Ionospheric Radio Propagation Models and Predictions—A Mini-Review

CHARLES M. RUSH, SENIOR MEMBER, IEEE

Abstract—The ionosphere affects radio waves that are propagated within and through it. The magnitude of the effects depends upon the structure of the ionosphere and the frequency of the radio wave. Ionospheric models have been developed over the years to aid in predicting the impact of the ionosphere on ionospheric-dependent telecommunication systems. The status of ionospheric modeling and prediction efforts that are geared toward radio wave propagation system assessment is reviewed.

I. INTRODUCTION

The ionosphere is that region of the earth’s atmosphere in which free ions and electrons exist in sufficient abundance to affect the properties of electromagnetic waves that are propagated within and through it. For practical purposes, the ionosphere can usually be assumed to extend from about 30 to roughly 2000 km above the earth’s surface. The structure of the ionosphere is highly variable, and this variability is imparted onto the performance of telecommunication systems whose signals are propagated via the ionosphere. The prediction of the ionosphere and the performance of ionospheric-dependent radio systems is often assumed to be identical. Ionospheric predictions are generally made using models that are either physically, statistically, or empirically based. Predictions of the performance of ionospheric-dependent radio systems are generally made by using the ionospheric predictions in conjunction with other elements (models, formulas, equations, etc.) that permit the determination of system characteristics.

II. IONOSPHERIC MODELS

A. General Comments

Historically the D region of the ionosphere is treated as the lowest ionospheric region. It has an altitude range from 30 to 90 km and the electron density increases rapidly with altitude. The D region is under strong influence of the sun with the maximum values of the electron density occurring near local noon during summer. The ionization in the D region between 70 and 90 km is caused primarily by solar X rays; below 70 km, cosmic ray-produced ionization dominates [1]. The high collision frequency between the electrons and neutral particles in the D region gives rise to substantial absorption of radio waves that are propagated into it.

The E region is the next highest ionospheric region. It spans the altitude range from about 90 to 130 km. The normal E layer closely resembles a “Chapman” layer [2] with a maximum density near noon and a seasonal maximum in summer. The maximum density occurs near 100 km, although this height varies with local time. During the nighttime, the ionization in the E region approaches small residual levels [3]. The normal E layer is formed by ultraviolet radiation ionizing atomic oxygen. Collisions between electrons and neutral particles, while important in the E region, are not as numerous as in the D region. The electron-neutral collision frequency generally decreases exponentially with altitude throughout the E region.

Embedded within the E region is the so-called sporadic-E layer. This layer is an anomalous ionization layer that assumes different forms—irregular and patchy, smooth and disklike—and has little direct bearing to solar radiation. The properties of the sporadic-E layer vary substantially with location and are markedly different at equatorial, temperate, and high latitudes. Matsushita and Smith [4] have provided a compilation of the status of our understanding of sporadic E.

The highest ionospheric region is termed the F region. The lower part of the F region (130 to 200 km) displays different variations than the upper part, and for this reason the terms F1 and F2 (region above 200 km) are applied. The F1 region, like the E region, is under strong solar control. It reaches a maximum ionization level about one hour after local noon and its presence is generally only obvious during the summer. At night the F1 and F2 regions merge and are termed simply the F region [1].

The F2 region is the highest ionospheric region. It is also the most variable in time and in space. The maximum values of electron density in the F2 region can be as large as 2 × 10^12/m^3. The maximum value generally occurs well after noon, sometimes in the evening hours. The height of the maximum ranges from 250 to 350 km at midlatitudes to 350 to 500 km at equatorial latitudes. At midlatitudes, the height of the maximum electron density is higher at
night than in the daytime. At equatorial latitudes, the opposite behavior occurs.

The F2 region is strongly influenced by neutral-air winds, electrodynamic drift, and ambipolar diffusion that compete along with ionization processes to control the ionization distribution. The relationship between the direction of the geomagnetic field and the direction of the neutral winds and electrodynamic drifts plays a major role in the resultant F2 region structure. It is the plasma response to the dynamic processes in the presence of the geomagnetic field that gives rise to the observed variations in the F2 region.

Within the F region, the collision frequency between electrons and neutral particles decreases markedly. However, collisions between electrons and ions, being Coulomb-type collisions, can give rise to relatively high effective collision frequencies. Substantial absorption of HF radio waves can occur, for example, near the peak of the F region [5].

The F region extends upward into the topside ionosphere. The topside ionosphere is as variable, if not more so, as the F region. The variations become increasingly larger with altitude. Because the electron density continuously decreases in the topside ionosphere, the ionization in the topside becomes less and less important in terms of affecting most radio propagation systems.

Fig. 1 provides a rather simplistic example of the vertical distribution of electrons in the ionosphere. This particular distribution is characteristic of midlatitudes at summer noon, solar maximum conditions. At any location on the earth, the vertical distribution can be expected to differ from that of Fig. 1. Many of the ionospheric models that have been developed over the years are limited to specific geographic regions because the mechanisms that lead to the formation and changes of the ionosphere tend to vary in their dominance of the overall distribution in specific geographical regions. This is particularly true for the ionosphere in the equatorial latitudes and at high latitudes. A detailed discussion, however, of the special features of the equatorial and high-latitude ionosphere is outside the scope of this paper; the material contained in [1], [6], and [7] provides outstanding descriptions.

B. Theoretical Models

Theoretical models provide the means to determine how well our current understanding of the physical mechanisms that are believed to be responsible for the formation of the ionosphere is consistent with the observed ionospheric behavior. The theoretical models that have evolved in recent years are generally very complex requiring numerical solutions on high-speed computers. These models are time-dependent and provide ionospheric information as a function of height, location, and time. The most sophisticated of these models is the one reported by Sojka and Schunk [8]. This model is a global ionospheric model that employs the time-dependent continuity, momentum, and energy equations for each of the ions NO+, O2+, N2+, O+, N+, and He+. Physical processes that are included in the model are field-designed diffusion, electrodynamic drifts, thermospheric winds, chemical reactions, ionization production, particle precipitation, and heating. The ionospheric parameters that are calculated between 120 and 1000 km include the electron and ion densities, the electron and ion temperatures, and the plasma velocities. Depending upon the form of the calculation, between 12 and 30 h of CRAY computer time are required to obtain a complete global evaluation for 24 h. The primary application of this model has been the study of the high-latitude ionosphere [9], [10], rather than the global ionosphere. Most of the results are concerned with F region phenomena in the high-latitude ionosphere in which the interaction between the magnetosphere and the ionosphere is of paramount interest.

Theoretical models of the low latitude F region have also evolved over the years. They, too, require access to large computers. The models of Baxter and Kendall [11], Sterling et al. [12], and Anderson [13] are examples of this type of model. The time-dependent continuity and momentum equations are applied for the NO+, O2+, N2+, and O+ ions; and thermospheric winds, ambipolar diffusion, and electrodynamic drifts are included. Calculated parameters are the ion and electron densities and the ion and electron temperatures. These models have been used to determine the structure of the low latitude ionosphere, particularly the formation of the equatorial anomaly, for various thermospheric wind and electrodynamic drift patterns.

Theoretical models of the lower ionosphere are limited. This is due in large measure to the lack of long-term and consistent observations of the lower ionospheric parameters that are needed as input to such models. Notable exceptions are models of the D region under extremely disturbed (geophysically and man-made) conditions. The D region theoretical models are large-scale chemical computer codes and have as their application the prediction of the changes in D-region chemistry resulting from outside forces [14], [15]. These models also provide a fairly good representation of the E region under normal conditions. Because it is very much solar-dependent and well understood, theoretical models of the E region ionization distribution generally hold little interest to the theorist [16].

Theoretical models have also been used to study the behavior of irregularities, and their generation, in the ionosphere. This use of models is also outside the scope of this review. The numerical simulations such as reported in [17]–[19] have done much to further our understanding of how irregularities in the ionization distribution are formed and are transported. The application of the results obtained by these models to transitionospheric propagation phenomena is given by Aarons [20].

C. Statistical Models

The theoretical models described above generally have been developed to study the response of the ionosphere to particular
physical or chemical processes. For the most part, the models that form the basis for ionospheric prediction methods are statistical in nature. These models permit the selection of ionospheric parameters on a global or regional scale as a function of time, season, and solar activity. The solar activity representation is usually given in the form of an index [21], which must be predicted; the relationship between the predicted index and the ionospheric parameter provides the method of ionospheric prediction.

Models of the monthly median critical frequency of the E, F1, and F2 regions exist that are based on observations obtained around the world. The observations were made using vertical-incidence ionosondes that measure numerous ionospheric parameters [22]. The critical frequency for a given ionospheric region is the highest (ordinary-wave) frequency that can be reflected from that region when it is propagated in the vertical direction. The ordinary-wave critical frequency is related to the electron density by the equation

\[ N_m = 1.24 \times 10^{10} \cdot f_0^2 \]

where \( N_m \) is the maximum electron density in the region expressed in electrons/m\(^3\) and \( f_0 \) is the critical frequency in megahertz.

A representation of the monthly median value of \( f_0E \), the E region critical frequency is available from Muggelton [23]. It is based on data observed at 55 locations throughout the world. A more complete representation of \( f_0E \) can be obtained from [24]. This model is expressed in terms of numerical coefficients that have been determined by application of a spherical harmonic analysis to the observed monthly median values. A more simplified representation for \( f_0E \) is given as [25]

\[ f_0E = 0.9[(180 + 1.44R_{12}) \cos \chi]^{0.25} \]

where \( R_{12} \) is the 12-month running mean sunspot number and \( \chi \) is the solar zenith angle evaluated at the midpoint of the month for which (2) is evaluated. For many prediction applications that require only a simplified model of the E region, (2) is more than adequate.

A representation of the critical frequency of the sporadic-E layer, \( f_0Es \), is available [26] that also is cast in the form of numerical coefficients. Models of the critical frequency of the F1 region, \( f_0F1 \), have also been developed [27], [28].

Models of the critical frequency of the F2 region, \( f_0F2 \), are also available in the form of numerical coefficients [29], [30]. Recently a new set of coefficients has been developed [31] that was deduced using observed values of \( f_0F2 \) and theoretically generated values of \( f_0F2 \) in order to improve the representation of \( f_0F2 \) over ocean areas and other inaccessible areas. Other F2-region parameters such as the M(3000)F2 factor, which can be shown to be related to the height of maximum ionization in the F2 region, \( hmF2 \), and the minimum virtual height of the F2 region are also available in the form of numerical coefficients [30].

The statistical models for \( f_0E \), \( f_0F1 \), and the F2-region parameters are based on monthly median ionospheric data. The representations that result are often less accurate than is desired, particularly in regions of the world that are characterized by the presence of large gradients in the ionosphere. This has led to the generation of phenomenological models that can be used in conjunction with the statistical models to provide a "correction" to the results obtained from a purely statistical model. Such approaches have been applied particularly to the polar ionosphere [32]-[36]. An indication of the results that can be achieved by combining a phenomenological model with a statistical one is illustrated in Fig. 2. Shown is a latitudinal (idealized) distribution of plasma frequencies in the polar ionosphere. The location of the trough and its intensity as well as the location of the enhanced D region absorption and the E and F region irregularities are depicted. The values assigned to the plasma frequency are consistent with those obtained using the models given in [30] and [34].

The statistical models provide results for particular ionospheric parameters. In order to obtain a complete electron density profile, the results available from these models must be combined with an assumed vertical distribution for the ionization. Approaches to achieving this are readily available [33], [35], [37], [38].

In addition to statistical models of parameters confined to individual ionospheric regions, statistical models of the integrated electron density exist. These models provide an estimate of the integrated electron content between the surface of the earth and some specified height. The source of the data used to generate these models generally has been VHF transmissions from orbiting and geostationary satellites. A summary of these models is provided in [39] and in the references contained in [1].

D. Empirical Models

There exists a family of ionospheric models that combine certain features of the theoretical models with the statistical models. These models are generally used to specify the electron density on a global scale by virtue of the global nature of the statistical model contained within them. Usually these empirical models employ a physically (or chemically) based representation of the lower ionosphere with a statistical representation of the upper ionosphere. This is done because the F2 region is highly variable and requires complex phenomena to represent it on purely physical grounds.

The International Reference Ionosphere (IRI) developed under the auspices of the International Union of Radio Science (URSI) is perhaps the best known model of this type [40]. A physical and chemical model is used to determine the electron and ion density in the D, E, and F1 regions. The electron and ion temperatures can be calculated throughout the entire ionosphere. The electron density in the F2 region is calculated by combining the diffusion equation with the values of \( f_0F2 \) and \( hmF2 \) determined from the statistical model given in [30]. The approach adopted in the generation of this model follows very closely that advocated by Nesbit [41] in the early 1970’s.
The empirical approach to ionospheric modeling has been used for many specific applications. Bent et al. [38] have developed an empirical model of total electron content using observed electron density values obtained from the Alouette I and Ariel II satellites. The observed topside profile was represented in terms of three overlapping exponential profiles and was tied to the F2 region represented by the parameters given in [30]. A biparabola was used to represent the electron density below the F2 region maximum height. The total electron content is determined by integrating the predicted electron density profile.

Empirical models have also been developed for limited ionospheric regions. Vondrak et al. [42] have combined electron density and electron temperature data observed at the Chatanika radar site in Alaska with the high-latitude model given by Elkins [33] to provide predicted electron density profiles that are consistent with incoherent scatter observations. The degree to which this model represents the entire polar region needs to be evaluated further. At the other end of the latitudinal range, Anderson et al. [43] have developed a semi-empirical model of the low-latitude ionosphere based on theoretical calculations. The model is expressed by coefficients that represent the vertical electron density distribution between ±20° geomagnetic latitude. Values of the electron density are obtained by combining the predicted vertical distribution with predicted (or observed) values of foF2 and hmF2 determined as in [30], or it can be provided externally. This model is also undergoing extensive verification.

III. IONOSPHERIC PERFORMANCE PREDICTIONS

A. General Comments

In order to determine the performance of an ionospheric-dependent radio system, more than just an ionospheric model is needed. The ionospheric model must be tied to a set of equations or a formulation that enables the simulation of the propagation of radio waves through the ionospheric model to be simulated. The set of equations or the formulation chosen, together with the ionospheric model, is often termed an ionospheric propagation model. When the ionospheric model that is contained in the propagation model can be used to make predictions of the ionospheric structure, the propagation model is termed an ionospheric propagation prediction model. The propagation model must provide the method for calculating the geometry pertinent to the radio system as well as methods for handling information about transmitter power and signal modulation, antenna characteristics, receiver location and noise environment, and required performance levels. The degree to which each of these is incorporated into the propagation model often determines the complexity of the model.

Although radio signals in all the frequency bands ranging from ELF to UHF (3 kHz to 1 GHz) are affected by the ionospheric structure if they are propagated within and through the ionosphere, only models dealing with HF and VHF propagation will be considered here. Propagation models for ELF, VLF, LF, and MF systems that rely upon the ionosphere generally do not explicitly take the ionosphere into account. Information about these models can be obtained in [44]-[46].

Most of the HF propagation models available assume that signals are reflected from the ionospheric E and F regions according to strict geometrical considerations. The ionosphere at the reflection points is estimated from the ionospheric model and is used as input into the formulation relating to the reflection process. The details of the method used to evaluate the reflection of HF signals from the ionospheric regions (i.e., the evaluation of the modes) vary with the different propagation models.

For HF propagation models, the field strength of a radio signal is the fundamental parameter that is calculated. This can be expressed as [47]

$$E = 136.6 + P_T + G_r + 20 \log f - L_{bf} - L_i - L_g$$

(3)

where

- $E$ is the field strength in dB above 1 µV/m
- $P_T$ is the transmitter power in dB relative to 1 kW
- $G_r$ is the antenna gain of the transmitting antenna in dB above an isotope
- $f$ is the transmitting frequency in MHz
- $L_{bf}$ is the basic free space loss in dB
- $L_i$ is the loss due to ionospheric propagation effects in dB
- $L_g$ is the loss due to ground reflection in dB.

Different models incorporate representations of the terms in (3) with different degrees of complexity. The ionospheric loss term ($L_i$) in (3) is generally determined by use of specific formulations or methods in the propagation prediction model rather than by involving collision frequency and D-E region electron density models. This loss is dependent upon the wave frequency and the angle at which the radio wave enters the ionosphere. The angle with which the radio wave enters the ionosphere is dependent upon the form of the ionospheric model that is assumed. The distance to which a given frequency will propagate for a given incidence angle also depends upon the ionospheric model. The types of modes calculated (i.e., the number of reflections of the radio wave from the E and F regions in traveling between the receiving and transmitting site) will differ with different ionospheric models.

The VHF propagation models in use generally relate to evaluating the refraction or time delay of VHF signals that are propagated through the ionosphere between the ground and satellites. The methods used vary with application. If not empirical in scope, they usually employ a specific electron density model and a simplified (straight-line) geometrical calculation method to determine the amount of time delay. The amount of time delay is dependent upon the total electron content encountered by the radio wave on its passage through the ionosphere and is given by [48]

$$\Delta t = \frac{40.3}{f^2} \cdot \text{TEC}$$

(4)

where $\Delta t$ is the time delay in seconds, $c$ is the velocity of light in m/s, $f$ is the frequency in Hz, and TEC is the total electron content along the propagation path. Models that evaluate (4) using electron density profiles have been given by [30]. Predictions on any time scale can hypothetically be made if the ionospheric model that is used in the evaluation of the refraction is adjusted to produce short-term values of the pertinent ionospheric parameters. The accuracy of these short-term models is dependent upon the availability and accuracy of the data used to generate the short-term predictions.

Performance predictions are made for a variety of purposes—for system design, for frequency management, for operational improvements. Most of the propagation methods were originally intended to provide information of a long-term predictive nature using monthly or median predictions of the ionospheric structure. However, a trend has emerged in recent years to utilize propagation predictions on much shorter time scales. The complexity of the long-term and short-term propagation prediction methods is generally very different as are the approaches that are used.

B. Long-Term Predictions

The best known long-term performance prediction methods involve the use of large-scale computer programs. The work of...
Barghausen et al. [49] was the first long-term, computer-based program of its sort to gain international usage. It has subsequently been replaced by the IONCAP [50] program. These programs provide the means to calculate HF propagation parameters at any location on the earth. Field strength, mode reliability, and the maximum usable frequency (MUF) are but a few of the parameters that are obtained from these programs. They enable the user of the program to specify antenna gains as a function of take-off angle and to specify required system performance in terms of the signal-to-noise ratio evaluated at the receiving point of the circuit. Both programs have common features such as use of the same sets of numerical coefficients to represent the morphological behavior of the ionospheric structure and the atmospheric noise expected at the reception point. There are, however, significant differences between the two programs. The ionospheric loss term (the $L$ term in (3)) in the IONCAP [50] program differs from that of the Barghausen et al. [49] program. Also, the manner in which the various modes are computed in both programs is different. Consequently, the resultant field strength that is calculated by each of the programs for the same circuit conditions is different. The IONCAP [50] program has a distinct advantage over the Barghausen et al. [49] program by enabling the user to incorporate into the calculation specific knowledge about the ionosphere such as an electron density profile obtained from independent information.

In utilizing a propagation prediction method like that of IONCAP, the user must specify the particulars of the circuit such as transmitter and receiver location, transmitter power, transmitting antenna, and quality of service that is required. In addition, the universal time, month, and sunspot number that are appropriate for the period for which calculations are to be performed must be specified. There are numerous output options that are available including maximum usable frequency (MUF) for the circuit, the lowest useful frequency (LUF), and the field strength for any frequency that has been indicated by the user. The mode, signal-to-noise ratio, predicted signal reliability, and take-off angle for each mode is likewise available. More detailed information about the various output options is found in [50].

The IONCAP [50] and the Barghausen et al. [49] programs are complete HF propagation performance prediction programs. There is a class of programs that exists that can be considered a subset of these. These programs are concerned primarily with evaluating the field strength of an ionospheric-dependent radio system. Models of this type are given in CCIR Report 252 [51], the Supplement to CCIR Report 252 [52], and CCIR Report 894 [47]. The field strength calculations given in Report 252 [51] are consistent with the method of field strength calculation that was included in the Barghausen et al. [49] and the IONCAP [50] propagation prediction programs. The field strength calculations that are given in the Supplement to Report 252 [52] are more complex than the methods of calculation of field strength given in [49] and [50]. The complexity is due in large measure to a significant difference in the manner in which the ionospheric modes are evaluated. In the CCIR Report 252 [51] approach to ionospheric reflection estimation and mode evaluation, the pertinent calculations are performed at specific points, called control points, along the propagation path determined by the path length. No account is taken of the change or gradient in the electron density along or transverse to the propagation path. The Supplement to CCIR Report 252 computer program does account for gradients at the control points. It thus provides a more physically appealing calculation. This is, however, achieved at a cost-increased computation time—that often exceeds that of [51] by factors of 10 to 30.

The field strength prediction method given in CCIR Report 894 [47] had, as its roots, the work performed by CCIR Interim Working Party 6/12 to develop a sky-wave propagation prediction program for use in planning the HF broadcasting service [53]. This field strength model is actually a combination of two field strength programs: a simplified version of the IONCAP field strength prediction method is used for path lengths less than 7000 km and the field strength model developed by the Deutsche Bundespost (FTZ) [54] is used for path lengths greater than 9000 km. A linear interpolation scheme is employed for distances 7000 to 9000 km.

For the propagation models given in [49]-[52], the field strength is evaluated for each mode that is determined according to the geometry incorporated into the program. The selection of the modes that are chosen to determine the overall field strength for a given frequency are not the same for each of the models. Generally, however, three or four of the modes that are associated with the least amount of loss are chosen and the antenna gain is then incorporated into the field strength calculation for each mode and a root-sum-square is performed to obtain the resultant field strength.

The FTZ propagation program [54] employs a field strength calculation that is based upon observations collected over specific HF circuits, most of which terminate in Germany. The data that have been gathered for more than 10 years for certain circuits are related to predicted ionospheric critical frequencies to obtain an empirical method for determining field strength. The method permits rapid calculation of the field strength and is useful when this is a primary consideration [55]. Because the method does not calculate individual modes, it suffers from the fact that the antenna gain cannot be added into the computation in a consistent manner. This can severely limit the usefulness of this method except for those instances where antenna gain is not important (such as the computation of the MUF) or where the gain is effectively confined to a limited range of radiation angles (such as long-distance, i.e., >9000 km circuits).

It was mentioned that the FTZ model was used in conjunction with a version of the IONCAP model to produce a model described in Report 894 [47]. The model of Report 894 provides the basis of yet another propagation model that was developed in 1984 at the First Session of the HF Broadcasting Conference [56]. This model, referred to as HFBC84, was developed specifically for planning the use of the HF spectrum for broadcasting purposes. The primary difference between HFBC84 and the Report 894 model is the manner in which the antenna gain is taken into account in the computation of field strength. Before the selection of the modes that are to be combined to determine the field strength of a given frequency on paths of less than 7000 km, the antenna gain at the appropriate take-off angle for each mode is added to the field strength. The resultant field strength is determined using the strongest E mode and the two strongest F modes for paths up to 4000 km. Between 4000 and 7000 km, only the two strongest F modes are considered. For paths greater than 9000 km, the maximum antenna gain that occurs between $9^\circ$ and $8^\circ$ elevation angle is used in the field strength computation. The inclusion of the antenna gain in the field strength calculation prior to the selection of the modes that are to be combined to form the resultant field strength leads to the determination of a much improved estimate of the field strength. The HFBC84 program provides an efficient means to determine the area serviced by an HF broadcast transmitter and to assess the likely interference. Fig. 3 shows an illustration of the field strength for a Voice of America transmitter located at Kavalla, Greece, operating on a frequency of 11.855 MHz with a power of 250 kW for 2000 h UTC in March 1985. The contours are in decibels above 1 $\mu$V/m (dBuV). The calculations were performed assuming a horizontal dipole reflector curtain antenna two half-waves wide, with four horizontal rows one above the other, the lowest row of elements being one-half wavelength above the ground (designated HR 2/4/0.5). The levels of field strength illustrated in the
figure indicate a high-quality service (in the absence of interference) is provided to the intended service area.

The ionospheric propagation methods described above have not been tested in a consistent fashion largely due to the lack of an appropriate (independent) data base. The testing and evaluation that have been undertaken are generally somewhat limited and are reported by the CCIR [57]. Recent studies by Millman and Swanson [58] are a welcome addition.

C. Short-Term Predictions

The ionospheric prediction methods described above are based upon monthly median predictions of the ionospheric structure. In principle, they could be utilized to predict radio propagation conditions on a time scale that is shorter than a monthly median if the ionospheric structure for the comparable time scale was available. In order to obtain this information, observations are needed that can be used to determine what the predicted structure will be. These can be observations of the sun or solar processes [59] or of particular ionospheric parameters [60]. The ionospheric structure is “updated” from its median value according to the observed information and new propagation conditions can be calculated in the manner described in the previous section.

This procedure is in fact generally not used because short-term ionospheric predictions tend to be directed toward specific applications in support of operational telecommunication systems. Short-term prediction methodologies have evolved over the years being driven primarily by the ability to monitor the status of the earth’s environment and to report this monitored information to a location where it could be used to predict the ionospheric structure and the results disseminated. The papers contained in [61]–[63] provide excellent summaries of the status of short-term prediction capabilities as of 1970, 1979, and 1984, respectively.

The type of short-term predictions that are provided vary with the organization providing the prediction. An up-to-date summary of these organizations is given in [64]. In addition to these services provided by the organizations listed in [64], short-term prediction methods have also been developed that are applicable to a wide range of radio systems. The PROPHET prediction program [55] incorporates updated solar and ionospheric information to predict ionospheric propagation conditions on an hourly or daily basis. The program also uses techniques to predict rapidly ionospheric propagation parameters such as the maximum usable frequency and the lowest useful frequency. A related technique using the MINIMUF [65] program has been used in a variety of short-term applications [66], [67].

The accuracy of a short-term ionospheric propagation prediction method depends on the ability to observe the pertinent geophysical parameters on a spatial and time scale that is consistent with the phenomena being predicted [68], [69]. The usefulness of the prediction in support of operational radio systems depends not only on the accuracy but on the ability to disseminate the information in a time frame adequate for the user to make decisions.

IV. Conclusion

Ionospheric models and ionospheric predictions techniques continue to be developed. In recent years there has been a definite trend toward the development of generalized ionospheric models and
specialized ionospheric prediction methods. It remains to be seen if these apparently conflicting approaches lead to an improved capability to predict and assess the performance of ionospheric-dependent telecommunications systems.

REFERENCES


