ANNEX 2 [1]
PERFORMANCE PREDICTION METHODS

A2-1 Annex Summary

For those involved in development of communication technology and its applications, variabilities and fluctuations in the HF channel present a serious and formidable task. To these workers, the relatively unpredictable nature of skywave signaling is both imposing and challenging. The excitement of communicating around the world with relatively elementary equipment has not been diminished by the development of satellite communications. The mechanism—ionospheric channeling—that is principally responsible for allowing such communications, is essentially a gift of nature.

In this annex, we address the need for predictions of HF communication performance. We then address the relationships between short-term and long-term predictions. We review extant HF performance prediction models with regard to the errors that arise in a) the ionospheric models and b) the prediction methods used. A secondary issue is the unmistakable principle that HF system performance predictions agree best with reality when the associated prediction models are updated with measured data. This is manifest because ionospheric variability is substantial, and typically only median representations of ionospherically dependent parameters are incorporated into the modeling process. Several techniques for accommodating or tracking variability are possible, but this possibility suggests that the spectrum planning process should be made more flexible. The process of model updating is examined only briefly in this Annex. The Annex addresses principally the unadulterated prediction methods.

Although this Annex stresses mainstream Institute for Telecommunication Sciences (ITS) prediction methods (such as the IONCAP family of programs) and internationally sanctioned CCIR techniques, other models may also furnish helpful results. A general summary of the features of major models is provided in this Annex. The Annex concludes with a section addressing the ongoing work to improve long-term predictions.

A.2-2 Introduction

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

Predictions have improved over recent years as a result of two factors:

a) the evolution of computers (along with advanced computational methods) and
b) the development of advanced sensors and telemetry.

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[1] Annex 2 is largely based upon Chapter 5 of the book *HF Communications: Science and Technology,* by J.M. Goodman, and published by Van Nostrand Reinhold (VNR, New York, 1991-92. Permission is granted to use this material by the author, by VNR, and the current holder of the copyright, Kluwer Academic Publishers. Dated 9-30-98.

The advent of communication satellites has prompted a significant advance in our global perspective, especially valuable in weather forecasting and its affect on telecommunications. Satellites have provided a unique collection of scientific data that has supplemented our basic understanding of cause and effect. Radio methods for earth-space and terrestrial skywave telecommunications are clearly influenced by ionospheric phenomena in a manner that is dependent upon the frequency used. HF is the most vulnerable to the widest range of ionospheric effects, and the magnitude of HF propagation effects provides a good index of intrinsic ionospheric variability. By allowing for compensations, predictions allow one to cope with the HF vulnerabilities to this ionospheric variability. Since HF is the most vulnerable to the greatest range of ionospheric effects, a major component of ionospheric remote sensing technology has been dominated by HF probes and sounding systems.

One of the elements that can promote relatively accurate short-term predictions of HF system performance involves the process of model updating by incorporating live data from sensors that probe the temporal and spatial regions of the path of concern. In the context of HF skywave propagation, any sensor—including an oblique-incidence-sounder—that permits ionospheric characterization of the critical portions of the path can be a very useful probe. Under disturbed conditions, forecasts can lose significance in less than an hour (corresponding to the period of an atmospheric gravity wave) if probe information is less than complete or if the probe is not in close proximity to the control point (*i.e.,* within a few hundred kilometers)[2]. Other factors may similarly affect forecasts. For instance, the update data from the probe is subject to its own built-in errors in scaling and its own imprecision in converting raw data into useful information. Nevertheless, it is possible, in principle, to prepare forecasts that are accurate and useful.

Long-term predictions of path performance, although they are necessarily inaccurate because of ionospheric variability, do provide helpful information for users of the HF spectrum. The validity of these predictions arises from the fact that short-term variability has been appropriately bounded under the propagation regimes or geophysical conditions for the specific long-term predictions under study.

A2-3 Requirements: predictions and spectrum management guidance

A2-3.1 General broadcast requirements

As discussed above, HF is the most critically influenced of the radiofrequency transmission schemes with regard to skywave propagation effects. This wide variability may result in either positive or negative traits in broadcasting and point-to-point transmissions, and may require much flexibility in choosing the optimum set of system parameters to succeed in

[2] Control point is a term that flows naturally from the mirror model of HF skywave propagation. In view of the fact that most of the refraction experienced by a *reflected* mode is in the neighborhood of the ray trajectory apogee, exclusive of any high-ray modes, convenience suggests that the *control point* should refer to the midpoint of the (presumed) great circle trajectory. Accordingly, midpath ionospheric properties that are reckoned at some appropriate height are assumed to control the propagation. Factors that will render the *control point* notion invalid include: strong tilts and gradients, dominance of the *high ray,* above-the-MOF modes, non-great-circle modes, and sundry scatter modes. Another difficulty is the azimuthal insensitivity of the control point approach, a fact that certainly affects the capability to associate data derived from nonorganic sounders with operational HF paths. This is especially troublesome when the sounder path and the wanted path are virtually orthogonal, even when the control points are common (*i.e.*, paths form a cross in plan view).

reaching an intended receiver. Of all users, those who are concerned with HF broadcasting may find themselves facing the greatest challenge. Facets contributing to this include:

a) requirement for distended signal *laydown* pattern to cover reception centers that are widely separated geographically,
b) a technique to compensate for skip zone variations for designated receivers even when the diurnal period of transmission is limited.

Skip distance variability may be great. Military broadcast services provide for enhanced performance through incorporation of frequency-management techniques; and spectral use efficiency (as a percent of the MUF-to-LUF envelope) is improved by the use of diversity, which may partially compensate for fading and intersymbol interference. Since the listeners of civilian broadcasts are disadvantaged (they have no access to sophisticated radio equipment and no real-time feedback capability), it is obvious that the broadcasting community needs a credible long-term prediction capability before they can offer (and advertise) a reasonable set of broadcast channels to potential listeners in designated reception areas. The successful transmission of programs using the shortwave band must account for a number of parameters, including:

- location of the source transmitter,
- time and duration of the transmission, and
- the specified reception area for the program.

Also, serious attention should be paid to phenomenological elements of the propagation medium, such as the ionospheric heights and critical frequencies, which, in the end, determine the broadcast coverage for a specified frequency.

While predictions are helpful for other HF spectrum users (including tactical- and strategic-military communication services) federal and state emergency communication networks, military affiliated radio systems, and even the amateur radio service, predictions are almost an imperative for the civilian broadcast community.

Coverage prediction depends on an ability to predict the ionospheric conditions. These ionospheric predictions typically comprise the exploitation of models of ionospheric structure, which are coupled to some appropriate radiowave propagation algorithm. As mentioned above, the ionosphere is typically modeled by spatial and temporal functions and some external parameters reflecting solar and magnetic activity control. Usually, the geography for the prediction problem is known, and the ionospheric conditions are prescribed by the model, after one or more input control parameters have been specified. Such a model places too much weight on a single parameter like the sunspot number, and the result is often unsatisfactory if precision is required. Nevertheless, requirements-driven predictions will rely on some equivalent solar activity index in most applications for some time in the future. Models that have been tailored to the needs of the point-to-point service are not always satisfactory for resolution of broadcast coverage, and most models fall into this category. The VOA (Voice of America)[3] has developed a broadcast coverage mapping capability in connection with a CCIR computer method called "HFBC-84." The Institute for Telecommunication Sciences (ITS) of the U.S. Department of Commerce has packaged three useful programs as part of its Windows®–based "PC-HF Propagation Prediction Programs." These programs may be obtained over the Internet at URL http://elbert.its.bldrdoc.gov/hf.html . Two of these programs, (*i.e.*, VOACAP and ICEPAC) are direct descendents of IONCAP, and the third is an implementation of the ITU Recommendation 533. The development of VOACAP and REC533 were motivated by broadcast applications although

[3] The Voice of America is now organized as a component of the International Bureau of Broadcasting (IBB).

VOACAP allows execution of the complete set of original IONCAP methods. All three programs in the ITS suite include area coverage as well as point-to-point versions.

For guidance in future operations, a measure of ionospheric support variability is also needed. Beyond this, variability in received signal level (or alternatively, the basic transmission loss) is required. Models of ionospheric variability expressed in terms of the upper and lower deciles for both the transmission loss and the MUF are available in CCIR publications such as Report 252-2 [CCIR, 1970] and its supplement [CCIR, 1982a] for specified conditions. Interestingly, the CCIR MUF variability tables are largely based upon data obtained in the early sixties [Barghausen *et al.*, 1969] [Davis and Groome, 1964]. The CCIR [1986a] has published another field-strength variability model specific to the needs of broadcasters. Even so, significant deviations from CCIR *suggestions* have been observed [Gibson and Bradley, 1987] [Fox and Wilkinson, 1986]. The exploitation of existing data banks along with the certification of additional data sets that provide variability information is clearly an important effort in performance predictions.

A2-3.2 Military and related requirements

Operational requirements of military users has often led to simplifications of the established main frame procedures in order to provide spectrum guidance in a more accessible manner. This was especially true for tactical commanders who may not have had access to real-time sounding information. Tactical frequency management systems, while they may allow for incorporation of real-time data for decision-making in the field, typically *default* to predictions which may be derived from the long-term models similar to IONCAP. The tactical user was typically disadvantaged as a result of the severe limitation in speed and accuracy afforded by the microprocessors of the 1970’s and 1980’s. This constraint led to the development of simplified codes and databases to solve specialized problems, and a cottage industry of simple programs evolved during the adolescence of personal computer development. The PROPHET system [Rose, 1982] is a good example of a resource management tool that originally exploited simplicity to provide tailored products to the user. Steps were eventually taken in recent years to improve the models organic to PROPHET and similar systems while retaining user-friendly features for the tactical user. With the advent of smaller, faster Windows®-based microprocessors, the constraints of form factor, weight, and code complexity have been mitigated. By the late 1990’s, the distinction between small, mini/microcomputer programs and large mainframe programs virtually disappeared. In this new environment, there is little need to develop simplified methods.

The U.S. Army has published communication charts and the U.S. Navy has published a document called the NTP 6 Supp-1 [1990] *Recommended Frequency Bands and Frequency Guide.* This guide is based on IONCAP methods and the actual recommendations are based on sunspot number ranges specific to a particular year. The range of sunspot numbers for a specified year are based upon long-term running averages reckoned near the publication date and, therefore, may not precisely match currently required conditions. NTP 6 Supp-1 has two methods that are available for users. Both use look-up tables to retrieve MUF and FOT data. The first method is for users who are communicating over *arbitrary* maritime paths, while the second is tailored for use by communicators terminating at established Communication Stations (COMMSTAs) or Communication Units (COMMUs). The NTP 6 Supp-1 *Guide* has been published by the Naval Electromagnetic Spectrum Center, Washington, DC. It is anticipated that the requirement for this guide will diminish with the incorporation of the publication of ALE systems for frequency management, and with access to Windows®-based versions of the IONCAP family of programs.

The U.S. Air Force has shortwave frequency-management challenges which are quite similar to those of the U.S. Army and the U.S. Navy. Nevertheless, embedded ALE systems, which exploit optimal sounding protocols for frequency management, have eroded the requirement for predictions in a number of applications. By the same token, the U.S. Air Force has taken the lead in solar-terrestrial environment predictions, including ionospheric predictions. Surveys by the U.S. Air Force Space Forecast Center have consistently shown that HF users are the predominant claimants to the predictions services. The National Space Weather Program, sponsored by DoD, the National Science Foundation (NSF), and NOAA Space Environment Laboratory—while geared more toward fundamental understanding of the hierarchy of solar/terrestrial interactions—has proved to be a catalyst for development of improved HF prediction services. Moreover, there is a growth in the number of third-party vendors that are offering forecasting products for application in systems that are sensitive to ionospheric disturbances.

A2-3.3 The spectrum management process

Several methods are used for spectrum planning. The ITU has long recognized that the HF skywave channel is a valuable resource, and one of the ITU's technical arms, the CCIR, has developed methods that can be applied by various administrations for optimization of communication and broadcast performance, while limiting the potential for interference with other users. These methods represent the best the community can achieve in the long-term prediction of ionospheric behavior. The various processes by which radiowaves interact with the ionosphere are not ultimately as critical as is the ionospheric definition in the prediction process.

The ITU, created in 1865 at the Paris International Telegraph Convention, is now composed of 163 nations. Objectives of the ITU are promulgated and maintained through the *International Radio Regulations.* These regulations are updated through agreements reached at the World Administrative Radio Conferences (WARCs). The WARC is one of six major entities constituting the ITU. The period between WARCs is at least 10 years but may be as much as 20 years. The most recent meeting was held in 1997 in Geneva. Another agency within the ITU is the Radio Regulations Board (formerly the International Frequency Registration Board), which serves as the official agency for registering the date, purpose, and technical properties of frequency assignments made by member countries. Technical branches of the ITU include the CCIR (International Radio Consultative Committee) now called the ITU-R and the CCITT (International Telegraph and Telephone Consultative Committee), now called the ITU-T. The ITU-R provides much of the guidance to the ITU for outstanding technical issues. Officially this guidance takes the form of published *Recommendations.* The HF prediction methods suggested by the ITU-R, therefore, are quite significant for establishing *Recommendations* for spectral planning by the ITU. These documents are taken up at the WARCs and may lead to reallocation of the radio spectrum. This is of considerable importance to all member nations.

In the United States, the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) of the U.S. Department of Commerce jointly regulate use of the radiofrequency spectrum. NTIA is responsible for government use and the FCC is responsible for regulation of private use services. Within the government, the Interdepartment Radio Advisory Committee (IRAC) oversees government use of the radio spectrum, and resolves outstanding issues. Each government department, having a member in the IRAC, establishes its own procedures consistent with IRAC decisions. The U.S. Department of Defense, for example, places authority for policy establishment and guidance in the Joint Staff (formerly the Joint Chiefs of Staff, the "JCS"). The U.S. Military Communications Electronics Board (USMCEB) develops procedures for implementing the JS guidance. This includes the assignment of frequencies for areas not appropriate for the Commanders-in-Chief (CINCs), who have their own special frequency assignment responsibilities. All DoD components participate in a record system for all frequency resources, and notification is given when a frequency is no longer required. This will make the frequency available for reassignment to other components. Intracommand frequency requirements are passed from the commander to the USMCEB if new assignments are sought. Outside of the United States and if host countries agree, intracommand frequencies may be locally assigned by the commander under certain conditions.

The whole process is rather cumbersome. It is geared to spectral use based upon 1960s technology. Spread spectrum technology and the concepts of frequency pooling, resource sharing, and networking should influence the process in the future. To examine the impact of new spectrum management schemes, it is necessary to request a suite of frequencies on a temporary basis. It has been the experience of one author that such requests are generally approved if it may be shown that little or no interference will be created by the test or experiment.

A2-4 Relationships between prediction, forecasting, nowcasting, and hindcasting

The term *prediction* has a rather elusive meaning, depending upon the nature of the requirement for knowledge[4] about the future. In the case of the ionosphere, a distinction is made between long-term predictions and short-term predictions. Long-term predictions of ionospheric behavior may typically be based upon climatological models developed from historical records for specified solar and/or magnetic activity levels, season, time of day, geographical area involved, etc. Very often, the ionospheric prediction is itself based upon a prediction of the solar activity level. In short, the long-term prediction process relies upon the recognition of loosely established tendencies as they relate to relatively simple (and extraterrestrial) driving parameters, and the result is usually an estimate of median behavior. Two sources of error occur in long-term predictions, one arising because of an imprecise estimate of the driving parameter, such as sunspot number, and the second arising from ionospheric variability which is not properly accounted for in the model. Given these difficulties, it may appear surprising that the process can yield useful results, and yet it often does. Long-term predictions are necessary in HF broadcast planning and in other spectrum management activities where significant lead times are involved. Short-term predictions involve time scales from minutes to days. The term *forecast* is sometimes used to describe those prediction schemes that are based on established cause-and-effect relationships, rather than upon simple tendencies based upon crude indices. In the limit, a short-term *forecast* becomes a real-time ionospheric assessment or a *nowcast.* In the context of HF communications, real-time-channel-evaluation (or RTCE) systems, such as oblique sounders, may be exercised to provide a *nowcast*. Such procedures are useful in adaptive HF

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[4] *Knowledge of the future* appears to be a contradiction in terms. Given the variability of the ionosphere and the observation of the considerable variability in the MUF and field strength, it is anticipated that future values of HF system parameters cannot be predicted with great accuracy. Prediction systems should be evaluated in terms of the success achieved in bounding the parameter variation over selected epochs. In bounding, we imply the *least-upper-bound.*

communication systems. The term *hindcast* is sometimes used to describe an *after-the-fact* analysis of ionospherically dependent system disturbances. Solar control data are usually available for this purpose, and this may be augmented by ionospheric observation data. Figure A2-2 shows the relationship between the various prediction epochs.

The error associated with any prediction method is critically dependent upon the parameter being assessed, the lead-time for the prediction, and other factors. One of the most important parameters in the prediction of the propagation component of HF communication performance is the maximum electron density of the ionosphere, since this determines the communication coverage at a specified broadcast (or transmission) frequency. The ordinary ray critical frequency, given by the term foF2, may be directly related to maximum F2 layer electron density, and foF2, together with the effective ray launch angle, will determine the so-called Maximum Usable Frequency (or MUF) for a specified transmission distance. Thus, the ability to predict foF2 or the maximum electron density of the ionosphere by a specified method is a necessary step in the prediction of HF system performance if skywave propagation is involved.

The next section discusses the general use of ionospheric models in the present-day prediction process.

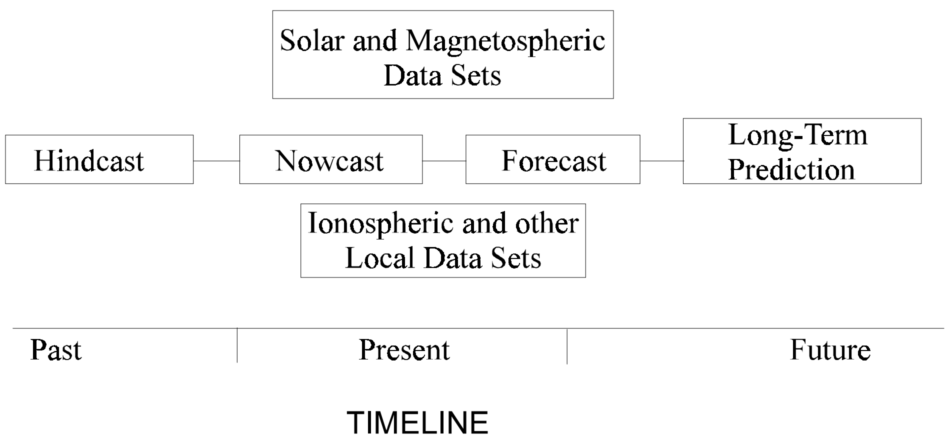


FIGURE A2-1

Relationships among prediction, forecasting, assessment, nowcasting, and hindcasting

Because the sources of ionospheric disturbance cannot be adequately monitored at their points of origin and as they propagate, prediction algorithms are inefficient. An additional complication arises as a result of distortion and attenuation experienced by the propagating disturbance. Moreover, the science that allows us to translate the physical processes in control at the disturbance source to other geographical regimes and times is incomplete. Figure A2-1 depicts the hierarchy of ionospheric disturbances; Table A2-1 provides an estimate of time duration and occurrence frequency for each class of disturbance.

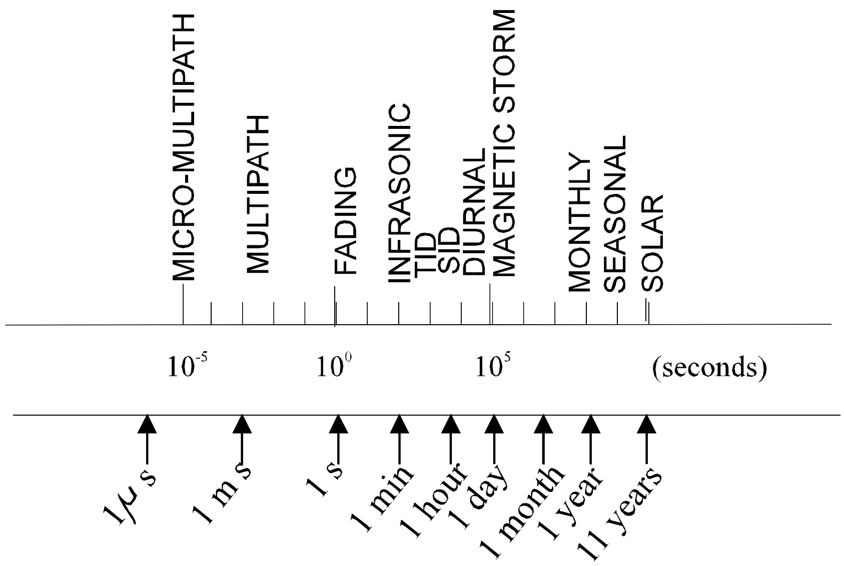


FIGURE A2-2
Hierarchy of ionospheric disturbances

A2-5 The Use of Ionospheric Models for Prediction

The nature of ionospheric variability is quite complex, since it arises from temporal and geographic variabilities in upper atmospheric chemistry, ionization production and loss mechanisms, particle diffusion and electrodynamical phenomena. As indicated earlier, genera. tendencies are fairly well modeled, and much of the variability is understood from a physical point of view. Unfortunately, an understanding of cause and effect does not always translate into a prediction capability.

Several models of varying degrees of complexity have been crafted for the purpose of making ionospheric or propagation predictions, or for use in theoretical studies. The historical development of prediction methods until the middle 1950s is given in an account by Rawer [1975], and post World War II activities are summarized by Lucas [1987]. A survey of ionospheric models has been provided by Goodman [1982], following a review by Kohnlein [1978]. Additional information of a general nature may be found in a report by Bilitza [1990] and further insight may be derived from selected technical surveys [Secan, 1989; CSC, 1985]. Unfortunately, the survey reports have not been distributed widely. A mini-review of models has been published by Rush [1986]. The paper by Rush includes pure ionospheric models but stress is placed on propagation methods that are in current use and under development.

TABLE A2-1

Temporal variations of HF effects†

EFFECT	**TIME PERIOD {seconds in ( )}**	**FREQUENCY {Hertz}**
Solar Cycle	11 years (3.5×10^8)	2.9×10^{-9}
Seasonal	3 months (7.9×10^6)	1.3×10^{-7}
Diurnal Cycle	24 hours (8.6×10^4)	1.2×10^{-5}
Large-Scale TID	1 hour (3.6×10^3)	2.8×10^{-4}
Short-Wave Fade	0.5 Hour (1.8×10^3)	5.6×10^{-4}
Small-Scale TID	10 minutes (6×10^2)	1.7×10^{-2}
Faraday Fading	0.1 – 10 seconds	10 - 0.1
Interference Fading	0.01 – 1 second	100 - 1

†The equivalent frequencies are also provided. A spectral decomposition of the effects will demonstrate a rather featureless continuum for periodicities smaller than a day (or frequencies greater than 10^{-5} Hz). Low frequency terms, being related to well-defined source terms, will cause that part of the spectrum to be discrete.

Some of the models that have been used recently include those of Bent, *et al*. [1975], the international Reference Ionosphere (or IRI) [Rawer *et al.,* 1978 and 1981], and the Ching-Chiu model [Ching and Chiu, 1973; Chiu, 1975]. Of more interest to the HF community are models that use the bottomside properties of the ionosphere which influence the skywave propagation model directly. The models that are largely based upon the very substantial database derived from vertical incidence sounders are the ones of choice. For several years much effort has been directed toward the analysis of this database and in the development of suitable mapping techniques and numerical methods for predicting ionospheric properties. Global maps of ionospheric properties have been published, and these data form the basis for many semi-empirical and climatological (statistical) models of the ionosphere. The ionospheric models will play the role of submodels in relative large HF performance prediction codes. We shall return to prediction modeling in Section A2-6.

The U.S. Air Force has developed a class of ionospheric models that are designed to accommodate the insertion of *live* ionospheric data from satellites, terrestrial sensors, and solar observances. The first model was the so-called Air Force 4-D model [Tascione *et al.,* 1979]. The most recent one is the ICED model [Tascione, 1988], which uses an *effective* sunspot number and a geomagnetic Q-index, the latter being associated with in-situ satellite data describing auroral characteristics. The effective sunspot number used in ICED is based on near-real-time ionospheric measurements derived from a worldwide network of vertical-incidence sounders; the effective number being that value which, if it were to have occurred, would provide the best match between data and model. The effective sunspot number used in ICED is reminiscent of the *T-index* developed by the Australians [IPSD, 1968] as a replacement for the running 12-month average sunspot number, but the number is more closely related to the real-time pseudoflux concept developed by NRL workers [Goodman *et al.,* 1983, 1984]. Exploitation of this scheme allows for the incorporation of dynamic ionospheric behavior. The model should therefore be applicable to HF broadcasting predictions, and should be particularly appropriate for the modeling of high latitude effects. The topside profile is modeled rather simplistically in ICED, and improvements could include incorporation of multiple scale heights above the F2 peak and a correction for a plasmaspheric contribution to the TEC at great heights. However, these matters are more relevant to considerations of transionospheric propagation. The manipulation of models to derive forecasting information is covered below in a separate annex that stresses real-time and near-real-time assessment of the propagation path for solution of the *nowcasting* problem.

Work by Anderson *et al*. [1985] has covered the calculation of ionospheric profiles on a global scale in response to physical driving parameters, such as the underlying neutral composition, temperature, and wind; the magnetospheric and equatorial electric field distributions; the auroral precipitation pattern; and the solar EUV spectrum. A subset of these parameters has been used in profile calculations for the development of semi-empirical low-latitude ionospheric model (SLIM) [Anderson *et al.,* 1985, 1987] [Sojka and Schunk, 1985]. This kind of approach is computationally very intensive, but the use of coefficient maps from these calculations, which depend on the appropriate parameter values, appears feasible. The Fully Analytical Ionospheric Model (FAIM) [Anderson *et al.*, 1989] uses the structure and formalism of the Chiu model with coefficients fitted to the SLIM model profiles. The development of such programs is required to eliminate the use of oversimplified driving parameters in prediction models and to describe completely the chain of events involved in the solar wind-magnetosphere-ionosphere-atmosphere system. Brief descriptions of SLIM and FAIM are contained in a report by Bilitza [1990]. As indicated in section 2.3.2, ITS has packaged a triad of programs, two of which are direct descendents of IONCAP. One of these, ICEPAC, was motivated by U.S. Air Force scientists who recognized that most variations in HF were related to variations in the ionosphere. The ITS modified IONCAP to reflect an improved electron-density model as well as an improved representation of the polar region. ICEPAC is quite similar to IONCAP for the user, but employs the ICED model as the electron-density model of choice.

A2-6 The ingredients of skywave prediction programs

The primary purpose of an HF performance prediction model is to provide an estimate of how well a system will work under a given set of circumstances. Typically this translates into some measure of system reliability (see Section 2.9). The components of a complete skywave performance prediction model should include:

- full documentation
  - (including basis in theory,
  - user's guide,
  - I/O interface data, and
  - machine-specific information),
- a *user-friendly* preprocessor routine which enables the analyst to set up a computation strategy efficiently, the underlying ionospheric submodel structure,
- the database or coefficients upon which the ionospheric submodel depends,
- the noise and interference submodels with associated databases,
- the antenna and siting factor submodels and their databases,
- procedures or rules by which propagation is treated, and
- a set of output products (for each method or option). These major components are shown in Figure A2-3.

Models typically require inputs of

- path geometry (terminal locations in geomagnetic and geographic coordinates),
- day of year (or month/season),
- time of day (or some time block), and

- an index set to *drive* the ionospheric personality (*i.e.*, solar and possibly magnetic activity).

In addition,

- certain terrain and siting information,
- antenna configuration/type and
- other forms of system data are necessary.

Because of the well-established diurnal and seasonal variabilities of the ionosphere, it is not surprising that time-of-day and month (or equivalent) are required as input parameters. Moreover, time block and seasonal data inputs along with receiver location are needed to deduce atmospheric noise, galactic noise, and man-made interference levels. Noise considerations are covered briefly in a later section of this Annex.

DOCUMENTATION

Theory Manual with References
User's Guide with Examples
Technical Specifications
Configuration Control Strategy

PRE-PROCESSOR

IONOSPHERIC SUBMODEL

NOISE & INTERFERENCE SUBMODEL

ANTENNA & SITING FACTOR SUBMODELS

PROPAGATION PROCEDURES & ALGORITHMS

PROGRAM DELIVERABLES

ARCHIVAL FUNCTION & POST-PROCESSOR

FIGURE. A2-3
Major Components of a Complete Skywave Prediction Program

A2-7 Brief synopsis of prediction models

Propagation prediction models have been developed over the years, and many have incorporated features shown in Figure A2-3. Table A2-2 is a listing of various models and appropriate references.

TABLE A2-2

Skywave propagation prediction models

Model Name	**Originator**	**Reference**
SPIM method	SPIM: France	Rawer [1952] Halley [1965]
CRPL Method	CRPL: U.S.A.	NBS Circular 462 [1948]
DSIR Method	Appleton Lab Slough, UK	Piggott [1959]
USSR Method	Soviet Acad. Sci.: USSR	Kasantsev [1947, 1956]
FTZ Model	Deutsche Bundespost	Ochs [1970]
REC533 (CCIR)	CCIR	ITU-R Rec. 533[Replaces CCIR 252, 894, & HFBC84]
CCIR-252-2 †	CCIR/ITU	Rpt. 252-2 [CCIR, 1970]
CCIR-252-2 † Supplement	CCIR/ITU	Rpt 252-2 Supplement [CCIR, 1982A]
CCIR-894-1 †	CCIR/ITU	Rpt. 894 [CCIR, 1986a]
HFBC84	WARC/ITU	ITU [1984a]
ITSA-1	ITS-Boulder	Lucas and Haydon [1986]
ITS-78	ITS-Boulder	Barghausen *et al.* [1969]
HFMUFES4	ITS-Boulder	Haydon *et al.* [1976]
IONCAP	ITS-Boulder	Teters *et al.* [1983]
AMBCOM RADARC	SRI ITS-Boulder NRL-Wash.,DC	Hatfield [1980] Lucas *et al.* [1972] Headrick *et al.* [1971] Headrick and Skolnik [1974]
ICEPAC	ITS-Boulder	Hand, http://elbert.its.bldrdoc.gov/f.html
VOACAP	ITS-Boulder, *et al.*	Hand, http://elbert.its.bldrdoc.gov/f.html
REC533	ITS Boulder, *et al.*	Hand, http://elbert.its.bldrdoc.gov/f.html

†The CCIR Secretariat (ITU, Geneva) retains computer codes for CCIR-252 (HFMLOSS for mainframes); CCIR-252 Supplement (SUP252 for mainframes); and CCIR Report 894 (REP894 for mainframes and micros). See Section A2.14 of this annex for a discussion of microcomputer methods.

A2-7.1 Historical development

Current methodologies for HF performance prediction evolved gradually, beginning with uncoordinated studies by workers from many countries and organizations. Serious work to establish prediction methods began in earnest during World War II because of the obvious military communication requirements. The earliest methods by the Allies, Germany, and Japan were of the graphical type to speed analysis, because computer methods were not available. The long-distance methods used by Germany and those used by the Allies [IRPL, 1943] form an interesting contrast. (The Interagency Radio Propagation Laboratory, IRPL, was a forerunner to the Central Radio Propagation Laboratory, CRPL—now the Institute for Telecommunication Sciences—at Boulder, Colorado).

In Germany, long-distance propagation was analyzed by examination of each mode and path independently. According to an account by Rawer [1975], short paths assumed 1E, 2E, 1F and 2F mode possibilities while for long paths multiple F layer modes alone were considered. At each reflection point (or *control point,* see Footnote No. 1 of this annex) the MUF was deduced by extraction of a value of foF2 for that point (from crude maps) and the appropriate MUF factor was applied. The overall MUF was logically determined as the lowest of the set of subhop MUFs for each path to be reckoned. Because of noise extension, scatter effects, and the possibility of ducted or chordal mode propagation, this approach, while intuitively pleasing, was pessimistic. The American long-path approach, influenced by a more global perspective, used modified control point method that accounted for only two *minor points* along the great circle path linking communication terminals. These two control points were 2000 km from the communication terminals. This produced a rather optimistic result.

In the period during World War II and after, sounding *networks* were established to provide a basis for the construction of better maps from which foF2 and MUF variation with latitude (and longitude) could be assessed. As previously indicated, significant equatorial anomalies were discovered through examination of this data [Appleton, 1946]. Following WW II, the French organization SPIM was established, while in the United States the agency IRPL became known as CRPL. Both SPIM and CRPL continued the development of more analytical methods to replace simpler procedures. Significant improvements in mapping resulted from the incorporation of a modified dip latitude concept to account for geomagnetic control of the ionospheric parameters [Rawer, 1963]. By 1950 Gallet of SPIM developed a mapping technique which soon became part of a computerized method for developing MUF maps. By the early 1960s Gallet had moved to the United States where he joined with Jones in formulating a basis for the current method for mapping ionospheric parameters [Jones and Gallet, 1962].

A2-7.2 Commentary on selected models

Models that stem from methods developed by Department of Commerce scientists at Boulder, Colorado, include ITSA-1, ITS-78, HFMUFES-4, IONCAP, RADARC, and, more recently, ICEPAC and VOACAP. These methods have influenced the design of other prediction models. The CCIR (currently the ITU-R) has developed methods for estimating field strength and transmission loss based upon empirical data, and a computer method for propagation prediction was developed for the WARC-HFBC under the aegis of the International Frequency Registration Board (now the Radio Regulations Board), an organ of the ITU. For more information, the reader is referred to the following: Report 252-2 [CCIR, 1970] and its Supplement [CCIR, 1982a] (both previously cited and published separately), as well as Report 894-1 [CCIR, 1986a] and Recommendation 621 [CCIR, 1986b], which are contained in the 1986 "Green Book" [CCIR, 1986c]. Methods have also been developed in the United Kingdom, Canada, France, the USSR, and India. Many of these have been listed in Table A2-2.

It should be noted that the ITU underwent reorganization in the mid 1990's. As part of this reorganization, the CCIR was abolished and effectively replaced by the Radio Communications Sector (ITU-R). While the ITU-R still develops Recommendations, it seldom produces Reports, as CCIR did in the past. Most of the relevant CCIR Recommendations have been replaced by ITU-R Recommendations, and the ITU-R also publishes special purpose handbooks as necessary. Documentation from the ITU may be obtained through the Internet at the URL

http://WWW.itu.ch/index.html

The appropriate ITU-R Study Groups involved in HF propagation and HF communication issues are SG-3 and SG-9, respectively. Working Party 3L investigates HF modeling. Work on HF broadcasting is carried out within the working parties of Study Group 10. A synopsis of selected computer models follows:

ITSA-1: [Lucas and Haydon, 1966]. This model was developed by the U.S Commerce Department's ITS. At the time it was published it represented one of the first computer methods for exploiting augmentations in the underlying ionospheric and geophysical databases. Probably the first computerized method was a program called MUFLUF, which was developed by the Central Radio Propagation Laboratory, a forerunner to the ITS organization at Boulder. The ITSA-1 model superseded MUFLUF soon after publication. ITSA-1 did not include separate D or F1 layers, and sporadic E was not accounted for. In this program the concepts of circuit reliability and service probability were introduced. MUF variability data were included.

ITS-78 (HFMUFES): [Barghausen *et al.*, 1969] [Haydon *et al.*, 1976]. ITS-78 actually represents a series of codes developed at ITS in Boulder beginning with ITS-78, and culminating with HFMUFES4. These programs did not include an F1 layer but do include sporadic E. Most of the features of ITSA-1 were included, but with revised F-layer ionospheric data.

IONCAP: [Teters *et al*., 1983] [Lucas, 1987]. Now replaced by ICEPAC or VOACAP, this IONCAP was one of a string of *mainframe* programs developed by ITS and its predecessor organizations. The following improvements over previous ITS models are contained in IONCAP:

- a more complete ionospheric description
- modification in loss equations
- empirical adjustment to Martyn's Theorem
- revised loss statistics to account for Es and above-the-MUF-losses
- new methodology for long-distance modeling; and
- revision to antenna gain models.

A *User's Guide* has been distributed.

RADARC: [Lucas *et al.*, 1972] [Headrick *et al.*, 1971] [Headrick and Skolnik, 1974]. This program was promoted by the Naval Research Laboratory for use in analyzing the performance of over-the-horizon radar facilities. It is a close relative of IONCAP and HFMUFES, however, the computational strategy is tailored to provide information along specified radials (and arbitrary distances) from a transmitter rather than for point-to-point communication paths.

FTZ [Ochs, 1970]: This model was developed by the Deutsche Bundespost. It includes an empirical representation of field strength. This method is based upon observations of signal level associated with a large number of circuit-hours and paths, with the majority of the paths terminating in Germany. Since data were obtained without accounting for the individual modes that may have contributed to the result, the model is not fully satisfactory for arbitrary antennas (and patterns). Nevertheless for long-distance communication where elevation angles are minimized, the model is quite useful. Furthermore, computations require a limited amount of machine time, making the FTZ model a valuable method for preliminary screening of a large number of paths.

CCIR 252-2: [CCIR, 1970]. Now replaced by CCIR's "Rec 533," this model, termed "CCIR Interim Method for Estimating Skywave Field Strength and Transmission Loss Between Approximate Limits of 2 and 30 MHz," was initially adopted by CCIR at the 1970 New Delhi plenary. It was the first of three computer methods for field strength prediction that were sanctioned by the CCIR.

CCIR 252-2 Supplement: [CCIR, 1982a]. Now replaced by CCIR's "Rec 533," this Supplement is a field-strength prediction method entitled, "Second CCIR Computer-based Interim Method for Estimating Skywave Field Strength and Transmission Loss at Frequencies Between 2 and 30 MHz." The method is more complex than the method of CCIR 252-2 in a number of respects, and the machine time required reflects this additional complexity. A major change is the consideration of longitudinal gradients for the first time. A computer program was completed in 1987.

CCIR 894-1: [CCIR, 1986a]. Now replaced by CCIR's "Rec 533," this program was developed to assist in the WARC HF Broadcast Conference, a rapid computational method was documented as CCIR Rpt. 894. This document was the result of CCIR Interim Working Party (IWP 6/12) deliberations to produce a prediction program for use in planning by the HF broadcast service. This program is a simplification of CCIR 252-2 (or equivalently IONCAP) but incorporates the FTZ approach for long-distance applications. The IONCAP approach is used for paths less than 7000 km, FTZ is used for paths greater than 9000 km, and a linear interpolation scheme is applied for path lengths between 7000 and 9000 km.

HFBC84: [ITU, 1984a]. Now replaced by CCIR's "Rec 533," this program was a computer code based upon Report 894. An improved estimate of field strength is obtained by taking the antenna gain (of appropriate broadcast antennas) into account when selecting modes to be included in the calculations. HFBC84 provides the analyst with a practical procedure for mapping the coverage of a specified broadcast antenna. Such a coverage pattern is given in Figure A2-5.

AMBCOM: [Hatfield, 1980]. This program was developed by SRI International in connection with work supported by the Defense Nuclear Agency, and it is a companion program to NUCOM, another propagation program specific to the nuclear environment. One difference between the ITS series of programs and AMBCOM is that the latter uses a 2-D raytrace program, while the former programs use virtual methods. In addition, AMBCOM contains within its ionospheric submodel structure a considerable amount of high latitude information including improved auroral absorption models. This should provide for an improved prediction capability for paths through the high-latitude region or within its neighborhood. The model allows insertion of as many as 41 ionospheric data points along the paths of interest. This capability should make AMBCOM highly suitable for a detailed analysis of links or coverage areas in situations in which the underlying ionosphere is well sampled. The 1-D approach used in AMBCOM is a relaxation of the ionospheric specification requirements implicit in the use of full 3-D methods, but provides a more realistic explanation of coverage than simple (and artificial) virtual methods. A major distinction between AMBCOM and virtual methods used by the CCIR is that the ionosphere defines the path of the ensemble of rays in AMBCOM, whereas a predetermined path is used to define the effective part of the ionosphere (*i.e.*, the "control point") in the virtual or "mirror" methods. Because of added complexity, the program is generally slower than simpler models. Because AMBCOM uses raytracing and will operate against large electron density gradients, it will predict asymmetric hops and unconventional modes. AMBCOM documentation is not as widely distributed as IONCAP or the CCIR methods.

VOACAP. This prediction program was developed for use on a PC. The developers—NRL, ITS, and VOA made more than 60 changes to the computer code. Most of the changes improved the computation speed, corrected errors in IONCAP coding and logic, and improved input/output graphics. The program addresses broadcasting predictions. These changes are well documented and the source code of IONCAP was maintained with numerous comment cards for each change.

In 1985, the Voice of America (VOA) adopted the Ionospheric Communications Analysis and Prediction Program (Teters, *et al.*, 1983) as the approved engineering model to be used for broadcast relay station design and antenna specification. As the program was modified for these purposes, the name was changed to the Voice of America Coverage Analysis Program (VOACAP) to distinguish it from the official National Telecommunications and Information Administration (NTIA) IONCAP program. The development of VOACAP was accomplished for VOA by the Naval Research Laboratory and the Institute for Telecommunication Sciences (Department of Commerce, NTIA).

The Voice of America Coverage Analysis Program (VOACAP) predicts the expected performance of high frequency (HF) broadcast systems, and in doing so is useful in the planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location.

This current version of VOACAP running on a PC under Windows, incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

ICEPAC. For many years, numerous organizations have been using the HF spectrum to communicate over long distances. It was recognized in the late 1930's that these communication systems were subject to marked variations in performance. The effective operation of long-distance HF systems increased in proportion to the ability to predict variations in the ionosphere, since such an ability permitted the selection of optimum frequencies, antennas, and other circuit parameters. Research demonstrated that most variations in HF system performance were directly related to changes in the ionosphere, which, in turn, are affected in a complex manner by solar activity, seasonal and diurnal variations, as well as latitude and longitude. Various organizations developed computer models to analyze HF circuit performance. The ionospheric Communications Analysis and Prediction Program (IONCAP) developed by ITS and its predecessor organizations, became one of the more accepted and widely used models for HF propagation predictions. However, IONCAP demonstrated poor performance in the polar region and use some of the older electron density profile structures. To correct these problems, IONCAP was transformed into ICEPAC by adding the ionospheric Conductivity and Electron Density (ICED) profile model described in Tascione *et al.* [1987]. The ICED profile model is a statistical model of the large-scale features of the northern hemisphere. the model recognizes the different physical processes that exist in the different regions of the ionosphere. It contains distinct algorithms for the sub-Auroral trough, Auroral zone, and polar cap.

The Ionospheric Communications Enhanced Profile Analysis and Circuit Prediction Program (ICEPAC) predicts the expected performance of high frequency (HF) broadcast systems, and in do9ing so is useful in the planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location.

This current version of ICEPAC (a descendent of IONCAP) running on a PC under Windows, incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

This general prediction program was designed with a windows front end, and has been modified to provide more graphical results (see Fig. A2.5, for an example).

REC 533: [ITU-R, 1995]. This prediction program—which replaces CCIR 894-1, and HFBC894—improves prediction methods to enhance operational facilities and to improve accuracy. The program deals with basic maximum usable frequencies (MUFs) of the various propagation modes evaluated in terms of the corresponding ionospheric layer critical frequencies and in terms of hop length. Its algorithms are documented in Recommendation ITU-R P.533-5 (1995), and the computer program itself is available from the ITU (see the ITU/BR *Catalogue of Software for Radio Spectrum Management).*

This propagation prediction method is for use in estimating reliability and compatibility between frequencies of about 3 MHz and 30 MHz. REC533 derives from a method first proposed in 1983 by CCIR Interim Working Party 6/12 with later refinements following considerations by WARCs for HF broadcasting, the CCIR, broadcasting, and other organizations. The procedure applies a ray-path analysis for path lengths up to 7000 km, composite mode empirical formulations from the fit to measured data beyond 9000 km, and a smooth transition between these approaches over the 7000-9000 km distance range.

Monthly median basic MUF, incident skywave field strength, and available receiver power from a lossless receiving antenna of given gain are determined. Signal strengths are standardized against a CCIR measurement data bank. The method requires the determination of a number of ionospheric characteristics and propagation parameters at specified “control points”.

The propagation program was made available to the ITU in July 1993 by Working Party 6A (WP6A). Information on the availability of that program is found in Resolution 63. This implementation was simultaneously developed by the U.S. Department of Commerce NTIA/ITS in Boulder, Colorado, under contract from the Voice of America. It includes the point-to-point and area coverage models.

This current version of REC533, running on a PC under Windows®, was developed and is maintained by the United States Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (NTIA/ITS) located in Boulder, Colorado. It incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

A2-7.3 Ionospheric data used in prediction models

The parameters used in major prediction models are the same in many instances and the data sets that represent a given parameter may also be the same. Nevertheless, the manner in which the data are used can lead to extraordinary differences in detail. Fortunately, for purposes of deriving an intuitive idea of the various influences on HF propagation/performance, most models are adequate. Indeed, if updating is possible, then many differences may be unimportant, except to the purist.

Table A2-4 is based on a previously unpublished review by Lucas [1987]. It summarizes some of the most important ionospheric parameters, and indicates the models that incorporate the specified data sets.

For convenience, selected ionosonde characteristics and their definitions are listed in Table A2-4. The original papers, indicated in the table, review how each parameter is derived and over what period of time the empirical data were assembled. The references in Table A2-3 indicate the specific usage of parameters in a given model.

Statistical distributions are required for certain ionospheric parameters for at least two reasons. First, parameters such as f_oF2, f_oEs and hF2 fail to follow Chapmanlike rules, a fact that makes prediction of the average behavior of these parameters less successful than it might otherwise be. Secondly, departures from the mean are perceived to be random variables, and not subject to the prediction process, at least in the deterministic sense. The sporadic E layer and the F2 layer are obvious candidates for statistical treatment. Statistical distributions for f_oF2 [Lucas and Haydon, 1966] and Es [Leftin *et al.*, 1968] are available.

The only ionospheric height that is explicitly computed in listed computer prediction models is hF2. Still, the variability in hF2 arising from unpredictable sources, such as traveling ionospheric disturbances (TIDs), is a significant fraction of the mean diurnal variation. Typically Shimazaki's formula (or some derivative) is used for estimating the mean value in hF2, but other approaches may also be used.

TABLE A2-4

Ionospheric parameters, data sources, and models

Models	**Layer Criticals**				**Layer Heights**				**Layer Semi-thickness**			
	foEs	**foE**	**foF1**	**foF2**	**hEs**	**hE**	**hF1**	**hF2**	**yEs**	**yE**	**yF1**	**yF2**
RADARC	1	2	3	4	k	k	e	5	k	k	k	6
IONCAP	1	2	3	4	k	k	k	5	k	k	k	6
ITS-78	1	2	n	13	n	k	n	5	k	k	n	7
ITSA-1	n	8	n	4,12	n	k	n	5	n	k	n	6
HFBC84	n	8	n	4	k	k	n	9	n	n	n	n
CCIR-252	1	2	n	4	k	k	n	5,11	n	k	n	7
AMBCOM	1	2,10	n	13	k	k	n	5	k	k	n	7
ICEPAC												
VOACAP												

Key

1. Leftin, *et al.* [1968]
2. Leftin [1976]
3. Rosich and Jones [1973]
4. CCIR [1966a]
5. Shimazaki [1955]
6. Lucas and Haydon [1966]
7. Leftin, *et al.*, [1967]
8. Knecht [1962]
9. Lockwood [1984]
10. Hatfield [1980]
11. Leftin [1969]
12. Jones and Gallet [1962]
13. CCIR [1970]

e determined empirically
k constant
n not applicable or undefined layer

(Information in this table is based in part upon unpublished material from Lucas [1987].)

TABLE A2-4

Ionosonde parameters and definitions

Ionosonde Parameter	Definition
foE	Critical frequency of the ordinary ray component of the normal E layer. It is the frequency that just penetrates the ionospheric E layer. It is proportional to the square root of Nmax for region E.
h'E	Minimum virtual height of the E layer. This is determined at the point where the ionosonde trace becomes horizontal.
foEs	Critical frequency of the ordinary ray component of the Es (sporadic E) layer.
h'Es	Minimum virtual height of the sporadic E layer, and reckoned at the height where the trace becomes horizontal.
fbEs	The blanketing frequency for the Es layer. This corresponds to the lowest ordinary wave frequency for which the Es layer allows penetration to a higher layer; *i.e.,* begins to become transparent.
foF2	The critical frequency of the ordinary wave component of the F2 layer. It is proportional to the square root of Nmax for the layer. It is the frequency that just penetrates the F2 layer.
foF	Critical frequency of the ordinary wave component of layer F1. The ionosonde frequency that just penetrates the F1 layer.
h'F2	Minimum virtual height of the F2 layer. It is measured at the point where the trace becomes horizontal.
h'F	Minimum virtual height of the night F layer and the day F1 layer. Again, it is measured at the point where the F trace involved becomes horizontal.
h'F1	Minimum virtual height of the F1 layer, measured at the point where the F1 trace becomes horizontal.
h'FF2	Alternative tabulation of the minimum virtual height of the F layer. It corresponds to the minimum virtual height of the night F layer and the day F2 layer. Again, it is measured at the point where the appropriate traces become horizontal.
hpF2	Virtual height of the F2 layer corresponding to the frequency f = 0.834 foF2. Based upon a parabolic layer approximation.
M(3000)F2	Ratio of MUF(3000)F2 to the critical frequency foF2.

A new mirror height method having similarities to the Shimazaki approach has been used in HFBC84 [Lockwood, 1984]. The basis for hF2 estimation in the CCIR-252 model is virtual height data (*i.e.,* h'FF2) from Leftin *et al.* [1967] and Leftin [1969]. Recognizing that hF2 is simply the (nonvirtual) height of the F2 maximum, $h_{max}F2$, the Shimazaki relation says:

$$h_{max}F2 = 1490/M(3000)F2 - 176 \qquad (4.1)$$

We recognize that M(3000)F2 is MUF(3000)F2 ÷ foF2, and that it is proportional to the secant of the ray zenith angle Ø. If the layer descends, it is apparent that the secant of Ø will increase.

Consequently, M(3000)F2 increases as layer height decreases, and vice versa. This fact is reflected in equation 4.1. Taking h_{max}F2 to be a nominal 300 km, then M(3000)F2 is nearly 3.2. Under this condition, dh/dM(3000)F2 ≈ - 150 km. Hence an increase in M(3000)F2 of 0.2 will correspond to a height reduction of 30 km.

Maps of f_oF2 and M(3000)F2 have been of major importance in HF propagation prediction for years. They are used in various ionospheric models to provide a global distribution of electron density and F2 layer height in other applications. The CCIR [1966a] model, documented as CCIR Report 340-1, consists of an *Atlas of Ionospheric Coefficients* defining f_oF2 and M(3000)F2, plus actual maps of the parameters EJF(zero)F2 and EJF(4000)F2,which have been defined above. The CCIR [1970] model, termed *Supplement No. 1*, is an update of the Report 340, which replaces the CCIR [1966a] foF2 *Oslo* coefficients with new ones that better fit the existing database. Improvements included replacement of the linear dependence of foF2 on sunspot number by a polynomial dependence, and a Fourier representation of the annual variation so that any day could be examined in terms of its surrounding monthly median. The CCIR [1970] coefficients were conceived by Jones and Obitts and are sometimes referred to as the *New Delhi* coefficients. Screen or *phantom* points were required over sparsely sounded oceanic areas for both the *Oslo* and *New Delhi* coefficients. Early versions of ITS-78 (HFMUFES) used *Oslo* coefficients that were reproduced on red computer cards. Later versions used the *New Delhi* coefficients reproduced on blue cards. Thus the terms *red deck* and *blue deck* are sometimes used in references.

There have been steps to improve the ionospheric coefficients. Within the URSI community (Working Group G.5) Rush *et al.*, [1983, 1984] developed a new coefficient set based upon more fundamental theory. The extensive database assembled by Rush and his colleagues included *new* data points deduced using a method developed by Anderson [1981]. As pointed out by Rush *et al.* [1989], in order not to depart too significantly from established CCIR recommendations and long-term prediction methods, consistency with the structure of the CCIR [1966a] Jones-Gallet coefficient set was required. Fox and McNamara [1986, 1988] have continued the work and have proposed a final set of coefficients. Fox and McNamara organized their data in terms of the T-index rather than in terms of sunspot number, they included more foF2 data in the analysis, and they sought consistency with independent data derived from the Japanese topside sounder ISS-B. They also used methods in which the coefficients were of higher order at low latitudes than the CCIR/URSI maps. This provides more detail at lower latitudes. The new approach is the basis for a new set of coefficients used by the Australian agency IPS. The improvement over the original set is more than satisfactory. To achieve consistency with the standard format of existing internationally sanctioned maps, the IPS coefficients were transformed by URSI to coincide with the existing number of coefficients. This process had the effect of degrading the output from the IPS approach somewhat, but consistently smaller residual errors have been noted when compared with the CCIR maps. Ultimately Rush *et al.* [1989], including the IPS group, have published an update of the foF2 coefficients. Since this revised set, also termed the *1988 URSI coefficient set*, has the same structure as the earlier *1966 CCIR coefficient set* used in IONCAP, an upgrade of IONCAP climatology is straightforward.

Several terms have been used to describe the various CCIR coefficients. As noted above, the first set to be published as a separate booklet by the CCIR is due to Jones and Gallet [1962], and was approved by the CCIR at its 1966 plenary held in Oslo, Norway. When used in early versions of ITS-78, the coefficient set was reproduced on red cards. The CCIR took note of an alternative coefficient set at its 1970 plenary held in New Delhi, India. This set, developed by Jones and Obitts [1970], and published by the CCIR in 1971, was an improvement in a number of areas over the previous set, was only recommended for use in short-term predictions. Differences in the two sets of coefficients were described in CCIR Report 340 as revised in 1983. A summary of existing coefficient sets is given in Table A2-5.

TABLE A2-5
Various sets of ionospheric coefficients

Coefficients Epoch	**Authors**	**Plenary Session Location**	**Computer Designation**	**Usage**
CCIR 1966	Jones-Gallet	Oslo	Red Deck	Long-term
CCIR 1971	Jones-Obitts	New Delhi	Blue Deck	Short-term
URSI 1988	Rush *et al.*	N/A	N/A	Long-term

A2-7.4 The System Noise Figure Concept

Note: The noise factor is designated by the letter f in this discussion, and should not be confused with the radio frequency. To avoid the possibility of misinterpretation, f(MHz) is used to denote frequency for instances that appear warranted. This comment is specifically relevant to figure A2-7 and to the next three sections.

To estimate the impact of external noise sources on system operation it is necessary to establish the pre-detection signal-to-noise ratio. Figure A2-4 schematically represents a generic receiver system from input to output, the noise factor and the signal-to-noise ratio associated with the receiver, and the location at which these parameters are reckoned. The system noise factor is given by [Spaulding and Stewart, 1987]:

$$f = f_a + (L_c - 1)(T_c/T_o) + L_c(L_t\text{-}1)(T_t/T_o) - L_cL_t(f_r - 1) \qquad \text{(A2-2)}$$

where f_a is the external noise factor given by P_n/kT_ob, F_a is the external noise figure given by 10 $\log_{10}f_a$, p_n is the available noise power from a lossless antenna, L_c is the antenna circuit loss (input power/output power), T_c is the temperature (^oK) of the antenna and neighboring ground, L5 is the transmission line, T_o is the reference temperature (^oK), and f_r is the noise factor of the receiver (^oK). The noise *figure* in dB is simply $F_r = 10 \log_{10}f_r$. To avoid confusion, capital letters are used when discussing the noise figure as well as other terms that may be expressed in decibels, and lower-case letters are used when dealing with receiver and antenna noise factors. The noise power in watts is simply:

$$n = f\,k\,T_o\,b \qquad \text{(A2-3)}$$

where k is Boltzmann's constant = 1.38×10^{-23} J/(^oK), T_o = 288(^oK), and b is the noise power bandwidth of the receiving system. For an antenna and transmission line that may be taken to be lossless, then the overall system noise figure F is approximately the sum of F_a and F_r.

Recognizing that 10 $\log_{10}kT_o = -204$, we may rewrite equation 4.3, specifically for the external noise component, in a convenient decibel form:

$$P_n = F_a + B - 204 \qquad \text{(A2-4)}$$

where P_n is in dBW and F_a and B are expressed in dB (where B is in dB-Hz).

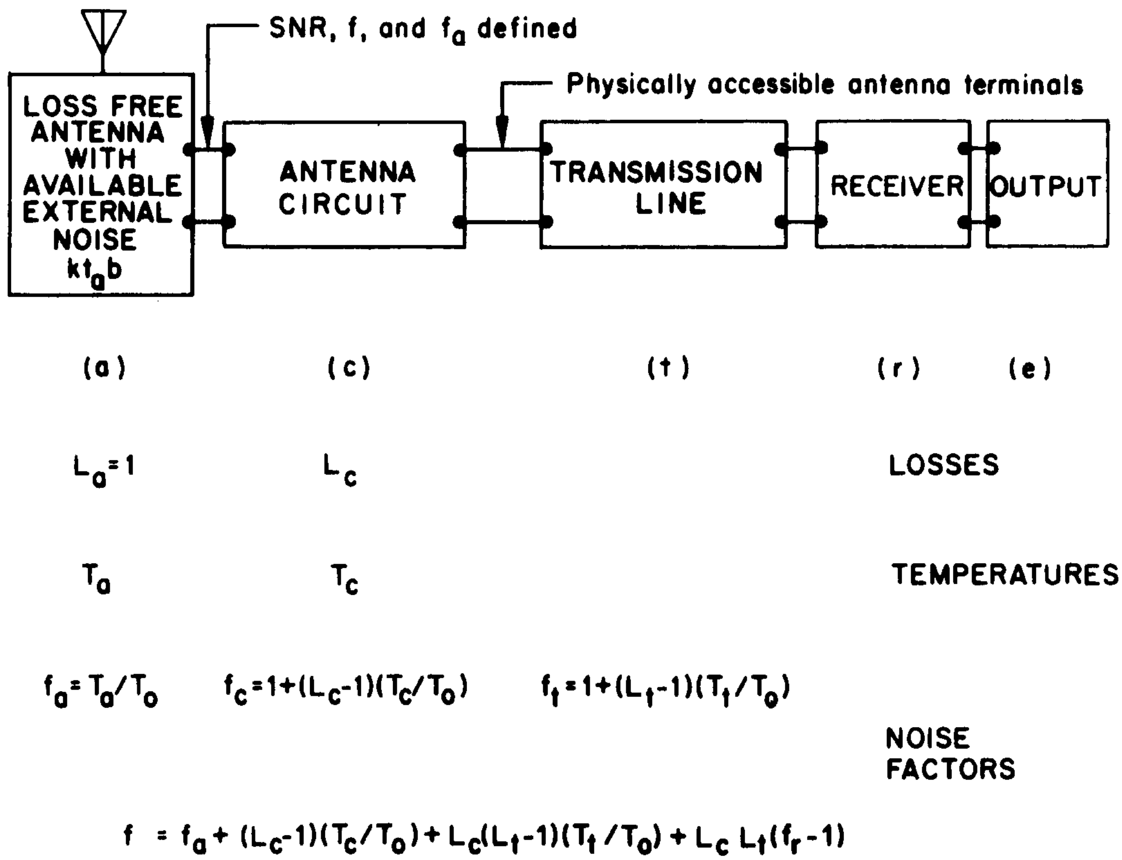


FIGURE A2-4

Generic receiver system concept, illustrating the locations at which signal and noise parameters may be reckoned. [Here, f_a is the external (antenna) noise factor and f_r is the receiver noise factor.] (From Spaulding and Stewart [1987].)

Another way to represent the external noise factor f_a is as a temperature, where f_a is taken to be the ratio of antenna temperature (resulting from external noise) to T_o.

For specified antennas, it is possible to obtain an expression for the field strength in dB (above 1µ V/m). Such expressions take the form:

$$E_n = F_a + 20 \log_{10} f \text{ (MHz)} + B - \Gamma_A \qquad \text{(A2-5)}$$

where Γ_A is a constant dependent upon antenna type and configuration. For a short grounded vertical monopole $\Gamma_A = -95.5$ dB. Thus the noise figure (or factor) is a fundamental parameter since it defines for a specified antenna configuration and noise bandwidth the noise level with which the desired signal must compete. We shall now examine the major sources of noise and therefore F_a.

A2-7.5 Noise models and data

Noise at HF has three major components: atmospheric, galactic, and man-made noise. Another category of noise sources are associated with intentional interferers (jammers). These latter sources will not be discussed here. Figure A2-5 gives the range of expected values for noise. Several features in the figure are of interest. First, we see that except for business areas, galactic noise would appear to dominate in the upper half of the HF band. At midband and below, man-made sources become quite important as the galactic component suffers a cutoff because of the high pass filter properties of the ionospheric plasma. Depending upon conditions, atmospheric noise caused by lightning has an enormous range, and may become the dominant noise source, especially in the lower part of the HF band.

A2-7.5.1 Atmospheric

The major cause of atmospheric noise is lightning strokes that produce broadband noise, and that arise during thunderstorms. Clearly this suggests a preferred source and time distribution for the atmospheric noise contribution. Atmospheric noise, like desirable HF signals, obeys the same physical laws, and may propagate over considerable distances beyond the line of sight. Noise originating in the opposite hemisphere or from sources across the day-night terminator are major contributors to F_a. Even though the events are isolated and of short duration, the composite result, as reckoned from a given receiver may be characterized as quasi-constant for any specified hour. The long-distance propagation characteristic of HF has the effect of populating the time domain with signals from the global distribution, but with each individual source being constrained by its own LUF-MUF bandpass filtering operation. Receiver latitude plays an important role at HF. In fact, noise is considerably reduced as the latitude increases commensurate with an average increase in distance from the low latitude source regions. Regions where noise is most severe include the African equatorial zone, the Caribbean area, and the East Indies. No account is provided in existing models for effects from a localized source distribution, and azimuthal information is not available because of the manner in which the database (comprising the CCIR 322 model) was generated. Clearly, local noise is important, and its omission will lead to underestimates for anticipated external noise, especially during the summertime rainy season. On the other hand, actual antennas may have nonuniform patterns in the bearing (and elevation) plane; and this will modify the noise distributions. Highly directive antennas may yield optimistic or pessimistic values for the observed F_a.

Sailors and Brown [1982] have developed a minicomputer atmospheric noise model using simplified methods. With the advance of computer technology, code simplification is no longer a practical necessity.

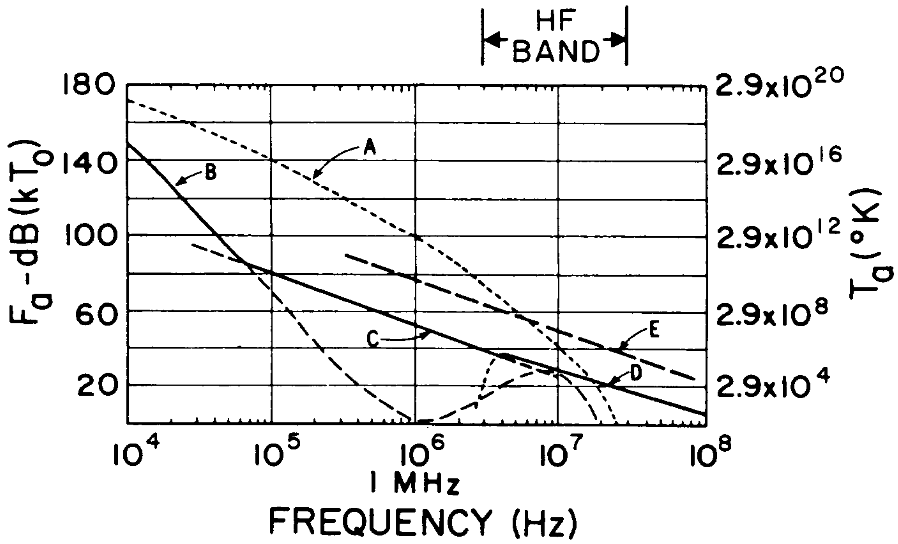


FIGURE A2-5

Noise figure (dB/kTo) (LH-scale), and antenna temperature, °K (RH-scale)

[A: Atmospheric noise from lightning, value exceeded 0.5% of the time; B: Atmospheric noise from lightning exceeded 99.5% of the time; C: Man-made noise at a quiet receiving site; D: Galactic Noise; E: Median business-area, man-made noise.] (From Report 670 [CCIR, 1982c])

A2-7.5.2 Galactic

Figure A2-6 shows the effective temperature of an antenna that is receiving galactic noise. Galactic (or cosmic) noise originates outside the ionosphere, but for signals to be received at an Earth terminal, ionospheric penetration is necessary. Signals in excess of the overhead critical frequency may be received; however, if antennas (such as vertical monopoles) have limited gain in the vertical direction, then available lower frequencies will not effectively contribute. Rules for ionospheric penetration imply that the available cosmic noise distribution will always be confined to a small iris near the zenith direction when operating near the critical frequency. As the radiofrequency f exceeds f_c by a large amount, the iris will become distended being defined by a dimension $\phi \approx \sec^{-1} (f/f_c)$, where ϕ is the ray zenith angle.

A2-7.5.3 Man-made

Man-made noise is not only influenced by the population density, but it also depends upon the technological sophistication of the society. Attempts to relate man-made noise and population density have not been entirely successful, although Lucas and Haydon [1966] have provided an estimate of how population might be used in the prediction of the noise. Propagation may be by either skywave or groundwave methods. Primary sources are local ones, including nearby ignition noise, neon lights, and various electrical equipment.

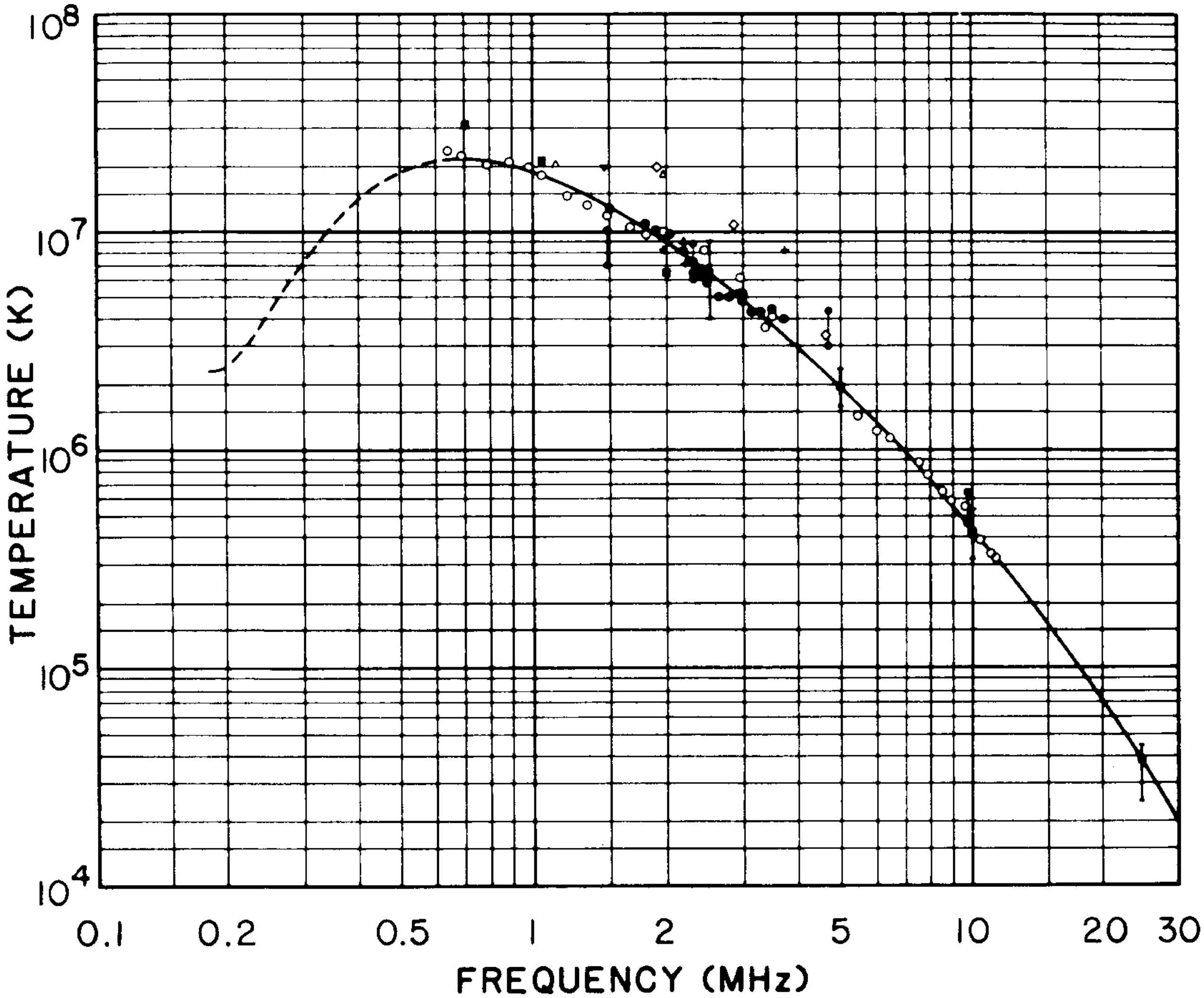


FIGURE A2-6
Galactic noise as a function of frequency

[Data points shown on the plot correspond to experimental results reported by a number of investigators.] (Report 342-5 [CCIR, 1986f])

Figure A2-7 provides a glimpse of residential noise variability across the RF spectrum. We note that the upper and lower deciles differ by approximately 15 to 25 dB throughout, and median values range between roughly 60 dB (at 3 MHz) and 30 dB (at 30 MHz).

A sample man-made noise distribution, expressed in terms of F_a, is given in Figure A2-8 at a frequency of 20 MHz for springtime morning conditions in a residential area. It is seen that the upper-to-lower decile range is about 15 dB. The two log-normal distributions tend to represent the data, one above and one below the median [Spaulding and Disney, 1974]. Galactic and atmospheric noise sources have also been observed to exhibit log-normal distributions.

The man-made noise model described in the earliest versions of CCIR 258 was based upon rf noise measurements originally made by ITS concentrating on sites in the United States. The most recent version of the report, CCIR-258-4 [1982] has been improved by the addition of more modern data, notably data obtained from the Soviet Union. Man-made noise, expressed in terms of F_a, is given in Figure A2-9.

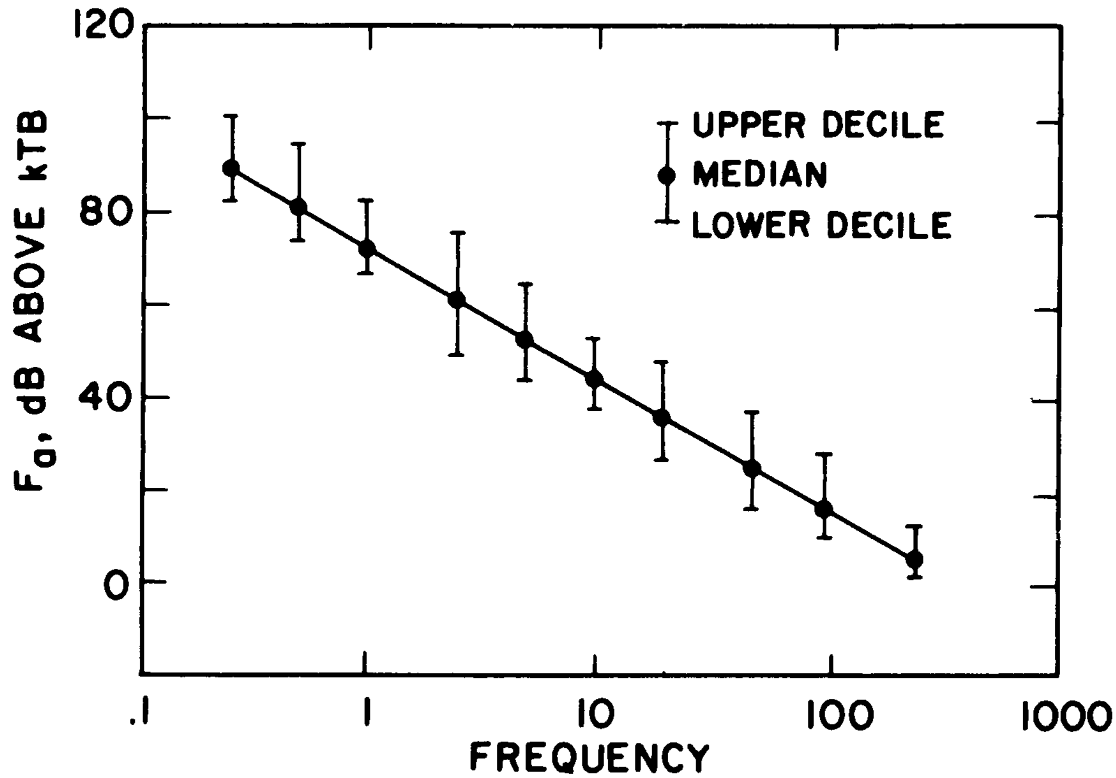


FIGURE A2-7
Man-made noise variability

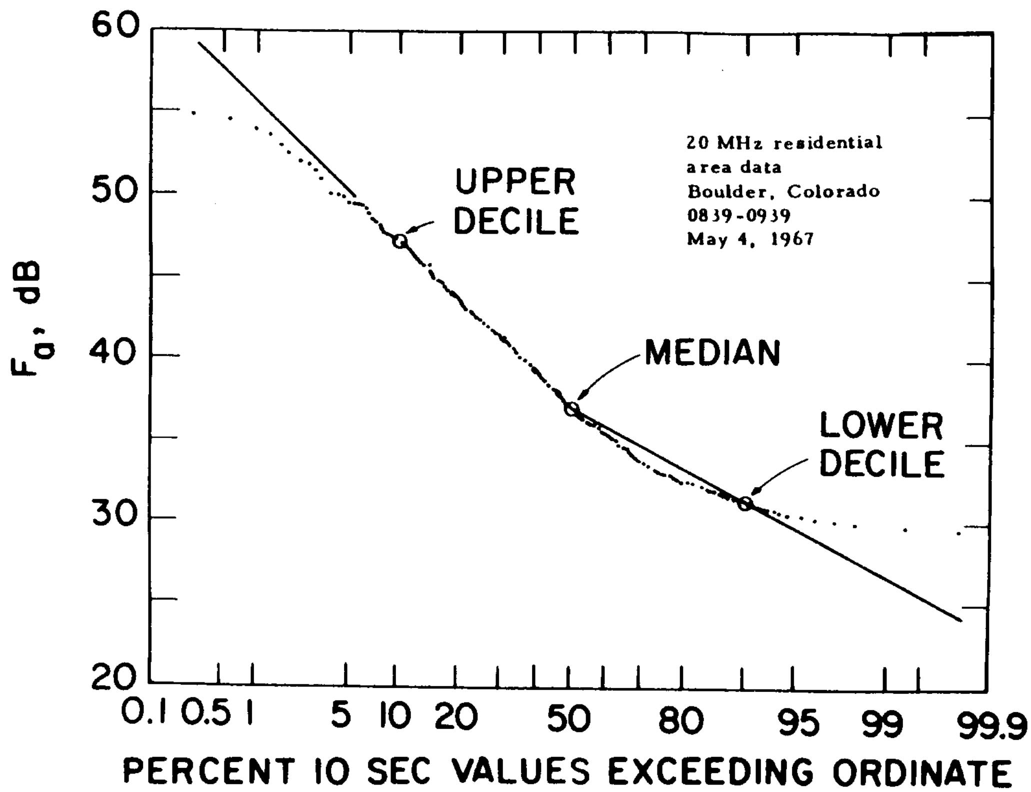


FIGURE A2-8

Noise distribution at 20 MHz, for spring and morning conditions. Residential area near Boulder, Colorado [from Spaulding and Disney [1974]).

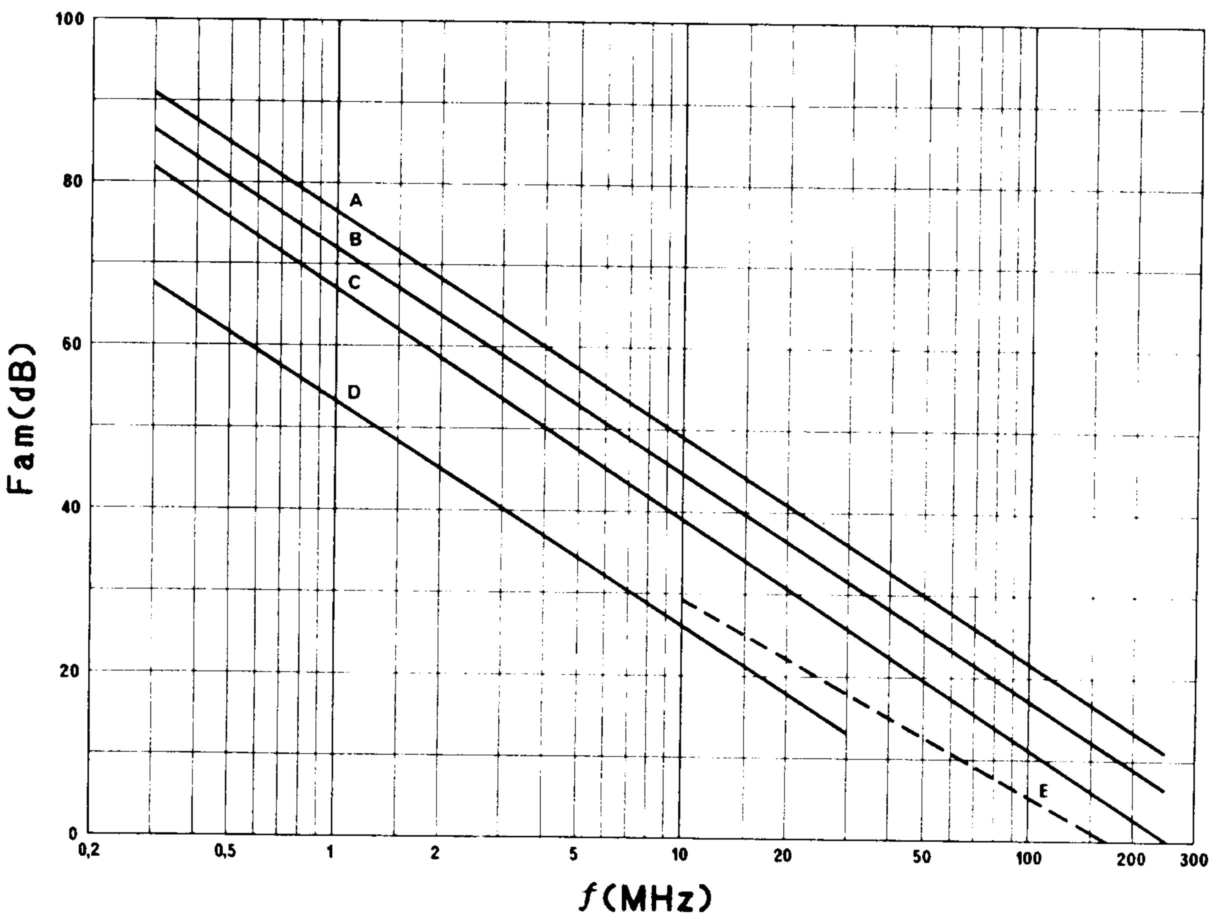


FIGURE A2-9
Man-made noise levels
A: business, B: residential, C: rural, D: Quiet rural, E: Galactic (from Report 258-4 [CCIR, 1982e]).

A2-7.5.4 The CCIR 322 noise model

Implementation of CCIR 322 may be illustrated through the use of three charts. The first chart (actually one of many) shows contours of Fam, the median value of the external noise, for a specified *local time* block at a frequency of 1 MHz. A second chart permits translation of the 1 MHz noise figure medians to the frequency desired. A third chart is used to obtain frequency-dependent statistical information. To obtain an estimate of the atmospheric noise level under specified conditions, we must select an appropriate seasonal map and read the 1 MHz noise estimate for the receiver location dictated.

Figure A2-10 is a CCIR map for the winter season for the 0000-0400 local time block. At Washington, DC, the value of median 1 MHz noise (*i.e.*, F_{am}) is about 70 dB above kT_ob. The next step is to shift this result to the appropriate frequency to be used. We do this with companion Figure A2-11. We see that a family of curves is displayed showing the frequency variation of Fam but parametric in terms of the 1 MHz value (already obtained). Locating the 70-dB curve, we slide to the frequency of interest. Assuming 10 MHz is that frequency, we see that F_{am} is 35 dB above kT_ob. From Figure A2-12 we may deduce noise variability statistics for the frequency of interest.

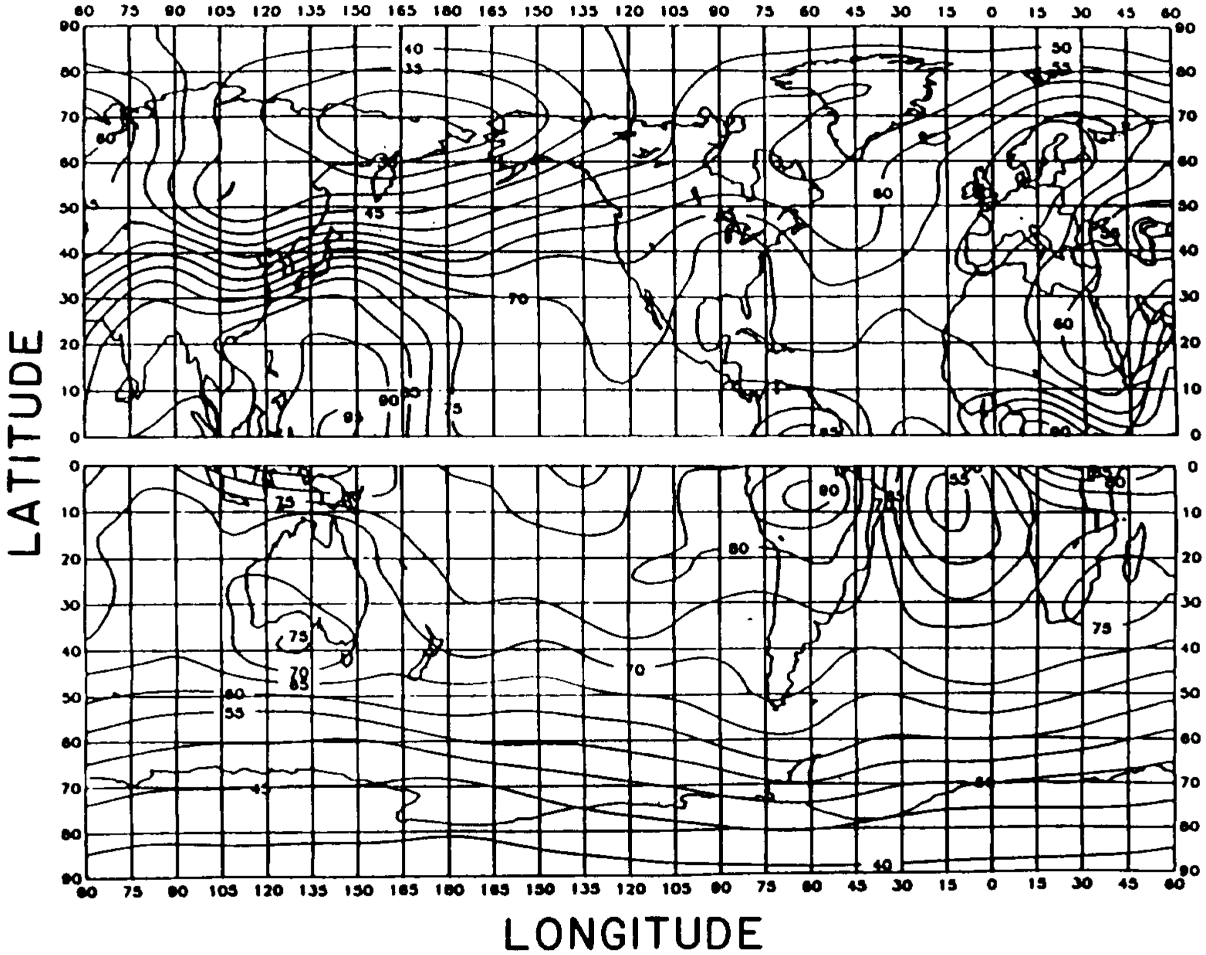


FIGURE A2-10

World map of atmospheric noise at 1 MHz. Winter. Time block: 0000-0400 Lt. Values in dB above kT_0b (from CCIR 322-3 [1966])

With respect to availability of computer codes from the CCIR Secretariat, the set of new noise coefficients associated with Report 322-3 [1966] is termed NOISEDAT and is applicable for microcomputer application. The program NOISY containing the older coefficients is available for mainframe computer versions of CCIR-322-2 [1964]. Understandably, a number of organizations such as NRL and VOA/USIA have modified the existing mainframe code to accommodate the newer coefficients. It should be noted that the way to atmospheric noise, galactic noise, and man-made noise are combined has also been modified.

A2-7.5.5 Combination of noise sources

Spaulding and Stewart [1987] have described how each of the noise sources should be combined to estimate system performance effects. At one time propagation prediction methods simply took as the largest of the atmospheric, man-made, and galactic sources as the composite. Over the years this approach has been modified, and a decidedly more attractive method of combining the three sources and obtaining the composite distribution function has been the result.

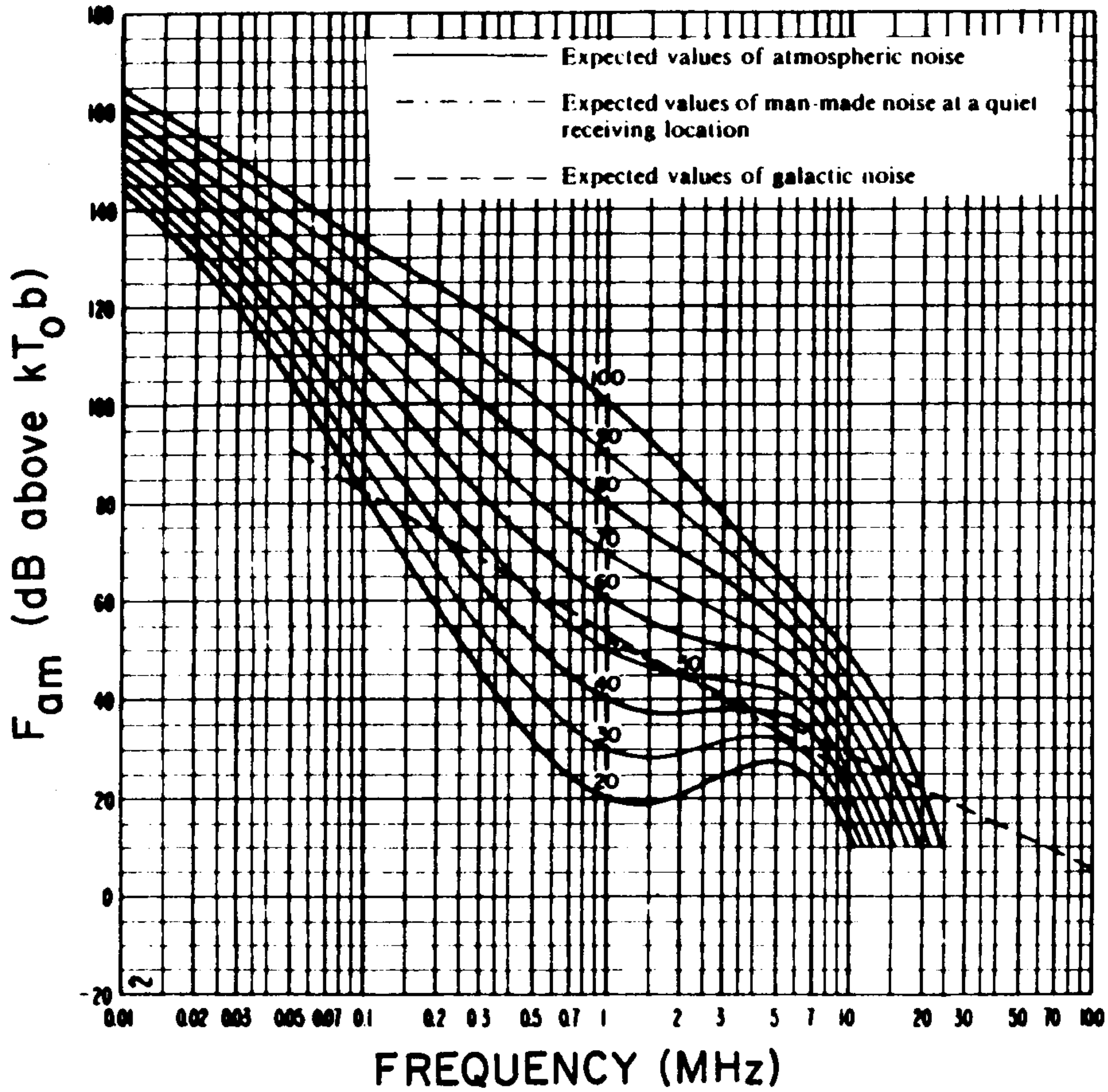


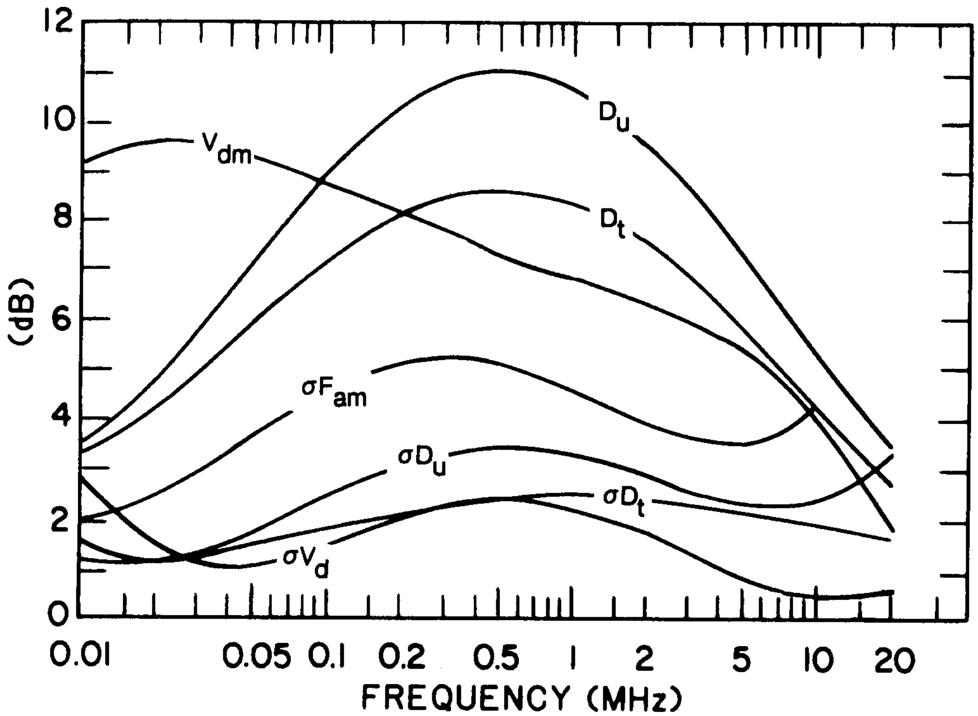
FIGURE A2-11

Variation of radio noise with frequency. Winter, time block: 0000=0400 LT

Values in dB above kT_ob (from CCIR 322-3 [1986])

A2-7.5.6 IONCAP implementations

A version of IONCAP containing the Spaulding-Stewart noise model approach contains the following subroutines: APIS1, which computes the 1 MHz atmospheric noise levels for two adjacent 4-hour time blocks by calling NOISY; NOISY, which uses supplied Fourier coefficients to compute the 1 MHz atmospheric noise value; GENFAM, which computes the atmospheric noise at the appropriate frequency as well as variability data; and GENOIS, which combines all of the sources of noise including atmospheric galactic, and man-made. The subroutine GENOIS has been modified from earlier versions of IONCAP. As indicated in section A2.7.2, ITS has made the PC/Windows® version of VOACAP and ICEPAC available over the Web. These programs also employ the revised Stewart noise model.



KEY

σF_{am}	:	Standard deviation of values of F_{am}
D_u	:	Ratio of upper decile to median value, F_{am}
σD_u	:	Standard deviation of values of D_u
D_t	:	Ratio of the median value, F_{am}, to lower decile
σD_t	:	Standard deviation of value of D_t
V_{dm}	:	Expected value of the median deviation of average voltage. (Values shown are for a bandwidth of 200 Hz.)
σV_d	:	Standard deviation of V_d

FIGURE A2-12

Noise variability. Winter, time block: 0000-0400 LT (from CCIR 322-3 [1986])

A2-7.6 Noise and interference mitigation

It should be obvious that noise and interfer3ence will have a profound influence on the performance of HF systems. Interference, which may be quite severe in the industrialized sections of the world, can dominate other sources. Such domination is not totally unexpected in the upper part of the HF spectrum, and is even consistent with the CCIR 322 and 258 noise models. We anticipate that atmospheric noise will assume a dominant role in the lowest portion of the HF band, certainly at middle latitudes. Nevertheless, high latitude observations have clearly indicated that this expectation is not observed. Within the auroral zone and possibly the cap region, other factors act to limit atmospheric sources relative to local man-made signals. A wideband (WBHF) approach allows the receiver to discriminate naturally against narrowband sources while retaining an intrinsic processing gain. Still it has been found that a few narrow-band and relatively high-power signals may even vulgarize WBHF performance. Interference excision techniques are powerful measures that, when applied in a wideband environment, may enable the maximum advantage of WBHF to be achieved. To determine the advantage that will accrue from such a strategy, it is necessary to model the WBHF channel to determine what might be lost by noise (and elementary frequency band) excision. Remarkably, low power level requirements, of the order of several milliwatts, may be enabled for low data rate transmission (say, 100 bps) for some skywave paths through use of this technique.

One strategy for coping with interference is simply to avoid it. Indeed, spectrum occupancy meters may be monitored by operators, and along with data derived from sounders, it is possible to avoid occupied channels within the LOF to MOF frequency profile. However, operational occupancy monitors may have insufficient bandwidth resolution relative to the spectral “holes,” which are sufficient for some applications. Moreover, manual determination of spectral holes may be inconsistent with the dynamic behavior of channel occupancy. We say “may” because the statement is dependent upon the category of use. Clearly the situation is different in the amateur bands than in the broadcast bands.

Dutta and Gott [1982] have explored the application of congestion information to HF operation and Doany [1981] has examined the impact of congestion on various FSK formats with arbitrary levels of diversity. If M diversity tones are transmitted (with at least a 1 kHz separation between adjacent tones), then the probability that at least two of them will be received free of interference is:

$$P(2,M) = 1 - Q^{M} - M(1 - Q)\,Q^{M-1} \qquad \text{(A2-6)}$$

where Q is the congestion index. The availability of at least two tones will allow a degree of frequency diversity to be accommodated. For Q = 50% and M – 6, then P(2, M) = 0.9. Since Q – 50% implies relatively heavy congestion, it is clear that a sixfold diversity will greatly improve performance under adverse conditions.

Another use that can be made of occupancy measurements is that of passive sounding. Occupancy statistics for skywave signals are strongly dependent upon ionospheric channel behavior. A continuously updated database of channel occupancy, suitably circulated around an HF network, may provide an alternative to active sounding. No operational system has been deployed using this philosophy.

A2-7.7 Effect of noise on system performance

Excision and avoidance strategies are not always possible. In most applications for which an HF system must coexist with the noise background, we simply recognize the error rates and attempt to minimize them by selecting appropriate diversity measures. The vulnerability to noise and interference, like multipath fading, is likewise a function of the modulation format selected.

Figure A2-13 shows how the bit error ratio (BER) depends on the degree of noise impulsiveness and the presence or absence of diversity as a function of SNR. *Waterfall* curves like this have been constructed for various channel conditions and modulation formats. In this case the fading channel was characterized by a Rayleigh distribution and the modulation was non-coherent FSK.

It is noteworthy that noise limits the performance of HF systems for the lower values of SNR, but propagation effects (such as multipath) cause the theoretical improvement in BER for high values of SNR to flatten out. In short, there is a BER floor below which it is not possible to descend since symbol decisions which are corrupted by intersymbol interference and selective fading may be little influenced by increases in the *wanted* signal level. Figure A2-14 bears this out.

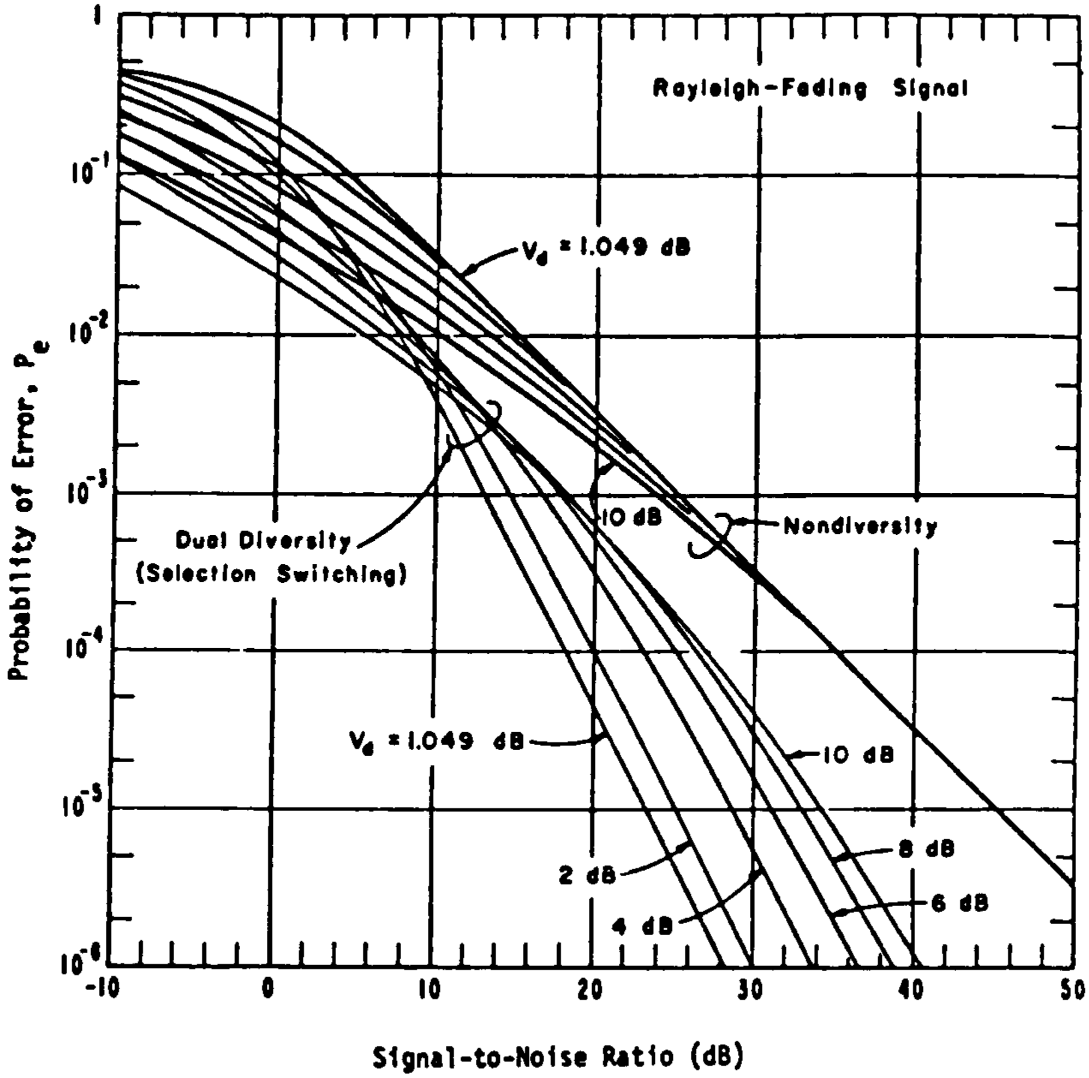


FIGURE A2-13

Probability of bit error for slow flat Rayleigh fading signal for a NCFSK system, for dual diversity and nondiversity reception (Spaulding [1976])

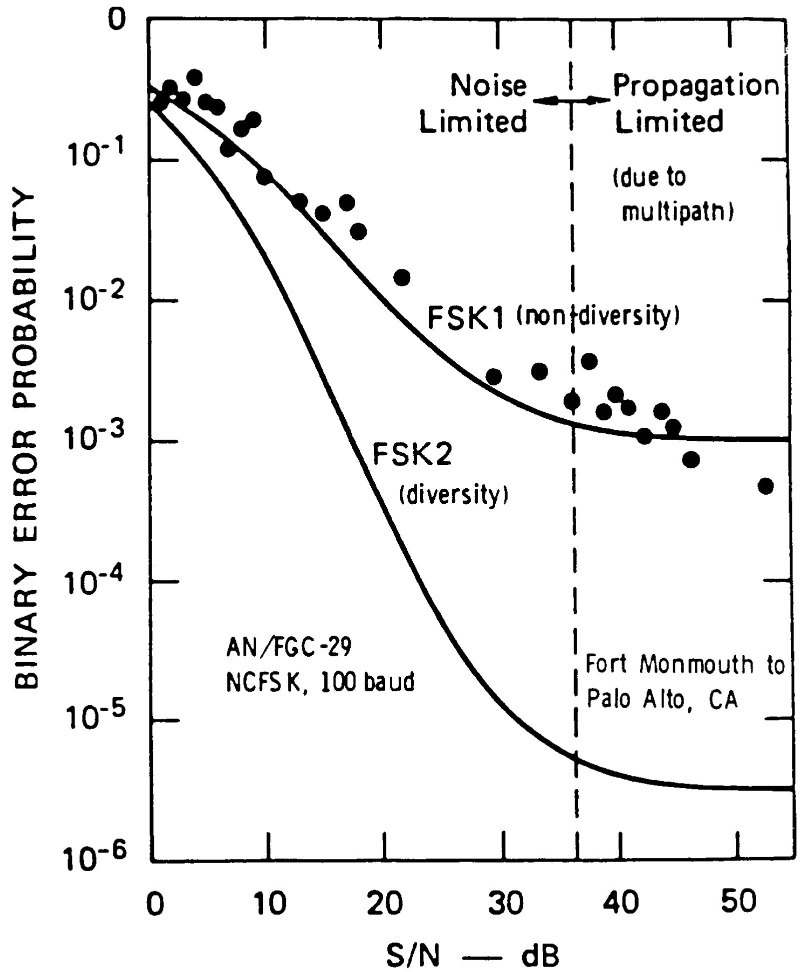


FIGURE A2-14

System performance as a function of signal-to-noise ratio (From Hagn [1988])

A2-8 Publications and computer programs

Publications available through the ITU-R (previously the CCIR) include the *Handbook on High Frequency Directional Antennae* [CCIR, 1965], the *CCIR Book of Antenna Diagrams* [1978], and the *CCIR Atlas of Antenna Diagrams* [1984]. Method-of-Moments (MOM) techniques provide the analyst with a fuller understanding of the complete antenna problem. Programs such as the Numerical Electromagnetics Code (NEC) are used for solution of practical problems, and microcomputer versions of NEC are available (*e.g.,* MININEC and MN as examples). For those interested in additional applications that may be analyzed on a microcomputer, several computer programs are available through the ITU Secretariat. Those programs include HFARRAYS, HFRHOMBS, HFMULSLW, HFDUASLW, and HFDUASLW1. See Resolution 63.2 [CCIR, 1986I] and Circulars 22 [ITU 1984.aA], 23 [ITU, 1984b], and 95 [ITU, 1986a,b]) for more details.

Programs such as HFMUFES, IONCAP, VOACAP, and ICEPAC contain antenna patterns that are used in the HF performance calculations. The antenna packages in the IONCAP family of programs include the ITSA-1 set due to Lucas and Haydon [1966] and an optional ITS-78 set due to Barghausen *et al.* [1969]. Using information extracted from ITS Report No. 74 [Ma and Walters, 1969], the IONCAP "theory manual" describes the evaluation of power gain, radiation resistance, and antenna efficiency for antennas that are included in the program. Methods used are somewhat approximate but are useful in most practical applications. An additional set of broadcast antenna patterns may also be obtained from the International Bureau of Broadcasting (IBB) in Washington, DC.

A2-9 Reliability

The performance of an HF radio system depends on field strength, competing interference, and other factors that may be functions of system configuration, mode of operation, and the type of service indicated. Everything else being equal, performance in transmission of facsimile is far superior to the performance in transmission of high-speed data. Given the same category of communication service, performance will be generally degraded by reduction in EIRP, by increased background noise or by the presence of interference. Reliability is a notion that indicates to the engineer a probability that the system will perform its function under a set of circumstances. Some pertinent definitions are provided below in Annex 8 of this document. Methods for computing reliability are listed in Table 4-11.

A2-9.1 Basic mode reliability

The mode reliability, denoted by the term R_m, is given by:

$$R_m = P_{SNR} \tag{A2.7}$$

where Q is the mode availability, and P_{SNR} is a conditional probability that the required signal-to-noise ratio (SNR) is exceeded, under the condition that the mode exists. Equation 4.7 presumes that mode presence is independent of signal strength. This approach is useful for computer methods that contain the median field strength for a specified mode of propagation under the condition that the reflection (or refraction) condition actually exists. (See CCIR method 252-2.) Methods CCIR 252-2 (Supplement) and 894 compute median field strength for all time, irrespective of a special mode availability.

Thus, the mode reliability that is consistent with these latter models is just the fraction of time that the SNR exceeds the required value. An expression for PSNR is given in Report 892-1 [CCIR, 1986h] based upon work by Bradley and Bedford [1976].

A2-9.2 Circuit reliability

As indicated in CCIR Report 892-1 [1986h], Liu and Bradley [1985] have developed a general expression for circuit reliability for the general situation corresponding to an arbitrary number of contributing modes. A practical situation involves only two contributing modes, and the resulting expression for reliability will involve expressions for mode availability and mode performance achievement. We have:

$$R_c = q_1P_1 + q_2P_2 + q_{12}P_{12} \tag{A2.8}$$

where R_c is the circuit reliability; q_1 and P_1 are the mode availability and mode performance achievement for the case when mode 1 is present; q_2 and P_2 are the mode availability and mode performance achievement for the case when mode 2 is present; q_{12} is the probability that modes 1 and 2 are present simultaneously; and P_{12} is the probability that the combination of modes 1 and 2 will lead to a signal-to-noise in excess of some required level. Even though equation A2.8 is limited to two contributing modes, its evaluation is not necessarily trivial. Other methods for computing reliability are listed in Table A2-6.

TABLE A2-6

Various reliability methods in use

Name of Method or "System" Use	**Reference**
IONCAP/VOACAP/ICEPAC	Teters *et al*. [1983-1995]
HFMUFES	Barghausen *et al*. [1969]
Liu-Bradley	Liu and Bradley [1985]
CRC-Canada	Petrie [1981]
CCIR Method	CCIR Report 892-1 [1986h]
Maslin Method	Maslin [1978]
Chernov Method	Chernov [1969]
HFBC Method	CCIR Report 892=1 [1986h]
REC533	ITU-R Recommendation PI 842-1

It is of interest to look at some special cases of an approximate method developed by Liu and Bradley [1985] for which correlation between two contributing mode MUFs may be taken into account, whereas correlation between mode SNRs is ignored. The method presumes that the basic MUF is normally distributed and the SNR is log-normal (*i.e.*, the SNR in dB is normally distributed). Taking the correlation between two modes as c_{12}, and $Q_1 = q_1 + q_{12}$, $Q_2 = q_2 + q_{12}$ where q_1 and q_{12} were defined previously, we have:

$$R_c \; = \; Q_1P_1 + Q_2P_2 \,\{1 - [c_{12}^2 + 1 - c_{12}^2)\, Q_1]\, P_1\} \qquad \text{(A2-9)}$$

where $Q_1 \geq Q_2$. For $c_{12} = 0$ and $c_{12} = 1$, obvious simplifications in equation 4.14 will result. For purposes of planning, one may take E and F1 modes to be fully correlated (*i.e.*, $c_{12} = 1$), E and F2 modes to be uncorrelated, and F1 and F2 modes to be uncorrelated. Also, correlation between dual modes from the same layer are taken to be highly correlated but not necessarily unity. For example, experience has shown that two F2 modes have a cross correlation coefficient of 0.8 for purposes of reliability calculations. The effect of vanishing correlation between two contributing modes is to limit the maximum reliability that may be achieved.

IONCAP uses another scheme for estimating circuit reliability. The method involves combining the signal power from all modes under the presumption that the relative phase relationships between the contributing modes are random. The SNR is taken to be the difference between the means for both signal and noise (in dB), while the variance of SNR is simply the sum of the respective variances. The circuit reliability is taken to be the fraction of days (over a month) that the SNR ≥ the required value. Clearly, if a specified mode does not propagate efficiently, the algorithm automatically disables any significant contribution of that mode to the overall reliability. There is no need to account for mode support explicitly. It is noteworthy that the ionospheric variability and mode support is accounted for implicitly (in terms of SNR variability, which is part of the IONCAP model). As expected, comparisons of the various methods for circuit reliability show some differences.

Table A2-7 gives the number of methods available within the IONCAP family of programs. The table is representative of VOACAP version 97.0327W. The newest release is 98.0908W. The reader is referred to the following Web site for more details:

http://elbert.its.bldrdoc.gov/hf.html

The descriptors of IONCAP methods listed in Table A2-7 are fairly self-explanatory. The term REL corresponds to reliability, and ANG refers to the elevation angle associated with the specified dominant mode. Methods 1 and 2 allow the user to see the underlying ionospheric data that is used in the other methods. A number of graphical and tabular methods that provide various combinations of propagation data such as HPF, MUF, LUF, FOT, ANG, and foEs are available. However, system performance methods set mainframe models apart from microcomputer models that compute only a limited set of parameters, typically only the propagation parameters and possibly a measure of signal strength. Popular methods in Table A2-12 include numbers 17, 20, and 25. A complete system performance is accommodated in method 20 and a condensed version of this is found in method 17. Method 25 allows the analyst to examine system effects mode-by-mode. The reliability vs. MUF table found in method 24 is also quite useful, while the antenna methods 13-15 are primarily available for reference purposes.

In the computation of reliability, the user must specify a number of system parameters as well as required SNR for a specified modulation format and grade of service. These data are found in various communication handbooks. Tables A2 and 5 in NTIA Report 83-127 give data for an assortment of conditions. The reader should not be surprised to see apparently enormous values in the tables just referenced since they reflect the required SNR for a signal in the occupied bandwidth versus noise in a 1-Hz bandwidth. To compare signal and noise in a common bandwidth, one must subtract the system (*i.e.*, noise) bandwidth in dB from the tabulated value.

TABLE A2-7.

Listing of IONCAP methods*

Method No.	**Method Description**
1	Ionospheric parameters
2	Ionograms
3	MUF-FOT lines (nomogram)
4	MUF-FOT graph (use 11 or 28)
5	HPF-MUF-FOT graph
6	MUF-FOT-Es graph (use 11)
7	FOT-MUF table (full ionosphere)
8	MUF-FOT graph (use 11 or 28)
9	HPF-MUF-FOT graph
10	MUF-FOT-ANG graph
11	MUF-FOT-Es graph—real graph, not line printer
12	MUF by magnetic indices, K (not implemented)
13	Transmitter antenna pattern
14	Receiver antenna pattern
15	Both transmitter and receiver patterns
16	System performance (SP)
17	Condensed system performance, reliability
18	Condenses system performance, service probability
19	Propagation path geometry
20	Complete system performance (C.S.P.)
21	Forced long path model (C.S.P.)
22	Forced short path model (C.S.P.)
23	User selected output (set by TOPLINES & BOTLINES)
24	MUF-REL table
25	All modes table
26	MUF-LUF-FOT table (nomogram)
27	FOT-LUF graph (Use 28)
28	MUF-FOT-LUF graph—real graph, not line printer
29	MUF-LUF graph (Use 28)
30	For VOACAP only—S/L path smoothing (7,000 – 10,000 km)

*The IONCAP documentation consists of a user's guide [Teters *et al.*, 1983] which outlines the various methods that may be selected. A listing of methods within this table is associated with VOACAP ver. 97.0327W. The latest Windows®, NT, and 95/98 32-bit version of ICEPAC/VOACAP/REC533 is 98.0908W. See Teters, 1983, *Estimating the Performance of Telecommunication Systems Using the Ionospheric Transmission Channel: Ionospheric Communications Analysis and Predictions Program (IONCAP) User's Manual,* NTIA Report 83-127.

See http://elbert.its.bldrdoc.gov/hf.html

A2-10 Small programs and personal-computer methods

Over the years, the computer mainframe methods in the IONCAP family have been replaced by PC-based versions that run in a convenient Windows® environment. In fact, the fully capable versions of programs such as VOACAP and ICEPAC made the transitions to the PC environment more directly. While this evolutionary process was taking place, it was necessary to solve practical problems with less capable machines. This gave birth to a class of so-called microcomputer methods in the 1980s. Many of these methods still have validity in special applications and are the subject of this section. See Report 1013 (CCIR 1986L). One of the first microcomputer models to be developed for general use by the public was MINIMUF [Rose, 1982a], which is part of the PROPHET family of programs [Rose, 1982b]. There have been a number of improvements to MINIMUF, the more recent versions being termed MINIMUF 3.5 and MINIMUF85 [Sailors *et al.*, 1986]. Other microprocessor-oriented frequency prediction models have followed: MICROMUF [Bakhuizen, 1984], FTZMUF2 as described by Damboldt and Suessmann [1988a, b], and a series of models based upon algorithms developed by Fricker [SES, 1988]. Daehler [1990] has developed a MUF-LUF-FOT prediction program having a number of simple models as its basis, but admitting to several update options. Table A2-8 is a compilation of microcomputer methods and corresponding references. A review of various microcomputer methods has been published by Davy *et al*. [1987]. Field strength models are represented by MINIFTZ4 and the most complete CCIR-sanctioned microprocessor model is REP894. A microcomputer program, developed in accordance with the specifications provided in CCIR Report 1013 and based upon CCIR 894 methodology, is the program MICROP2 [Dick and Miller, 1987].

The Ionospheric Prediction Service of Australia has developed a user friendly microcomputer program called the Advanced Stand-Alone Prediction System [ASAPS) [IPS, 1991]. This model exploits the T-index, which was developed by IPS investigators, and draws on a previously developed GRAFEX prediction method [Turner, 1980].

Although there is some concern that accuracy may be sacrificed in the development of the microcomputer models, this concern is tempered by the following considerations. First, there have been no in-depth studies as yet which show that the large mainframe prediction models significantly outperform their smaller cousins, at least in the prediction of a simple parameter such as the MUF where there is a common basis for comparison. Secondly, in the world of RTCE and ionospheric assessment technology, which may be used for frequent updating of the model input conditions, small microcomputer models may perform quite adequately. This is because temporal updating procedures typically involve the application of scale factors that effectively suppress the physics that may be contained within the more elegant mainframe model. Thus, more rapid temporal updating leads to a convergence in the performance metric of competing models. The same may also be said of spatial extrapolation using models, although in this case and “update” involves the number and location of ionospheric control points used in the extrapolation process. Naturally, one would prefer the flexibility of the larger more elegant model if the capability to update in either space or time is limited. It should be noted that the IONCAP family of programs and other sophisticated modes have been converted to PC operation, thus making the relative accuracy question moot.

TABLE A2-8

Microcomputer prediction methods and references

Model Name	**Reference**
FTXMUF2 (foF2 and M3000)	Damboldt and Suessmann [1988a, b]
Fricker (foF2 & hF2)	Fricker [1985]
Compact Ionospheric Model	Clarke [1985]
MINIMUF	Rose [1982a, b]
MICROMUF [based on Fricker's algorithms]	SESC [1988] [Bakhuizen, 1984]
MINIPROP [based on Fricker's algorithms]	SESC [1988]
MAXIMUF [based on Fricker's algorithms]	SESC [1988]
KWIKMUF [based on Fricker's algorithms]	SESC [1988]
Gerdes Approach [approach similar to MINIMUF]	Gerdes [1984]
EINMUF (MUF-LUF-FOT) [approach similar to MINIMUF]	Daehler [1990]
Devereux/Wilkinson Method [approach similar to MINIMUF]	Devereux & Wilkinson [1983]
Fricker (Field Strength)	Fricker [1987]
IONOSOND [based on Fricker's algorithms]	W1FM [Lexington, MA]
MINIFTZ4 (Field Strength)	Damboldt & Seussmann [1988a, b]
MICROPREDIC	Petrie *et al.* [1986]
HFBC84 (Micro Version) [Replaced by REC 533]	Pan and Ji [1985]
HFPC85-CNET Method	Davy *et al.* [1987]
REP894 [with CCIR Secretariat: also MICROP2, HFRPC8]	CCIR 894 [1986a]
PC-IONCAP (NTIS)	Teters *et al.* [1983]
ASAPS	IPS [1991]
VOACAP	G. Hand [1993]
REC533	Recommendation ITU-R PI.842-1
ICEPAC/VOACAP/REC533	http://elbert.its.bldrdoc.gov/hf.html
PROPMAN	Roesler of Rockwell Collins

A separate implementation of IONCAP, called PC-IONCAP has been developed by ITS and is available through NTIS along with an early version of IONCAP documentation [Teters *et al.*, 1983]. A number of companies have implemented IONCAP methods to support special-purpose programs. For example, Rockwell Collins has developed PROPMAN, a PC version of IONCAP that incorporates the capability for updating.

A2-11 Commentary on short-term prediction techniques

Short-term prediction methods typically involve the measurement of either an ionospheric or geophysical parameter that is applied to an empirical model or algorithm. We have seen just above that long-term prediction methods provide the system architect and the frequency planner with useful guidance, but that ionospheric variability with time scales of tens of minutes present a considerable challenge. Certainly the ubiquitous median models have no intrinsic short-term forecasting capabilities. One should expect very little correlation between the unfiltered real world and the predictions extracted from a median model. A summary of short-term methods is provided in Report 888-1 [CCIR, 1986m]. Even though long-term models have no capability to assess short-term variability in other than a statistical way, the Achilles heel of short-term forecasting is that there is a danger that long-term models may be used improperly by analysts. Milsom [1987] has listed the outstanding problems associated with short-term forecasting, and Goodman [1991] has examined ways of coping with short-term variability.

The deviation of short-term predictions (which we shall hereafter term forecasts) may entail the process of model update with an external geophysical parameter, an ionospheric parameter, or a combination of both. Forecasts that exploit ionospheric measurements for updating purposes are by far more successful.

A2-12 Toward improvement of long-term predictions

Long-term prediction of ionospheric behavior depends critically upon a reliable representation of past ionospheric data and a known correlation with solar activity, which is the derivative of yet another prediction process. Because of the general lack of a truly accurate representation or model of the ionosphere, which is compounded by the tendency to *drive* these models with a single parameter such as sunspot number, long-term predictions are not dependable. This is because short-term, apparently stochastic disturbance sources or factors, which occur in the actual physical process, are not properly accounted for in the prediction method. Thus, long-term methods for prediction are used to derive coarse guidance. The hope is that they at least reflect the median behavior.

There are long-term tendencies in the solar flux. Recommendation 371 [CCIR, 1986n], dealing with the choice of indices for long-term predictions of ionospheric behavior, recommends that predictions that are for dates more than one year ahead of the current period be treated different from periods that are less. If predictions are for epochs of more than 12 months in the future, the 12-month running mean sunspot number is to be used for the prediction of all ionospheric parameters, including foF2, M(3000)F2, foF1, and FoE. The 12-month average is used to average out the shorter period disturbances, which may disguise the long-term tendency of solar flux and its influence on the median ionospheric parameters. For shorter lead times, several indices, including a measure of the 10.7 cm solar flux, as well as the sunspot number, produce equivalent answers in connection with prediction of the parameters foF2 and M(3000F2. As far as the lower ionospheric parameters foF1 and foE are concerned, it turns out that the 10.7 cm solar flux is the best index for periods up to 6 months into the future, and perhaps even longer. The fact that actual flux (even at 10.7 cm, which does not itself interact with the ionosphere,) best represents the solar ionization flux, which produces the E and F1 regions of the ionosphere, is well-known and is implicit in the CCIR recommendations.

In the design stage, the driving parameters of a prediction model are allowed to take on a range of values, and the system is designed to encompass the results of the calibrations. While sunspot number may be an adequate driving parameter for this purpose, it is not optimum for predicting events that will occur in particular days, weeks, or months in the future. Mounting evidence has accumulated [Sheeley *et al.*, 1985] that shows that coronal holes and particular large sunspot groups on the Sun are the real sources of high-speed solar windstreams, which feed most immediately into high latitude ionospheric effects and are later felt elsewhere. Observed effects are ionospheric storms, shifted and expanded auroral rings, depressed critical frequencies at mid-latitudes, etc. In other words, a sunspot number that totals all the spots is too crude a parameter to predict these effects. Instead, the idea would be to view coronal holes and pertinent sunspot regions from the Earth, account for the correct number of days for solar rotation to carry these solar features to the central meridian, and then add 2-3 days for the solar wind perturbation to reach the Earth. Hence, ionospheric effects could be predicted from solar observations about a week in advance. If one accounts for the fact that several of these solar features last many solar rotations, then corresponding effects can be confidently predicted to occur every 27-28 days. This is the basis for prediction of effects from solar observations with lead times up to several months. These developments point to the redesign of ionospheric models on the basis of correlating synoptic ionospheric parameter data with a different batch of relevant solar parameters. Shorter term forecasts (on the scale of hours) may be related to the class of solar flare-related sudden ionospheric disturbances (SIDs), which are associated with bursts of short-wavelength electromagnetic radiation.

Difficulties associated with HF radio circuit performance predictions are outlined in Report 889-1 [CCIR, 1986o]. They are abbreviated in Table A2-9 below, and the list clearly illustrates why HF predictions have mixed reviews.

TABLE A2-9

Difficulties in making accurate predictions

1	Use of OWF's implies a loss of skywave support 10% of the time (quiet times)
2	Predictions generally ignore storm-time effects.
3	Sporadic E model is not sufficiently accurate.
4	Differences exist between model databases and observations.
5	The SNR is poorly modeled and an incomplete performance metric.
6	Other user interference is not accounted for properly.
7	Deficiencies in mapping ionospheric characteristics, modeling tilts and gradients, *etc.* exist.

A2-13 Web sites for ionospheric prediction programs

There are a number of prediction services and real-time data programs available over the World Wide Web. However, the reader is cautioned that new Internet sites are continually being introduced as the technology advances. Below is a collection of Web sites available at this writing.

Program Name/Resource	**URL Address**
Real-Time Inograms (NGDC)	http://www.NGDC.NOAA.gov/stp/IONO/grams.html
Ionosphere Home Page (NGDC)	http://www.NGDC.NOAA.gov/stp/IONO/ionohome.html
HF Propagation Models (NTIA/ITS)	http://elbert.its.bldrdoc.gov/hf.html
Space Environment Center (SEC) home page	http://www.sec.noaa.gov/
Space Physics Interactive Data Resource (SPIDR) (NGDC)	http://julius.ngdc.noaa.gov:8080/index.html
IPS Radio and Space Services (Australia)	http://www.ips.oz.au/
Space Weather Forecasts	http://nastol.astro.lu.se/~henrik/spwfo.html

A2-14 Conclusion

An overview of prominent ionospheric propagation prediction models was given, and their use for shortwave applications was discussed. The backbone of these programs is a climatological or monthly median ionospheric model, which does not account for short-term variability. Since all such ionospheric models admit to significant errors from this class of disturbance, the choice of prediction model may depend less on the phenomenology embodied in the model and more upon less esoteric matters such as: availability of computer assets, transportability of the model, software maintenance requirements, ease of use, and related issues. This has led to a bifurcation of prediction systems into two classes: one devoted to study of detailed physical processes and long-term planning, and the other driven by short-term tactical requirements. Certain longer period disturbances or features characterized by large geographical scales, may be better described by more detailed models, although a significant empirical component may be involved, and update procedures will be necessitated to improve accuracy significantly. Examples include: day-night transitions, equatorial anomaly regions, high latitude auroral and sub-auroral trough regions, *etc*. Today most of the original, large mainframe models and newly developed models are incorporated into microcomputers and PCs. Thus, we see that the most advanced models and methods are now available to even the most unsophisticated user, and these models have replaced some of the well-known skeletal models that were developed for microcomputers in the 1970s and early 1980s. Moreover, programs such as IONCAP may be incorporated within forecasting systems for near real-time frequency management of HF systems. In addition, similar models may be incorporated within advanced modems that use microprocessors for network management. A method for modifying the IONCAP family of codes to reflect real-time changes in the ionosphere has been developed and described by Goodman, *et al.*, 1997. The basis of the approach found in ITU-R Rec. F.1337 (ITU, 1997) entitled, *Frequency management of adaptive HF radio systems and networks using FMCW oblique incidence sounding.* This method can also be exploited in the context of adaptive HF system protocol structures such as ALE. For example, it may be used to organize ALE scan lists, thereby reducing the need to use in-band channel sounding, the latter being a process which limits the efficiency of networked communications under stressed or disturbed conditions.

Long-term predictions are likely to be required for broadcast planning for some time to come. They are also worthwhile for system studies and planning for military operations. It is unclear to what extent incremental improvements in long-term modeling will provide for anything but small incremental improvements in long-term prediction capability. Computer procedures and display formats may be improved, however, and these cosmetic changes will add value, since they will provide the analyst with a capability to examine the projected data more coherently and in a variety of scenarios. One potential area for long-term performance improvement may arise as the result of a newly developed scheme for mapping the tendencies of high-latitude propagation from 1 week to several months in advance, based upon observation of the evolution of coronal holes and related solar features. There are a number of deficiencies in current modeling approaches and we have identified most of them. Aside from taking more care in representing the ionospheric *personality*, and possible incorporation of 3-D ray-tracing methods, quantum improvements in prediction capability are not anticipated. The future realm is dynamic modeling.

Long-term modeling approaches may be used to benefit short-term predictions. More dynamic approaches, based on ionospheric soundings, have been developed. They may be shown to have viability in updating selected prediction models for short-term use. This approach has been found to be particularly useful for local removal of the DC bias errors in ionospheric models, which result from the use of monthly medians and imprecise driving parameters, such as the sunspot number. Updates are particularly relevant for the effective use of adaptive HF schemes. However, a present ionospheric specification decorrelates rapidly when compared with future reality. The update must be performed rapidly. The best application of update for military or civilian broadcast planning may well be in the context of relay station diversity. Thus, the broadcast planner could envision real-time resource management. The resources available in the future may involve backscatter sounder technology, as well as overhead imagery tailored to provide ionospheric *weather* maps. Ionospheric data extracted from the GPS constellation downlink waveforms may be used to provide a more meaningful spatial sampling. These data sources would be coupled to existing assets, such as conventional vertical and oblique sounders and total electron content sensors activated by GPS transmissions. All of this information could be merged with the real-time solar-terrestrial data available through various data services [Joselyn and Carran, 1984]. Relatively high-quality ionospheric information may result from inserting this data into sophisticated ionospheric models that are presently being developed. The possibility exists for the construction of a real-time ionosphere to serve a number of users, not unlike that which has been envisioned by the U.S. Air Force to serve its customers.

Finally, it must be stated that a substantial effort has gone into the general area of ionospheric modeling. From this investment, a considerable amount of insight has been derived, and a number of very interesting methods for performance assessment have evolved. Some of these models include a full range of ionospheric and propagation effects, while others stress simplicity. The modern era allows for selection of the more complex (and complete) models for use in microcomputers as system controllers. Further, these models will have *hooks* allowing real-time update methods to be used as the newer sensors become available. In short, prediction methods based on the evolution of long-term median models, and have been an essential catalyst in the development of more dynamic models.