RECOMMENDATION ITU-R F.1337*

FREQUENCY MANAGEMENT OF ADAPTIVE HF RADIO SYSTEMS AND NETWORKS USING FMCW OBLIQUE-INCIDENCE SOUNDING

(Question ITU-R 205/9)

(1997)

The ITU Radiocommunication Assembly,

considering

a) the need for highly reliable HF communication services;

b) the limited amount of HF spectrum available for transmission of voice and data;

c) the constraints of the time-varying ionosphere, which limits the number of usable channels within the available spectrum;

d) that effective and efficient regulatory and frequency management techniques are essential to optimize use of the frequencies for fixed and some mobile services between 1.6 and 28 MHz;

e) that experimental studies, as outlined in the Annex 1, have shown that substantial improvements in channel utilization can be achieved through the use of frequency and path diversity;

f) that frequency modulated continuous wave (FMCW) oblique incident sounding schemes can provide an accurate real-time assessment of the HF channels available to a network thereby forming the basis of dynamic frequency management;

g) that the FMCW “chirp” sounding method can be engineered to limit harmful interference, and can be implemented as an external process thereby eliminating reductions in system capacity,

recommends

1 that automatic and adaptive management schemes be considered for adaptive HF networks to include dynamic selection of optimum frequencies, the sharing of frequencies within a network, and adaptive selection of alternate network paths;

2 that FMCW “chirp” sounding be considered for use in dynamic frequency management schemes including:

– as a real-time input data source for updating resource management and propagation prediction programmes;
– as a means for updating the frequency scan lists of adaptive HF systems;
– for modification and enhancement of the link quality analysis (LQA) matrices for adaptive HF systems;
– as a complement to the exclusive use of in-band channel sounding, thereby increasing network communication capacity and reducing interference introduced by channel sounding;

3 that for adaptive HF networks in the fixed and mobile services, the information contained in the Annex 1 be considered for general spectral planning and in the design of network topologies;

4 that further studies are required to evaluate the advantages of sounding technology for frequency management of regional and global adaptive HF networks, emphasizing high latitude and equatorial regions during solar maximum conditions.

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* This Recommendation should be brought to the attention of Radiocommunication Study Groups 1 and 8.

ANNEX 1

Long-term investigation of oblique incidence FMCW sounding as a method for dynamic frequency management of HF communication networks

1 Introduction

FMCW swept-frequency sounding has been used within centralized spectrum management networks to provide real-time channel evaluation (RTCE) for multiple HF circuits. Often referred to as “chirp” sounders, these devices provide the benefits associated with oblique incidence sounding, i.e. for use in the optimization of frequency utilization, improvement in circuit reliability, evaluation of signal-to-noise and interference ratios, and the measurement of ionospheric propagation parameters used by some adaptive HF systems. When linked to centralized spectrum management networks, these sounders can be operated in limited numbers on an intermittent, low-power basis, obtaining real-time spectrum management information for multiple users. This method decreases the need for sounding in general and also limits the total time that a sounder will operate co-channel with other HF transmitters. The net result is improved information to multiple users and a decrease in interference potential due to sounding.

2 System concept

Within centralized spectrum management networks, FMCW swept-frequency sounding information can be used to produce presentations, called ionograms, of received signal time delay versus frequency of transmission. Because the ionospheric channel may be comprised of multiple layers and scattering centres supporting HF communication, received signals at a given frequency will experience varying amounts of time delay distortion. Traces on the ionogram record are indicative of various ionospheric propagation modes which will support communication.

Ionograms are derived by processing a low power FMCW signal over a selectable frequency range, typically 2-30 MHz. The quality of these “chirp” ionograms is superior to those derived from pulse sounders for the same average power because the former employs a spread spectrum waveform characterized by processing gain which is applied against narrow-band interference effects. The nominal average power (and peak envelope power (PEP)) of these systems is 10-100 W or possibly less depending upon the circumstances.

FMCW sounding also reduces the amount of time when any particular frequency is occupied. The nominal rate at which these sounders sweep through the 2-30 MHz band is 100 kHz/s. Consequently, the entire HF band is sampled in about 5 min. The temporal separation between successive sweeps for a given transmitter, called the scan interval, is typically 15 min, but may be set at 30 min or longer. Therefore, the FMCW swept frequency transmitter not only uses modest power, but it has a momentary effect on other HF users within each scan, and the scan interval is relatively long. If a co-channel user is within the coverage pattern of the FMCW sounder, a typical 3 kHz channel may experience a 30 ms blip no more than twice an hour if the scan interval is 30 min.

When used within a centralized spectrum management network, the number of sounders can be limited while providing regional or worldwide coverage to a large number of users. This process eliminates the need for individual HF operators to perform their own sounding thereby decreasing the total amount of sounding needed to support a number of users. Channel sounding by individual transmitters, though providing useful information, can add to the congestion of the HF frequency range. FMCW swept-frequency sounding used in conjunction with centralized spectrum management networks can greatly decrease the potential for interference due to sounding.

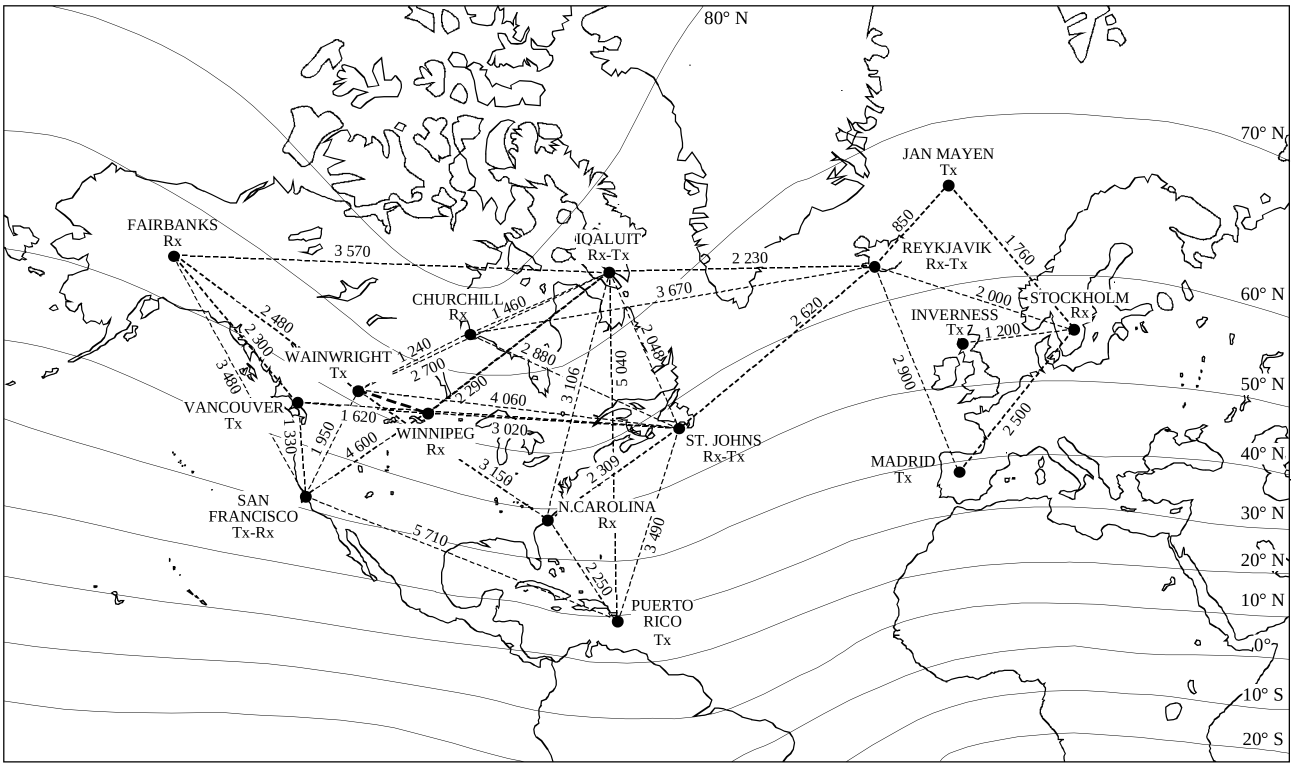
3 Experimental implications of relevance to the Recommendation

Many experiments have been conducted over the years using FMCW swept-frequency oblique incidence sounders. An extensive experimental program of the potential of frequency and path diversity was conducted between 1993 and 1996, a period of low solar activity. The program was conducted using ten sites in the Northern hemisphere. Figure 1 provides the geometry. The investigation was directed toward resolving problems associated with adaptive HF communication systems with special emphasis on automatic digital data communication. Other issues of concern included those of radio propagation, frequency management, and system architecture. Paths that were examined have provided information related to circuits within the polar cap, auroral zone, high-latitude trough, as well as mid-latitude channel environments.

FIGURE 1

Geometry of the propagation experiments

Distances between the transmitter and receiver
sites are given in kilometres. Data were obtained between 1993 and 1996.



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Transmitter powers used in the experiments ranged between 10 and 100 W, and the sounder scan interval was set at 30 min. Over 40 path-years of data were collected and analysed, providing estimates of link and star-net communication availabilities under a variety of frequency and station diversity conditions.

Not only was the information significant derived from the data taken during the experiments, but the extensive long-term operations provided evidence of the decreased potential for interference resulting from the used of FMCW sounders with centralized spectrum management networks. During the entire period of operation of these FMCW sounders associated with the experimental activity conducted between 1993 and 1996, there were no reports of interference.

The following conclusions are based upon the analyses of the data collected. Some of the conclusions flow directly from axiomatic principles of HF propagation and the ionospheric interaction.

4 Factors relating to FMCW sounding

4.1 On spectrum

Adequate spectrum must be available to achieve optimum connectivity, whereas the conditions for adequacy will ultimately depend upon factors such as traffic loading. Studies of star networks have indicated that long-term communication availabilities approaching 100% may be achieved provided there is access to several widely-separated ground stations, and that dynamic selections based on real-time soundings can occur from among a pool of frequencies residing in a sufficient number of bands distributed across the HF spectrum. As a general rule, eight frequencies are generally adequate for good quality fixed and mobile service applications. The condition for adequacy, however, may require additional frequencies during disturbed conditions, when the number of diversity paths is reduced; or, whenever ionospheric correlation distances are increased. The converse is also true. That is, the frequency requirements can be reduced under benign conditions or during periods of low traffic loading.

In general the number of frequencies required to accommodate high levels of availability will be dependent upon the number of stations which are contributing to network capacity. Tests have examined this relationship and the following rule is found to hold under most circumstances:

$$N_f \sim a + b/N_s \tag{1}$$

where N_f is the number of frequencies, N_s is the number of stations, and a and b are functions of network topology (i.e., node separations), the geographical area over which the communication service is to be provided, the diurnal cycle, the season and the solar conditions. For the conditions tested, it has been found that $a \approx -4$ and $b \approx 48$ is fairly representative for $3 \leq N_s \leq 5$ except during disturbed conditions. There are also conditions during which sporadic E is a controlling feature over one or more propagation paths. The condition of sporadic E, when available, may enable a single station to host as many frequencies as necessary to accommodate all the traffic from a clusterhead to the ground station and still achieve high availability. In this instance station diversity is unnecessary, and equation (1) does not hold. A real-time frequency management system, based upon the FMCW technology outlined in this Annex will enable both normal and sporadic-E modes to be detected and evaluated.

4.2 On network topology

Star net configurations consisting of a central node (i.e., clusterhead) and a surrounding cluster of external nodes exhibit enhanced connectivities if the cluster population is increased. Moreover, the connectivity characteristic approaches saturation for designs incorporating four or more widely spaced nodes. Thus the number of participating paths and the degree of propagation independence of the specified paths is quite important. Another condition for connectivity is that the participating paths are viable, since a null path cannot contribute to connectivity. These principles suggest the following strategy for selection of cluster members: on one hand, association of paths having widely separated control points, on the other hand, association of paths residing in differing geophysical regimes, use of paths with largest propagating bandwidth, including: longest possible paths in the equatorward direction, and paths possessing the largest solar elevation angle. As a general rule, it is found that the region defined by great circle paths connecting nodes in the cluster should define the largest possible area containing the clusterhead thus enabling as much path diversity as possible. However, given the greater possibility of limited viability for paths in the poleward direction, there should be an effort to specify equatorward circuits with as much diurnal separation as possible.

An overall regional or global network may consist of an assembly of subnets or clusters where ionospheric properties at the clusterheads and at other nodes in each cluster continue to evolve. For fixed services, where the clusterhead is stationary, the evolution results from ionospheric variability. For mobile services, since the clusterhead may be in motion, the situation becomes more complicated. Frequencies which were once optimum will not remain so for very long. It points to the importance of dynamic management of network resources, including the inter-exchange of frequencies between nodes in the cluster. Evidence for an excess of capacity from a given node to a generalized coverage area, owing to the presence of sporadic E is abundant. While sporadic E is recognized as a summer daytime phenomenon for mid-latitudes, it is seen that sporadic E bands due to the auroral zone may be used to circumvent F-region propagation disturbances.

4.3 On the influence of magnetic activity

Magnetic storms may have a significant impact upon the available HF spectrum, an effect which is generated by significant departures of the maximum observed frequency (MOF). Because magnetic storm effects may occur over a vast area and can have such a long-lasting effect, it is evident that real-time ionospheric information over requisite links will be a decided improvement over long-term prediction methods which are sometimes used to define adaptive HF scan lists. The largest diminutions in available bandwidth resulting from magnetic storms arise for mid-latitude circuits.

While magnetic storms give rise to obvious MOF variations, there are also identifiable MOF fluctuations associated with elevated levels of magnetic activity. These may be associated with an increase in the number and magnitude of travelling ionospheric disturbances (TIDs) which may originate in the neighbourhood of the auroral zone and propagate equatorward. While these lower level disturbances are not sufficiently well-organized to produce a magnetic storm, they do introduce a variety of HF propagation effects, including: multipath, sidescatter, and spread-F. These effects are observed directly by means of FMCW sounders.

It is also well known that magnetic activity is correlated with the geographic position and strength of high latitude features, including the mid-latitude trough and the auroral oval. For example, the oval thickens and moves equatorward as magnetic activity increases, and these features contract as the activity becomes smaller. This is significant since magnetic activity may substantially alter the geophysical regime, and thus the variability profile, for fixed and mobile circuits. The use of real-time evaluation methods, such as FMCW sounding, will provide the most appropriate basis for assessing the current and near future performance of HF circuits within the high latitude region. The complete assessment and forecasting approach could involve the marriage of a constellation of sounders, selected solar-terrestrial data available from computer utility programmes, and other real-time data resources which may be available. This concept presupposes the existence of a constellation of sounders of sufficient density, and that there exists an infrastructure for distributing derived channel data, including frequency management information, to the adaptive HF network being served.

Figure 2a illustrates the impact of magnetic activity on circuits monitored during the experimental tests described herein. It is seen that there is a definite difference between “quiet” and “disturbed” conditions, but only for HF star networks at the higher latitudes.

4.4 Advantages of real-time sounding over prediction methods

Prediction methods have been used to specify and rank frequency lists for adaptive HF systems. These codes are based on median behavior of propagation parameters, there are variations between actual observation and the model predictions. Because of this, there is a requirement to update the models. Methods used to update the information includes the use of vertical and oblique sounder data sets. So-called pseudoflux methods have been used with some success to arrive at the information, and there are techniques which will incorporate a variety of near real-time data sets to improve communication model performance.

The most important factors in the performance of these methods appear to be:

– the time interval between measurement and application of result,

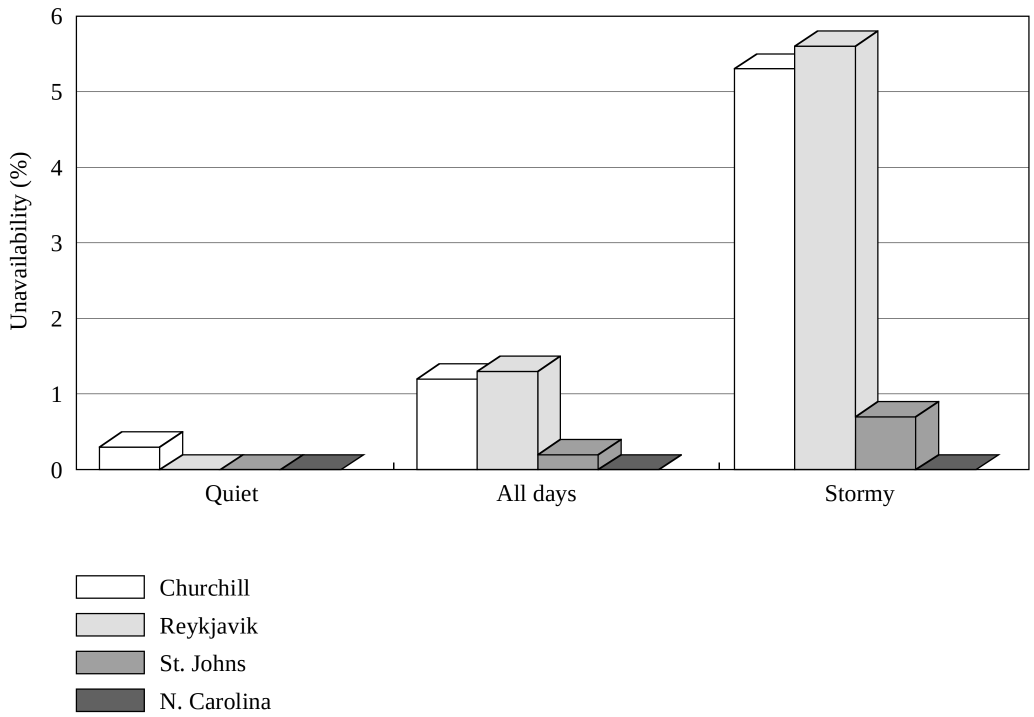
– the proximity of the updated model result to region of interest.

The latter factor is dependent upon the density of update sources, while the former is dependent upon the response time of the network upon receipt of frequency management information. Because of the variability of the environment updates lose value rapidly.

Figure 2b clearly illustrates the advantages of RTCE as embodied in the FMCW sounding scheme over prediction methods. The simulated service was HF data communications, and the required signal-to-noise ratio (S/N) for an acceptable grade of service was specified. The example shows how a prediction performs as compared with actual observation derived from an FMCW sounder system. Both frequency management systems had access to 11 frequency bands, and communication was deemed to be a success if the measured S/N exceeded a prespecified value (as determined by the grade of service) for at least one frequency. The prediction system was required to preselect the three “best” frequencies from the basic list of eleven. The RTCE system was an improvement over the “prediction” system if the FMCW sounder identified a viable frequency band not included among the three selected by the prediction system.

FIGURE 2a

Impact of magnetic activity



The unavailability of communication (expressed as a percentage) as a function of magnetic activity conditions for four star-net clusters during April of 1995, a month of wide-ranging variation in the magnetic activity parameter *Ap*. The clusterheads are located at Churchill, Reykjavik, St. Johns, and North Carolina, and each cluster consists of four paths terminating at the clusterhead. In this sample calculation, each star-net has access to one frequency in each of the eleven aeronautical-mobile bands, and these frequencies are shared between the four links in each cluster. The "stormy" period corresponds to the period 7 - 12 April during which time : 22 > *Ap* > 100. For the remainder of the period, the *Ap* was less than eight, and is termed "quiet".

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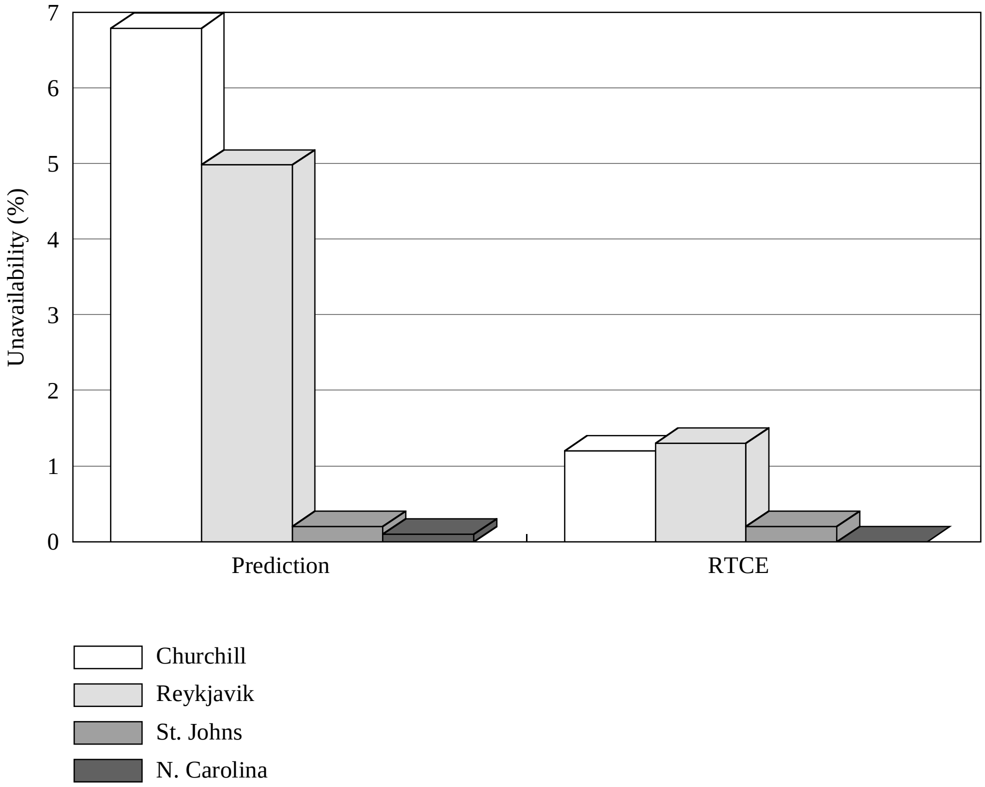
5 Long-term availability determinations

Consolidated network availability assessments have been made for a baseline data rate of 300 bit/s for the clusterheads indicated in Fig. 1. The average network availability is determined on the basis of establishment of connectivity for any one of 11 preselected frequency bands and any one of the participating links in the network, where connectivity is achieved if a prescribed *S*/*N* test is passed.

The composite availabilities are observed to be remarkably high, with most combinations of clusters and months exceeding 99% by a considerable margin. Moreover, there was found to be an enormous difference in the consolidated availabilities as a function of local time, with most outages occurring in the dawn to mid-day period (reckoned from the clusterhead). Clearly this will have important implications for frequency management for the ultimate HF data communication system.

FIGURE 2b

RTCE and prediction methods



The unavailability under two frequency management schemes. The scheme labelled "prediction" corresponds to the condition whereby an established prediction program is utilized to preselect the three most likely frequencies for consideration. The second scheme labelled RTCE (i.c. real-time channel evaluation) corresponds to the best frequency derived from real-time sounder measurement.

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6 Conclusion

Optimum performance of an HF network may be achieved when an oblique sounding system provides information to dynamically control the resources of the network. The FMCW "chirp" sounding method is preferred to other methods for this purpose since it has been shown to be relatively unobtrusive, causing no harmful interference to other users. Frequency sharing and dynamic re-allocation is a requisite condition for controlling network resources, but a full suite of frequencies populating all of the allowable bands is also needed to fully exploit the dynamic forecasting capability. Adaptive HF networks may have global dimensions, and considerable performance enhancements may be achieved if path diversity and frequency re-use technologies may be applied without introducing harmful interference. To promulgate these potential efficiencies, a global network of unobtrusive sounders can be the facilitating agent. More study of this concept would be beneficial. Also, the information used to arrive at this conclusion was obtained during a period of low solar activity, with only a few episodes of enhanced magnetic substorms. Similar information and data is needed for maximum levels of solar activity.