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.

2. Short-term forecasting of foF2 and operational MUF

2.1 *Causes of short-term MUF variations*

Short-term variations in ionospheric conditions due to solar flares, high speed solar wind streams emanating from coronal holes and due to changes in the ionizing flux from the Sun are discussed in Report 727. In general the variations due to solar flares and coronal holes have a fairly well defined start time, can be related to the solar event causing them and can be forecast with some success.

Even under magnetically quiet conditions, the ionosphere exhibits day-to-day variations due to changes in the ionizing ultraviolet (UV) flux from the Sun and to changes in the solar wind and its interaction with the magnetosphere and ionosphere. The total effect for the latter is very complex and the complete causal chain has not been established. The former also presents unsolvable problems because the UV flux can be measured only with great difficulty.

Superimposed on these variations are variations with a time scale of the order of 10 minutes to a few hours due to travelling ionospheric disturbances (TIDs), which are in fact the ionospheric signature of gravity waves in the neutral atmosphere [Hines, 1974]. Large TIDs have been found to originate at high latitudes in association with large geomagnetic disturbances [Francis, 1975; Richmond and Roble, 1979], while smaller ones would seem to be of local meteorological origin [Bertin *et al.*, 1978].

TIDs can change foF2 by 1 or 2 MHz and introduce multiple Doppler components which result in long period fading and consequent decrease in circuit quality. However the effects of TIDs can often be removed by the use of either space or polarization diversity.

2.2 *Forecasts using solar and geophysical parameters*

Short-term forecasts of foF2 have been made by relating changes in foF2 to corresponding changes in selected geophysical variables such as the 10.7 cm solar flux and the geomagnetic index, K_p [Bennett and Friedland, 1970; Ichinose *et al.*, 1980]. The disadvantage of this type of approach is that the independent geophysical variables upon which changes in foF2 are assumed to depend must themselves first be predicted. Even if this were done successfully, only limited succes in forecasting foF2 is possible [McNamara, 1976a; Wilkinson, 1979].

The high correlation between long-term average values of the solar 10.7 cm radio flux with ionospheric parameters is well established and has led to the use of ionospheric prediction indices based on the 10.7 cm flux (Recommendation 371). Although this high correlation suggests the possibility of developing a short-term forecasting system based on a forecast of the 10.7 cm flux, days to weeks ahead, in reality the correlation between 10.7 cm flux and foF2 over short time scales is limited. This is probably because it is the solar UV flux which ionizes the ionosphere and the relationship between the two fluxes is not known on short time scales [Hall *et al.*, 1969; Hall and Hinteregger, 1970].

Some success has been reported using long-term averages of the 10.7 cm flux [McNamara, 1976a; Da Rosa *et al.*, 1973], but in general the correlation between daily values of flux and foF2 or TEC is not high enough to provide useful forecasts of the latter parameters.

Zevakina and Lavrova [1980] report a correlation between the direction of the interplanetary magnetic field (IMF) and the sense of the departure of foF2 from its median value. On days when the IMF points away from the Sun the values of foF2 at high and mid latitudes are in most cases higher than the median values, whereas on days when the IMF is towards the Sun, the values are lower. The direction of the component of the IMF at right angles to the ecliptic also affects the sense of the departures of foF2 from its median values.

These relationships between the direction of the IMF and deviations of foF2 offer some forecasting capability but measurements of the IMF are usually not available in real-time and inferences of its direction from high latitude magnetograms [Svalgaard, 1972; Fougere, 1974; Wilcox, 1972] are not always correct.

A method which combines forecasts using associated geophysical parameters and sounder information has been developed [Reilly and Daehler, 1986]. In this method, the statistical monthly median model which is typically based on either an average sunspot number or 10.7 cm solar radio flux, is adjusted to fit sounder observations on a given path, thus defining an updated solar parameter which may be used to predict HF properties for other paths.

Kiseliova and Zevakina [1984] have reported some success in relating positive disturbances in foF2 to changes in solar wind parameters, the sector structure of the IMF, and geomagnetic activity indices. A review of recent progress made by the USSR on short-term forecasting of ionospheric disturbances has been prepared by Zevakina [1986].

2.3 *Forecasts using ionospheric parameters*

A more successful approach to the short-term forecasting of foF2 or alternatively of an operational MUF on a given circuit, is a prediction scheme based directly upon immediate past observations of foF2 or operational MUF. Such prediction schemes for foF2 are described, for example, by Rush and Gibbs [1973], Lyakhova and Kostina [1973], McNamara [1976b] and Wilkinson [1979].

Rush and Gibbs [1973] used a five-day weighted mean value of foF2 to predict daily and hourly values of that parameter. The method of Lyakhova and Kostina [1973] is based on the observation that correlation coefficients between the deviations of foF2 from median values remain greater than 0.5 for up to four hours. The high correlation between hour-to-hour variations of foF2 has been discussed by Lyakhova [1960], Radinov [1963], Gautier and Zacharisen [1965] and Rush [1972].

McNamara [1976b] made predictions of foF2 at a particular location up to 3 hours ahead by projecting forward the trend in the departures of the last few hours' observations from a 15-day running median. Wilkinson [1979] on the other hand, simply projected forward in time the deviation of an observed foF2 value from the predicted monthly median value of foF2. He found this technique to be effective for lead times of up to about 3 hours.

Similar techniques have been applied to oblique circuits by Ames and Egan [1967], Ames *et al.* [1970], Krause *et al.* [1970; 1973a and b] and D'Accardi [1978].

The success of any of these forecasting schemes will depend on the particular circumstances of its intended use, especially as regards the required accuracy of the forecast and the lead-time required. Most schemes are reasonably successful in forecasting an operational MUF which is closer to the actual value than is the predicted monthly median value, but only for lead-times of the order of an hour or less.

2.4 *Forecasts using ionospheric indices*

To make short-term forecasts for circuits for which no real-time observations exist, the behaviour of the ionosphere must be inferred from such data as are available, using these observations to infer the values along the required circuit.

Numerous studies have reported correlation coefficients which illustrate the degree to which hourly deviations of ionospheric parameters at two or more locations are related [Gautier and Zacharisen, 1965; Zacharisen, 1965; Zevakina *et al.*, 1967a; Rush, 1972].

McNamara [1979] used observations at nearby ionospheric stations to determine an effective ionospheric index which was then used in conjunction with synoptic monthly median maps of foF2 to predict the value of foF2 at the reflection point of the given circuit.

Forecasts were made by projecting the index forward in time. Lead-times of 0 to 3 hours and 24 hours were considered and it was found that forecasts 24 hours ahead were in general no more inaccurate than those made 0 to 3 hours ahead. Errors in forecast values of foF2 at two mid-latitude stations were less than 10% on 50 to 70% of occasions for the periods considered. Whether or not this is an acceptable level of error would depend on its intended application.

Other, more complicated, methods based on the updating of synoptic maps of ionospheric parameters in real-time are described by Thompson and Secan [1979] and Tascione *et al.* [1979]. A forecasting scheme based on the use of daily ionospheric indices has been described by Wilkinson [1986].

In the limit of zero lead-time, the "forecast" in fact becomes a real-time assessment of the ionosphere.

2.5 *Practical schemes for short- and medium-term forecasts*

Practical schemes for short- and medium-term forecasting of the ionosphere and radio propagation conditions rely on various combinations of the three approaches described above.

Forecasts based upon ionospheric data only a few hours old, and intended to cover only the next few hours, can take account of both the day-to-day deviations from long-term predictions and those due to magnetic disturbance in progress if the magnetic disturbance is not too severe. A difficulty which still remains is that the deviations vary not only with time, but between different places at the same time so that observations near or along the particular circuit path are necessary, using either vertical- or oblique-incidence or back-scatter techniques. Uffelman [1982] and Uffelman et al. [1982] have described a successful technique for applying oblique incidence sounder observations on one circuit to MUF forecasting on a nearby circuit.

Another approach is to make forecasts for zones, within which the deviations are less than between zones, e.g. the method of Zevakina *et al.* [1967b]. Investigation of topside sounding data for forecast purposes by Piggott [1970] served to point out the spatial anomalies, including the very large differences between the northern and southern hemispheres. Advanced digital ionosonde techniques [Bibl and Reinisch, 1978] offer the possibility of identification and interpretation of complex ionospheric conditions in near real-time [Reinisch and Huang, 1982; Wright and Pitteway, 1982]. A world-wide network of such ionosondes [Wright, 1981], sounding obliquely and vertically, could provide a global forecasting system.

The Deutsche Bundespost method relies on continuous recording of 20 European and overseas radio circuits in addition to the solar activity and magnetic disturbance forecasting techniques already described. Each 24 hours, percentage deviations from predictions are examined in relation to current solar/geophysical events and in relation to conditions at the same stage of past solar rotations. Since the forecasts are intended mainly for the circuits already being monitored, the effect of spatial anomalies is avoided, and the method is then subject to the same kind of uncertainties as those already mentioned. This method has been developed from the earlier techniques described by Ochs [1970]. A prediction approach based on solar-geophysical data and on real-time field strength measurements of distant HF transmitters on 26 frequencies has been reported by Damboldt [1979]. The distinctive feature of the predictions is that they are forecast in the form of a quality figure which is related to the daily expected field strength.

Some forecasting schemes are based on particular models. For example, the model of Obayashi and Matuura, [1972] which describes the distribution of electron density variations with height, latitude and season during the main phase of a geomagnetic storm has been used by Barclay [1976].

The method of short-term forecasting described by Barclay [1976] includes comparison of hourly foF2 values from two stations in Western Europe with the corresponding predictions. Operational MUFs are then forecast as low for the next period if magnetic disturbance above a given level is current, otherwise normal, unless spot number and radio flux are significantly different from their predicted values. LUFs are forecast high in winter if magnetic activity is high, and high or low depending again on predetermined deviations in sunspot numbers and radio flux level. Instructions of this nature enable unskilled persons to make up forecasts which have some utility, especially during quiet periods.

In the USSR, statistical studies of the changes in foF2 have indicated "forbidden" time intervals for storm commencements at their ionospheric stations [USSR, 1957]. Relatively stable communications have been predicted in the USSR in the auroral zone utilizing real-time monitoring since it has been observed that strong fluctuations in foF2 do not take place over periods of 15 to 30 minutes when F2 layer reflections exist. In the United States of America the deviations of the daily foF2 from the computed monthly median have been analysed for all stations for selected months in 1958. Systematic world-wide patterns are observed in the deviations, particularly during ionospheric disturbances [Jones *et al.*, 1973]. A review of the major progress made in the USSR in short-term forecasting of ionospheric disturbances is given by Zevakina [1986].

The medium-term (one week) forecasting method used by the French Administration is based on mathematical models established by the application of the theory of systems, models and their identification [Le Roux, 1980]. These models, which take into account the geomagnetic Ak and solar Φ indices, are sufficiently effective to enable the hourly basic MUFs to be predicted weekly for various geographical regions. Messages giving percentage basic MUF deviations in relation to previously published monthly forecasts are issued each week, one week in advance. A daily forecast of the expected MUF and LUF levels for the next 24 hours, divided into six-hourly intervals, is also made for a North European zone and a European zone, based on observations at Uppsala and Lannion [Bourdila *et al.* 1984].

3. Short-term forecasting of total electron content

General methods of predicting transionospheric effects on radio waves have been reported in the Solar-Terrestrial Predictions Proceedings [Klobuchar, 1979] and are also described in Report 263, whereas the relevant ionospheric parameters are described in Report 725.

Predictions of monthly average values of total electron content (TEC) are normally derived from electron density profiles, which are constructed from models of foF2 and M(3000)F2 [Jones *et al.*, 1969; Jones and Obitts, 1970]. They therefore include the errors inherent in both these empirical models.

Comparisons of median observed TEC with predicted values at mid- and low-latitude stations [McNamara and Wilkinson, 1983; McNamara, 1984] have shown that an error of 10% is not unusual at mid-latitudes, with a 20% to 30% error often occurring at low latitudes.

Short-term variability of TEC about the monthly average values is approximately 25% r.m.s., with a nearly normal distribution [Johanson *et al.*, 1978; Soicher *et al.*, 1982]. At mid-latitudes this is several times the error in predicted median values. The plasmaspheric (or protonospheric) contribution to TEC could be assumed to be 15% of TEC during the day [Donnelly, 1979 and 1980].

3.1 *Geomagnetic storm effects on TEC*

The major source of variation in TEC from monthly mean conditions is due to geomagnetic activity associated with events on the Sun. These variations are discussed in Report 727.

3.2 *Use of near-real-time TEC measurements to improve short-term predictions*

Monthly mean time-delay values, even with corrections for average magnetic storm-induced changes in TEC, may not be sufficiently accurate for certain systems or for some classes of users of systems. They may instead require near-real-time measurements of the local ionosphere, either of foF2 or of TEC, to up-date median models. Alternatively, the use of two, widely-spaced, frequencies to actually measure and correct for the first order ionospheric time-delay error in real-time should be considered. Up-dating techniques include producing improved weekly or monthly median values to serve as a basis for predicting values for the following several hours.

Studies of adaptive techniques that use real-time observations to reduce average monthly r.m.s. errors in predictions have been conducted using foF2 data [Wilkinson, 1979] and TEC data [Donatelli and Allen, 1978, 1981; Leitinger *et al.*, 1978]. In order to appreciably reduce the residual error (about 50%) when using observations at the same location, the prediction intervals should be less than the following:

- solar maximum
  - day-time: 3 h
  - night-time: 1 h
- solar minimum
  - day-time: 1 h
  - night-time: 30 min.

The intervals for useful up-dating during solar minimum should be shorter to effect the same percentage reduction. The residual error is much less during solar minimum conditions.

3.3 *Spatial projections of near-real-time measurements*

Spatial projection of observations has been discussed in correlation studies using foF2 [Rush, 1976] and TEC [Klobuchar and Johanson, 1977; Soicher, 1978, 1979]. The work by Klobuchar and Johanson [1977] indicates a latitudinal correlation distance that is approximately one-half the longitudinal correlation distance. This must be considered with the time effects for any adaptive technique in which real-time observations are used for up-dating at a location other than that from which the observation was made. This has been examined using TEC data from mid-latitude stations [Allen *et al.*, 1977]. The increased error growth rate represents a superposition of spatial and temporal fluctuations. By reducing the space-time interval to an equivalent time interval, a usable updating interval may be estimated. A good approximation for mid-latitude stations can be made with the following equation [Klobuchar, 1979]:

$$\Delta ET = \frac{1}{15}\left[(\Delta LON)^2 + (2\Delta LAT)^2\right]^{\frac{1}{2}} + \left\{\begin{array}{c}\Delta T \\ \text{or} \\ |\Delta T - \Delta LT|\end{array}\right\} \qquad (1)$$

where:

ΔLON: longitudinal separation (degrees)

ΔLAT: latitudinal separation (degrees)

ΔT: time interval between observation and up-date (hours)

ΔLT: $\Delta LON/15$ (hours)

ΔET: equivalent time interval (hours)

$\{\}$: refers to choice for east or west direction from observing to up-dating location; ΔT if W $\rightarrow$ E, $|\Delta T - \Delta LT|$ if $E \rightarrow W$

4. Forecasts of other parameters

The short-term forecasting of the operational MUF on a circuit is generally all that would be required for voice and low-speed telegraphy circuits. For medium-speed data links, other parameters such as fading periods and Doppler frequency spread become important, since these affect the error rates. While short-term forecasting of these parameters may be possible, it is generally agreed that real-time frequency management is essential for the operation of medium-speed data links [Clarke, 1979]. Sporadic E is especially important in this regard since it cannot be successfully forecast but can provide highly stable communications.

Because of the highly variable nature of the occurrence and intensity of sporadic-E ionization, predictions must be statistical in character.

Forecast possibilities of sporadic E "openings" based on measured E-region drifts were described by Harnischmacher and Rawer [1970] who described series of measurements of Es appearing day-by-day at the same local time plus one hour per day, with increased absorption at the end of such a sequence. Zevakina *et al.* [1967a] take account of seasonal Es variations in the USSR Manual.

In a study made over a solar cycle in South America, Giráldez and Mesterman [1973] have indicated that the occurrence of Es during a day depends upon the virtual height of the Es observed near sunrise.

Conditions in the magnetosphere, such as electron density and temperature, appear to be controlling factors in the basic pattern of particle dumping and electric fields and thus the most useful way of predicting auroral Es may be via satellites in operation for magnetospheric studies.

The high latitude ionosphere presents special problems because of its variability and complexity (Report 886). Besprozvannaya *et al.* [1979] suggest that the methods used for mid-latitude forecasting are unsuitable for high latitudes and that a more suitable method could be based on monitoring of large-scale features of ionization distribution that are the projections on the upper ionosphere of large-scale structural characteristics of magnetospheric plasma. This could be done using ground-based ionosondes at suitable locations or by using satellites.

Real-time assessment of the high latitude trough and its effects on communications can, for example, be made using DMSP (Defense Meteorological Satellite Programme) auroral photographs to indicate the poleward edge of the trough and then using the model of the trough described by Halcrow and Nisbet [1977].

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

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