelli and Guidice, 1976].

Cliver [1976], Akinyan *et al.*, [1979] and Akinyan and Chertok [1980] have developed methods for predicting the intensity of principal PCA events using 10.7 cm solar flux observations.

Smart and Shea [1979] have developed a procedure to generate a computerized time-intensity profile of the solar proton intensity expected at the Earth after the occurrence of a significant solar flare. The presence of type II and type IV radio bursts is a critical feature of proton acceleration [Cliver *et al.*, 1985]. The observed association between U-shaped spectral signatures of radio emissions and proton events probably results from the "big flare syndrome" [Kahler, 1982].

At VLF the effect may be greater than normal phase advance on navigational and positioning systems. An Omega navigational system correction model [Argo and Hill, 1976] translates high energy ( $E > 10\text{MeV}$ ) proton flux measured at satellite altitudes into phase error corrections. The model is derived from measurements of Omega phase errors. The parameters of the model are: integrated proton flux ( $E > 10\text{MeV}$ ), time of day and path length through the polar cap region.

#### 4.3 Geomagnetic storms

Solar activity often leads to geomagnetic disturbances through the interaction of the solar wind and the Earth's magnetic field. This modifies the existing system of ionospheric and magnetospheric currents and gives rise to geomagnetic and, indirectly, ionospheric storms.

The probability of a solar flare causing a geomagnetic storm depends on the position of the flare on the solar disk and on the energy of the flare as indicated by the accompanying optical brightening, X-ray enhancement and centimetric and metric radio bursts. The magnitude of the type IV spectral radio event is also an important precursor [McNamara, 1980].

The Comprehensive Flare Index is a useful indicator of the probability that a flare will cause a geomagnetic storm [Dodson-Prince *et al.*, 1978] as is the time-integrated X-ray flux between 1 and 8 Å (a measure of flare energy) [Heckman, 1979]. The time delay between the flare and the storm is typically 2-3 days but is very difficult to forecast accurately without *in situ* satellite measurements [Cook and Davies, 1979; Heckman, 1979].

As well as geomagnetic and ionospheric storms caused by solar flares, there exists a class of storms known as recurrent storms because of their marked tendency to recur after one solar rotation (27 days). These storms are associated with features of the solar corona known as coronal holes.

Coronal holes are the source of high speed solar wind streams (HSSWS) which travel at several times the velocity of the background solar wind [Sheeley and Harvey, 1978; Nolte *et al.*, 1976]. As an HSSWS sweeps over the Earth, typically 3 to 4 days after central meridian passage of the associated coronal hole, the changes induced in the Earth's magnetosphere and ionosphere can lead to geomagnetic and ionospheric storms. These storms can last up to about 7 days. Not all HSSWS are found to produce storms, their effectiveness in this regard being related to parameters of the solar wind and interplanetary field.

Recurrent storms are a feature of the declining phase of a solar cycle, when both the coronal holes and their associated HSSWS can last up to 10 solar rotations [Bohlin, 1977]. Forecasts of recurrent storms have historically been based on a 27 day recurrence pattern, with some account being taken of active regions near the supposed coronal hole [Cook and Davies, 1979]. The reliability of these forecasts is enhanced when direct observations of the holes themselves are possible at X-ray, XUV, EUV or radio wavelengths [Timothy *et al.*, 1975; Bohlin, 1977; Neupert and Pizzo, 1974; Dulk and Sheridan, 1974]. However, the observations of most relevance are *in situ* observations of relevant solar wind parameters and their changes as the HSSWS sweeps past.

Geomagnetic storms have also been attributed to ejections from the Sun associated with sudden disappearing filaments (SDF) [Joselyn and McIntosh, 1981; McNamara and Wright, 1982]. The time delay is 4 to 5 days, and the delay is least for large filaments and for filaments close to the central meridian [Wright and McNamara, 1983]. Magnetic field variations in the solar wind associated with SDF which directly control magnetic storms can be predicted from the solar magnetic field in the region surrounding the disappearing filaments. The filament produces a cylindrical magnetic structure (called the magnetic flux rope) the axis of which has a direction corresponding to that of the filament. The magnetic field configuration of the rope is right-handed for disappearing filaments in the southern hemisphere and left-handed for filaments in the northern hemisphere of the sun [Marubashi, 1986].

Studies of large-scale heliospheric transients using the method of interplanetary scintillation of radio sources, indicate that some non-recurrent geomagnetic activity usually ascribed to solar flares, can be attributed to intermittent eruptions of high speed solar wind from coronal holes [Hewish and Bravo, 1986; Houminer and Hewish, 1988].

#### 4.4 *Ionospheric storms*

The geomagnetic storm is often a good indication of the simultaneous existence of an ionospheric storm, i.e. of disturbances in the ionosphere which are more severe than the normal day-to-day variability.

From the point of view of communications, the most important ionospheric storm effects are those imposed on the F2 layer, which is in fact the layer most affected by storms. In terms of the maximum plasma frequency in the F2 layer, foF2, storm effects can be either an increase of foF2 (called a positive phase) or a decrease of foF2 (called a negative phase). The negative phase is the more important to the communicator because it reduces the available bandwidth. Physical mechanisms used to explain the features of ionospheric storms are discussed by Evans [1973] and Rishbeth [1975].

At mid-latitudes, a typical storm starts with a positive phase, which lasts for a few hours, and is followed by a negative phase which lasts for one or two days. However, the amplitude of each phase is a complicated function of the starting time of the storm, latitude and season, and only one type of phase may in fact occur for a given storm. Variations of ionospheric storm effects with the last three parameters have been described [Mendillo, 1973; Matuura, 1972; Mendillo and Klobuchar, 1980; Cander, 1985].

The ionospheric effects of recurrent storms seem to be essentially the same as those of flare-induced storms except that they tend to be somewhat less severe and to last longer [McNamara, 1977a, b]. A limited study of ionospheric storms associated with SDF indicates that the effects of SDF are not distinguishable from the effects of flares and HSSWS.

Changes in the basic MUF at low latitudes during magnetic storms tend to be less than the day-to-day fluctuations in foF2 observed during quiet days. The low-latitude increase in foF2 is compensated for by an accompanying increase in hmF2 so that the actual changes are not very significant [Aggarwal and Reddy, 1974].

At high latitudes there exist significant changes in both the basic MUF and the lowest usable frequency (LUF) during geomagnetic disturbances. The changes in the absorption associated with magnetic substorms display longitudinal and latitudinal variations in the region of the auroral oval [Jelly, 1970]. The use of the Auroral Electrojet index ——— is of value in estimating certain features of auroral substorm absorption [Elkins, 1972]. Verdile and Puig [1977] have studied storm effects which seem to correlate with auroral magnetic indices (AU, AL) and which appear to be due to the propagation of disturbances originating in the auroral oval.

#### 4.5 *Practical methods for short- and medium-term forecasting*

Forecasts of the duration and extent of an ionospheric storm are mainly based on climatological models of storm effects, little success being reported in forecasting the behaviour of a particular storm [Argo *et al.*, 1978b]. Kuleshova *et al.* [1980] have however achieved some success in forecasting basic MUF changes during storms by carefully analysing past storms in terms of the presence or absence of positive and negative phases, sudden or gradual commencement geomagnetic storms, and the severity of foF2 changes.

Accurate, quantitative, circuit parameter forecasts are not possible using only monthly median predictions and the probability of magnetic disturbances [Cook and McCue, 1975]. Such forecasts, however, are useful for many users, especially if backed up by confirmation when a disturbance has begun.

The behaviour of the ionosphere during an ionospheric storm attributable to a feature or event on the Sun (flare, coronal hole, sudden disappearing filament) can be considered as a special case of the normal day-to-day variability of the ionosphere, and can be forecast in practice using the same techniques [see § 2.5 of Report 888].

## 5. Geomagnetic storm effects on total electron content (TEC)

The major source of variation in TEC from monthly mean conditions is due to geomagnetic activity. Since theoretical modelling capabilities are not sufficiently advanced to predict the behaviour of the TEC during magnetic storms, morphology-based prediction schemes represent the only viable method currently available. The major needs for the transionospheric propagation community pertain to the daytime period when the greatest absolute differences in TEC from monthly mean conditions occur.

Mendillo and Klobuchar [1980] have outlined the state-of-the-art of TEC prediction capabilities during magnetic storms, while Mendillo [1973] has described how one could predict whether or not a storm in progress would be expected to produce a positive phase at mid-latitudes. Mendillo finds that a geomagnetic storm sudden commencement (SC) will produce an enhancement in total electron content at mid-latitudes during the afternoon period following the SC unless there is an intervening post-midnight period with a strong depression of the geomagnetic field. Operationally, this is taken to be a depression in the field of at least 100 gammas near 0300 h (local time), and provides a limited prediction ability with a lead-time of about 12 hours.

The major uncertainty encountered in attempting to apply morphology-based corrections to TEC during magnetic storms is the requirement to predict the storm commencement time, for both sudden storm commencements and for gradual storm commencements.

The world regions where the morphologies, and therefore prediction capabilities, of TEC behaviour during magnetic storms are lacking are the low and equatorial latitude regions and the entire southern hemisphere. Correlations between ionospheric variations and various geomagnetic disturbance indices (e.g. TEC versus  $K_p$  or  $D_{st}$ ) appear to be of little value in predicting the effects of magnetic storms on TEC.

## 6. Usefulness and reliability of short-term forecasts

Verification techniques have involved consideration of both the number of storm days for which correct forecasts were issued and the number of quiet days for which storm forecasts or false alarms were issued. Radio propagation quality figures for specific geographic areas have been prepared by the United States of America, the Federal Republic of Germany and Japan for use in forecasts and their verification.

Descriptions of different types of verification procedures are given by Heckman [1979], Marubashi *et al.* [1979], Minnis [1977] and Sawyer *et al.* [1986].

## 7. Operational short-term forecasting systems

This section lists the administrations and their organizations which currently issue short-term forecasts, including an outline of the services available. Further information on Regional Warning Centres (RWC) of the International Ursigram and World Days Service is published elsewhere [IUWDS, 1973]. Reports on current operations of most of the IUWDS-RWCs are given in Volume I of Solar-Terrestrial Predictions Proceedings [Donnelly, 1979].



### 7.1 *Australia*

*Ionospheric Prediction Service, Department of Science, Sydney (IUWDS-RWC)*

Daily operation, forecasts issued as required.

Shortwave fadeout (SWF) and magnetic disturbance in three grades of probability and three levels of intensity, with background notes on solar and geophysical activity.

Supplementary forecasts to users according to circuit path latitudes.

### 7.2 *France*

7.2.1 *Observatoire de Paris and Centre National d'Etudes des Télécommunications, Meudon (IUWDS-RWC)*

Closed Sundays and public holidays.

Solar activity and magnetic storm forecasts.

7.2.2 *CNET, Service des Prévisions Ionosphériques, Lannion*

Closed weekends and public holidays.

Daily and weekly forecasts of operational MUF and LUF.

### 7.3 *Federal Republic of Germany*

*Forschungsinstitut der Deutschen Bundespost beim Fernmeldetechnischen Zentralamt (IUWDS-RWC)*

Closed weekends and public holidays.

Review for past 24 hours and forecast for next 24 hours of solar and magnetic activity, foF2, and propagation conditions between the Federal Republic of Germany and five main regions.

### 7.4 *India*

*National Physical Laboratory, New Delhi (IUWDS Associate RWC)*

Closed Sundays and holidays.

Prediction for circuits within India.

### 7.5 *Japan*

*Ministry of Posts and Telecommunications, Radio Research Laboratories, Koganei and Hiraiso Branch (IUWDS-RWC)*

Daily operation.

Daily radio disturbance warnings (N = normal, U = unstable, W = disturbed) broadcast 6 times per hour by JJY.

Weekly propagation forecasts for next 7 days, issued by post.

Automated Radio Disturbance Warning Issuance System (RADWIS).

### 7.6 *United Kingdom*

*Marconi Research Centre, Great Baddow*

Closed weekends and public holidays.

Coded forecast of likely operational MUF and LUF deviations from predicted values in the European area for the next four 6-hour periods with assessment of likely quality figures. Plain language summary of likely conditions and report on past 24 hours.

### 7.7 *USA*

7.7.1 *National Oceanic and Atmospheric Administration, Space Environment Services Center (NOAA-SESC) Boulder*

(IUWDS-RWC and World Warning Agency).

Daily 24 hours.

Twice daily reports of solar and geophysical activity — current observation of the optical, radio and X-ray Sun, solar wind and magnetic field, and forecasts of trends in all of these. Immediate alerts of major events.

#### 7.7.2 United States Air Force Global Weather Center (AFGWC)

Space environment forecasts.

#### 7.8 USSR

*Hydrometeorological Service, Institute of Applied Geophysics, Moscow (IUWDS-RWC)*

Daily 24 hours.

Short-term predictions of ionospheric and magnetic disturbances (monthly, five-days, two-days and semi-diurnal) for five regions of the USSR (Polar, Auroral zone, European, Central Asia, Far East).

#### 7.9 The IUWDS Centres

Each IUWDS-RWC issues daily a Geoalert giving the activity level to be expected in each active solar region during the forecast day and its advice on expected geomagnetic activity. The IUWDS World Warning Agency (the Boulder USA Centre) collates these advices and issues a daily WWA Geoalert based on the advice from each Centre including its own. This Geoalert is of use mainly in programming scientific investigations but it is also of use to Centres which issue disturbance forecasts of various kinds. This system has been in continuous operation since 1957 [IUWDS, 1973].

### 8. International cooperation

Attention is drawn to Recommendation 313 and its Annex on exchange of information for short-term forecasts and the transmission of ionospheric disturbance warnings.

### REFERENCES

- AGGARWAL, S., and REDDY, B. M. [1974] Effects of magnetic and solar activity on HF communications via F2 region. *Indian J. Radio and Space Phys.*, Vol. 3, 4, 401-406.
- AKASOFU, S. I., PERREAULT, P. D., YASUHARA, F. and MENG, C. I. [1973] Auroral substorms and the interplanetary magnetic field. *J. Geophys. Res.*, Vol. 78, 7490-7508.
- AKINYAN, S. T. and CHERTOK, I. M. [1980] Determination of PCA values using integral parameters of solar microwave flares. *Geomag. i Aeronom.*, 20, 192-196.
- AKINYAN, S. T., CHERTOK, Z. M. and ZHULINA, E. M. [1979] Determination of PCA values from the characteristics of solar radio bursts. *STPP\**, Vol. III, D27-D33.
- ARGO, P. E. and HILL, J. R. [1976] Omega Navigation disturbance correction tables. Naval Electronics Laboratory Center TR 480, NTIS Accession No. AD A028 972. National Technical Information Service, Springfield, Va. 22161, USA.
- ARGO, P. E., HILL, J. R. and ROTHMULLER, I. J. [1978a] X-ray flare and short-wave fade duration model. Naval Ocean Systems Center TR 255, NTIS Accession No. AD A057 284. National Technical Information Service, Springfield, Va. 22161, USA.
- ARGO, P. E., HILL, J. R. and ROTHMULLER, I. J. [1978b] Magnetic substorms and ionospheric storms. Naval Ocean Systems Center TR 256, NTIS Accession No. AD A057 975. National Technical Information Service, Springfield, Va. 22161, USA.
- ARGO, P. E. and ROTHMULLER, I. J. [1979] PROPHET: An application of propagation forecasting principles. *STPP*, Vol. I, 312-321.
- BAILEY, D. K. [1964] Polar cap absorption. *Planet. and Space Sci.*, 12, 495-541.
- BLEIWEISS, M. P., WEFER, F. L. and KONIGES, A. E. [1977] Emission and absorption at wavelengths of 8.6 mm and 2.0 cm as determining factors of  $T_e$  and  $N_e$  in the filament. Naval Ocean Systems Center TR 136, NTIS Accession No. AD A044 559. National Technical Information Service, Springfield, Va., 22161, USA.
- BOHLIN, J. D. [1977] Extreme ultraviolet observations of coronal holes. 1. Locations, sizes and evolution of coronal holes, June 1973-January 1974. *Solar Phys.*, Vol. 51, 377-398.
- CANDER, L. R. [1985] A morphology-based study of ionospheric storms as seen at Grocka ionospheric station. Solar-Terrestrial Predictions: Proceedings of a Workshop at Meudon, France, June 18-22, 1984, 559, Ed. P. A. Simon, G. Heckman and M. A. Shea, published by National Oceanic and Atmospheric Administration, 325 Broadway, Boulder, CO 80303, USA, and Air Force Geophysics Laboratory; Hanscom AFB, Bedford, MA 01731, USA.

\* The abbreviation STPP refers to the Solar-Terrestrial Predictions Proceedings, published in four volumes by the National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce and edited by R. F. Donnelly (see [Donnelly, 1979 and 1980]).

- CASTELLI, J. P. and GUIDICE, D. A. [1976] Impact of current solar radio patrol observations. *Vistas in Astron.*, **19**, 355.
- CLIVER, E. W. [1976] Parent-flare emission at 2.8 GHz as a predictor of the peak absorption of polar-cap events. Naval Electronics Laboratory Center TR 2015, NTIS Accession No. AD A037 552 1761. National Technical Information Service, Springfield, Va. 22161, USA.
- CLIVER, E. W., McNAMARA, L. F. and GENTILE, D. C. [July, 1985] Peak-flux-density spectra of large solar radio bursts and proton emission from flares. *J. Geophys. Res.*, Vol. 90, A7, 6251-6266.
- COLES, W. A., RICKETT, B. J. and RUMSEY, V. H. [1974] Interplanetary scintillations in *Solar Wind Three*, 351-367. Ed. C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Calif., USA.
- COOK, F. E. and DAVIES, P. [1979] A review of the operation of the IUWDS Regional Warning Centre at the Ionospheric Prediction Service, Sydney. *STPP*, Vol. I, 229-238.
- COOK, F. E. and McCUE, C. G. [1975] Solar-terrestrial relations and short-term ionospheric forecasting. *Radio and Electron. Engr. (UK)*, Vol. 45, 11-30.
- CRONYN, W. M., ERSKINE, F., SHAWHAN, S. D., GOTWALS, B. L. A. and ROELOF, E. C. [1975] Prediction of ionospheric effects associated with solar wind disturbances using interplanetary scintillation observations at 34.3 MHz. Proc. Symposium on the Effects of the Ionosphere on Space Systems and Communications, Naval Research Laboratory, Arlington, Va., USA.
- CROOM, D. L. [1971] Forecasting the intensity of solar proton events from the time characteristics of solar microwave bursts. *Solar Phys.*, **19**, 171-185.
- DODSON-PRINCE, H. W., HEDEMAN, E. R. and MOHLER, D. C. [1978] Studies of geomagnetic storms and solar flares in the years of increasing solar activities, cycles 19 and 20 (1955-1957, 1965-1968). Report AFGL-TR-78-0267, Air Force Geophysical Lab., Hanscom AFB, Mass., USA.
- DONNELLY, R. F. [1979] Ed. Solar Terrestrial Predictions Proceedings:  
 Vol. I [1979] Prediction Group Reports. US Dept. of Commerce, US Govt. Printing Office, No. 003-023-00041-9, Washington, DC 20402.  
 Vol. II [1979] Working Group Reports and Reviews, US Dept. of Commerce, US Govt. Printing Office, No. 003-017-00471-6, Washington, DC 20402.  
 Vol. III [1980] Solar Activity Predictions. US Dept. of Commerce, US Govt. Printing Office, No. 003-017-00473-2, Washington, DC 20402.  
 Vol. IV [1980] Predictions of Terrestrial Effects of Solar Activity. US Dept. of Commerce, US Govt. Printing Office, No. 003-017-00479-1, Washington, DC 20402.
- DULK, G. A. and SHERIDAN, K. W. [1974] The structure of the middle corona from observations at 80 and 160 MHz. *Solar Phys.*, **36**, 191-202.
- ELKINS, T. J. [1972] A model of auroral substorm absorption. AFCRL Environmental Research Paper, No. 404, AFCRL-TR-72-0413. Air Force Cambridge Research Laboratories, Bedford, Mass., USA.
- EVANS, J. V. [1973] The causes of storm-time increases of the F-layer at mid-latitudes. *J. Atmos. Terr. Phys.*, Vol. 35, 593-616.
- FOSTER, J. C., FAIRFIELD, D. H., OGILVIE, K. W. and ROSENBERG, T. J. [1971] Relationship of interplanetary parameters and occurrence of magnetospheric substorms. *J. Geophys. Res.*, Vol. 76, 6971-6975.
- HECKMAN, G. [1979] Predictions of the Space Environment Services Center. *STPP*, Vol. I, 322-349.
- HEWISH, A. [1972] Observations of the solar plasma using radio scattering and scintillation methods. *Solar Wind*, Eds. C. P. Sonett *et al.*, NASA SP-308, 477-485 (and discussion, 485-493).
- HEWISH, A. and BRAVO, S. [1986] - The sources of large-scale heliospheric disturbances. *Solar Phys.* **106**, 185.
- HIRMAN, J., NEIDIG, D. F., SEAGRAVES, P. M., FLOWERS, W. E. and WIBORG, P. M. [1980] The application of multivariate discriminant analysis to solar flare forecasting. *STPP*, Vol. IV, C-64 to C-75.
- HOUMINER, Z. and HEWISH, A. [1988] - The solar origin of the 2-9 August 1972 events. *Planet. Space Sci.* **36**, 301.
- IUWDS (INTERNATIONAL URSIGRAM AND WORLD DAYS SERVICE) [1973] Synoptic Codes for Solar and Geophysical Data, third revised edition, IUWDS Secretariat, Boulder, Colo., USA.
- JELLY, D. H. [1970] On the morphology of auroral absorption during substorms. *Can. J. Phys.*, **48**, 335-345.
- JOSELYN, J. A. and McINTOSH, P. S. [1981] Disappearing solar filaments: A useful predictor of geomagnetic activity. *J. Geophys. Res.*, Vol. 86, 4555-4564.
- KAHLER, S. W. [1982] The role of the big flare syndrome in correlations of solar energetic proton fluxes and microwave burst parameters. *J. Geophys. Res.*, Vol. 87, 3439-3448.



- KLOS, Z. and STASIEWICZ, K. [1979] Estimation of solar flare influence on radio circuit transmission loss. *STPP*, Vol. I, 67-71.
- KULESHOVA, V. P., LAVROVA, E. V. and LYAKHOVA, L. N. [1980] Forecasting of  $\delta f_oF_2$  variation for ionospheric disturbance. *STPP*, Vol. IV, C-37 to C-40.
- LANGE-HESSE, G. and RINNERT, K. [1970] The reliability of transpolar VLF measurements as a method to forecast HF propagation disturbances. AGARD Conf. Proc. No. 49, *Ionospheric Forecasting*, Paper No. 30, Ed. V. Agy. NASA Accession No. N70-23112. National Technical Information Service, Springfield, VA 22161, USA.
- LARSEN, J. R. [1979] Effects of D-region ionization on radio wave propagation. *STPP*, Vol. II, 617-654.
- MARTRES, M. J., SORU-ESCAUT, I. and RAYROLE, J. [1973] Relationship between some photospheric motions and the evolution of active centres. *Solar Phys.*, **32**, 365-378.
- MARUBASHI, K. [1986] - Structure of the interplanetary magnetic clouds and their solar origins, *Adv. Space Res.*, Vol. 6, No. 6, 335-338.
- MARUBASHI, K., MIYAMOTO, Y., KIDIKORO, T. and ISHII, T. [1979] Forecasts of geomagnetic activities and HF radio propagation conditions made at Hiraiso, Japan. *STPP*, Vol. I, 182-204.
- MATUURA, N. [1972] Theoretical models of ionospheric storms. *Space Sci. Revs.*, **13**, 124-189.
- McINTOSH, P. S. and DRYER, M. (Eds.) [1972] Solar Activity Observations and Predictions, Vol. 30, *Progress in Astronautics and Aeronautics*, MIT Press, Cambridge, Mass., USA.
- McNAMARA, L. F. [1977a] Recurrent storms and their effects on HF radio communications. *Monitor-Proc.* IREE Australia, 48-55.
- McNAMARA, L. F. [1977b] Ionospheric storm effects on maximum usable frequencies on circuits around Australia. Ionospheric Prediction Service, Series R reports, IPS-R35, Sydney, Australia.
- McNAMARA, L. F. [1980] Geomagnetic effects of solar flares observed during 1968-1978. Ionospheric Prediction Service Series R Reports, IPS-R37, Sydney, Australia.
- McNAMARA, L. F. and WRIGHT, C.S. [1982] Disappearing solar filaments and geomagnetic activity. *Nature*, Vol. 299, **5883**, 537-538.
- MENDILLO, M. [1973] A study of the relationship between geomagnetic storms and ionospheric disturbances at mid-latitudes. *Planet and Space Sci.*, Vol. 21, 349-358.
- MENDILLO, M. and KLOBUCHAR, J. A. [1980] A morphology based prediction scheme for the coupled latitudinal and local-time development of F-region storms. *STPP*, Vol. IV, C-15 to C-26.
- MILSOM, J. D. [1986] Towards improving a short-term ionospheric forecasting service. Solar-Terrestrial Predictions: Proceedings of a Workshop at Meudon, France, June 18-22, 1984, 524, Ed. P. A. Simon, G. Heckman and M. A. Shea, published by National Oceanic and Atmospheric Administration, 325 Broadway, Boulder, CO 80303, USA, and Air Force Geophysics Laboratory; Hanscom AFB, Bedford, MA 01731, USA.
- MINNIS, C. M. [1977] Ionospheric storm forecasts: Assessment of their economic value. *Telecomm. J.*, Vol. 44, 328-330.
- MITRA, S. N. and GOYAL, R. K. [1984] Study of solar-terrestrial relationship through SCL. Paper presented at the "Workshop on Solar-Terrestrial Predictions", Meudon, France. 18-22 June, 1984.
- NEUPERT, W. M. and PIZZO, V. [1974] Solar coronal holes as sources of recurrent geomagnetic disturbances. *J. Geophys. Res.*, Vol. 79, 3701-3709.
- NOLTE, J. T., KRIEGER, A. S., TIMOTHY, A. F., GOLD, R. E., ROELOF, E. C., VAIANA, G., LAZARUS, A. J., SULLIVAN, J. D. and McIntosh, P. S. [1976] Coronal holes as sources of solar wind. *Solar Phys.*, **46**, 303-322.
- RISHBETH, H. [1975] F-region storms and thermospheric circulation. *J. Atmos. Terr. Phys.*, Vol. 37, 1055-1064.
- ROSE, R. B., HILL, J. R. and BLEIWEISS, M. P. [1974] Sudden ionospheric disturbance grid. Naval Electronics Laboratory Center Tech. Rep. 1938, NTIS Accession No. A006567, National Technical Information Service, Springfield, Va. 22161, USA.
- RUSSELL, C. T., BURTON, R. K. and McPHERRON, R. L. [1975] Some properties of the Svalgaard A/C index. *J. Geophys. Res.*, Vol. 80, 1349-1351.
- SAWYER, C., WARWICK, J.W. and DENNETT, J.T. [1986] - Solar flare prediction. Colorado Associated University Press, Boulder, Colorado.
- SEVERNY, A. B., STEPENYAN, N. N. and STESHENKO, N. V. [1979] Soviet short-term forecasts of active region evolution and flare activity. *STPP*, Vol. I, 72-88.
- SHEELEY, N. R., Jr. and HARVEY, J. W. [1978] Coronal holes, solar wind streams and geomagnetic activity during the new sunspot cycle. *Solar Phys.*, **59**, 159-178.
- SIMON, P., HECKMAN, G. and SHEA, M. A. [1986] Solar-Terrestrial Predictions: Proceedings of a Workshop at Meudon, France, June 18-22, 1984, published by National Oceanic and Atmospheric Administration, 325 Broadway, Boulder, CO 80303, USA, and Air Force Geophysics Laboratory; Hanscom AFB, Bedford, MA 01731, USA.

- SIMON, P., MARTRES, M. J. and LEGRAND, J. P. [1969] Flares forecasting. *Symposium on Solar Flares and Space Research*, North-Holland Publishing Co., New York, NY, USA.
- SMART, D. F. and SHEA, M. A. [1979] PPS76 — A computerized "event-mode" solar proton forecasting technique. *STPP*, Vol. I, 406-427.
- STASIEWICZ, K., MAKSYMIEŃKO, M. and JAKIMIEC, M. [1979] KAZIA — A computer system for solar-terrestrial data processing and objective prediction. *STPP*, Vol. I, 61-66.
- SVALGAARD, L. [1975] An atlas of interplanetary sector structure, 1957-1974, Stanford University, Institute for Plasma Research, Report No. 629, Stanford, Calif., USA.
- TANAKA, H. and ENOME, S. [1975] The microwave structure of coronal condensations and its relation to proton flares. *Solar Phys.*, 40 (1), 123-131.
- TIMOTHY, A. F., KRIEGER, A. S. and VAIANA, G. S. [1975] The structure and evolution of coronal holes. *Solar Phys.*, 42, 135-156.
- TSURUTANI, B. [1979] Substorm warnings: an ISEE-3 real time data system. *EOS Trans.*, 60, 702-703.
- VERDILE, J. L. and PUIG, L. I. [1977] Propagación hacia latitudes medias de perturbaciones aurorales. Report C-30, LIARA, Laboratorio Ionosférico de la Armada, República Argentina.
- WRIGHT, C. S. and McNAMARA, L. F. [1983] The relationships between disappearing solar filaments, coronal mass ejections, and geomagnetic activity. *Solar Phys.*, Vol. 87, 401-417.

---

REPORT 888-2 \*

## SHORT-TERM FORECASTING OF CRITICAL FREQUENCIES, OPERATIONAL MAXIMUM USABLE FREQUENCIES AND TOTAL ELECTRON CONTENT

(Study Programme 27C/6)

(1982-1986-1990)

### 1. Introduction

Daily values of foF2 are known to vary by about 15 to 20% from the monthly median value of foF2 during quiet times as well as during magnetic storms. These variations may be superimposed on slower upward or downward drifts in values over several days. It is desirable to predict all these variations for the purpose of efficient radiocommunications.

The need for forecasts of day-to-day variations of the ionosphere has been pointed out by King and Slater [1973], who show that at middle latitudes the monthly quartile range of observed daily values of foF2 at a particular place and local time is twice as great, on average, and five times as great in summer, as the error in the corresponding median value predicted by Report 340. The diagrams given by Wilkinson [1979] clearly illustrate the spread in foF2 at Australian ionospheric stations from low to high latitudes. Rush *et al.* [1974] have considered the implications of the daily variability of the F2 region to oblique HF communication circuits by simulating circuit performance using ray tracing techniques.

Forecasting the daily variations of the E and F1 regions presents little difficulty since they can be represented by monthly median values of foE and foF1 [Rush and Gibbs, 1973].

The basic method used in short-term forecasting of ionospheric parameters is extrapolation of a time series of past observations, on the assumption that the current trend will be maintained for at least the near future. Extrapolation can be done on the ionospheric parameter itself (e.g. foF2), on an index derived from ionospheric parameters or on a physical parameter known to possess a suitably high correlation with the ionospheric parameter.

Forecasts can be made with different lead-times, depending on how closely the variations in the ionosphere need to be tracked, and the sampling interval must match that lead-time. For example, if significant variations of the ionosphere occur within an hour, observations would be required every 5 to 10 minutes and forecasts made with similar lead-times.

The usefulness of, and the requirements for, a network of ground-based and satellite-borne ionospheric observations whose measurements are to be used for short-term prediction of radio propagation conditions, have been described in detail by Rush [1976]. However, it should be noted that the relatively high correlations found by Rush correspond to very disturbed days (that is, ionospheric storm days) and these same high correlations are not always obtained for days when the deviations from the median values are relatively small (McNamara and Wilkinson, 1986; Milsom, 1986).

---

\* This Report is brought to the attention of Study Groups 3 and 8.