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FEDERAL COMMUNICATIONS COMMISSION
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VIA HAND DELIVERY

Mr. William F. Caton
Acting Secretary
Federal Communications Commission
1919 M Street, N.W., Room 222
Washington, D.C. 20554

Re: PR Docket No. 92-257
Ex Parte Presentation

Dear Mr. Caton:

This letter reports that representatives of BR Communications (John M. Goodman and Daniel S. Goldberg) met today with members of the Commission's staff (Roger S. Noel and Ira R. Keltz) to discuss issues relating to Automatic Link Establishment in the maritime and aviation HF frequency bands. The parties' presentation is reflected in written submissions that already are part of this docket.

Additionally, Mr. Goodman provided copies of the attached documents to Mr. Noel and Mr. Keltz. Two copies of each of the attached documents are hereby submitted for the public record in this proceeding pursuant to 47 C.F.R. § 1.1206(a)(1).

If there are any questions in this regard, please contact the undersigned.

Sincerely,

Daniel S. Goldberg

Attachments

cc: Roger S. Noel
Ira R. Keltz
John Goodman

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JUSTIFICATION FOR CHIRP SOUNDING AT FREQUENCIES BETWEEN 27.5 and 30 MHz

Ex Parte Presentation
PR Docket No. 92-257
Two copies provided
to the Secretary

John M Goodman

August 3, 1996

Abstract

This paper provides additional information supporting the concept of FMCW-ALE "Chirp" sounding at frequencies from 2 -30 MHz to support communications within the maritime bands. While the largest maritime band is 26.100 MHz - 26.175 MHz, there is a decided benefit which obtains from sounding across the entire spectrum including the range 30.0 > f > 27.5 MHz, which we shall refer to as the extended frequency range. This benefit derives from the near-real-time assessment of the ionospheric subchannel which is a fundamental determinant of the HF communication channel. Indeed, without an ability to evaluate the properties of the ionosphere fairly continuously across the HF band, the accuracy of communication channel assessments at discrete frequencies between 2 and 27.5 MHz will be degraded. This degradation will render real-time spectrum management techniques far less effective. For this reason TCI/BR recommends that allowance be made for chirp transmission in the extended frequency range. Further justification for this recommendation derives from the fact that other systems and services which operate in bands higher than those allowed in the maritime-mobile service have need of the Chirpsounder® information in the extended range for their own spectral management requirements. Systems developed by TCI BR already operate between 2 and 30 MHz, which includes the extended frequency range, and it would be an unnecessary burden on the company to limit the transmission frequency upper limit. It would also harm operation of existing systems or those which are under development

1.0 Introduction

The Chirpsounder® system has been used for many years to evaluate the HF communication circuits in use by the U.S military, the NATO, and other government organizations. The system provided a quantum advance over static prediction methods which had been used previously, and it was shown to exhibit no harmful interference to other users in the spectrum. This is a direct result of the unobtrusive nature of the novel chirp pattern, which is formally a spread spectrum waveform. The processing gain associated with the waveform enables very low powers to be utilized while still obtaining useful results. Beyond all of this it

should be recognized that the Chirpsounder® system is also a sensor, and can be utilized to evaluate the intrinsic properties of the ionospheric electron density distribution. The roots of this capability are closely tied to the development of radio itself, and especially HF radio.

Ionospheric reflection for vertical incidence occurs at a specified ionospheric height when the radio signal has a frequency which matches the local plasma frequency, a frequency which is uniquely defined by the maximum electron concentration N. In fact we have:

$$N = 1.24 \times 10^{10} fp^2$$

where N is the electron density (el/m^3) and fp is plasma frequency (MHz). For a given ionospheric layer, the value for N increases with height up to its maximum value. Therefore the sounder signals are reflected at greater and greater heights (i.e., time delays) as the frequency is increased. The highest frequency at which reflections are returned is called the critical frequency fo, and this is also the maximum plasma frequency of the ionospheric layer involved. In general there are a number of ionospheric layers rendering a rather complex pattern of time delay versus frequency of transmission, a presentation we call a vertical incidence ionogram. Such patterns have been used to study the ionosphere for decades, and the archived data from such instruments form the basis for static prediction methods in use for many years. The ITU-R still sanctions such methods for HF performance prediction to this day.

Oblique sounding methods are an improvement over vertical methods in a number of respects. First they enable the evaluation of operational paths far removed from the location of vertical sounders. Specifically, the paths over oceanic regions are not accessible with vertical sounders. Secondly, oblique sounders provide the user with information which is more pertinent to the communication circuit to be evaluated, since the sounder and circuit paths exhibit a class of properties which are only evidenced over oblique radio paths. In recent years, there has been considerable interest in the process of updating ionosphere with sounder data. The Chirpsounder® instrument has been the system of choice for most U.S. government studies having application in the oceanic region. TCI/BR has developed a concept for updating static models such as VOACAP based upon the information derived from the Chirpsounder® system. This system, Dynacast®, relies upon Chirpsounder® transmissions throughout the 2- 30 MHz frequency range. Systems such as this are critical in the new era of adaptive HF systems which require advanced schemes for near-real-time assessment of the propagation channel. A useful background document, USSG/WP9C/4, is a Draft Recommendation outlining a methodology for worldwide frequency management.

2.0 Rationale for FMCW-ALE Chirp Sounding from 2 - 30 MHz

We now wish to supply additional information supporting the concept of FMCW-ALE "Chirp" sounding at frequencies from 2 -30 MHz to support communications within the maritime bands. While the largest maritime band is 27.2 MHz, there is a decided benefit which obtains from sounding across the entire spectrum including the range 30.0 > f >27.5 MHz, which we shall refer to as the extended frequency range. This benefit derives from the near-real-time assessment of the ionospheric subchannel which is a fundamental determinant of the HF communication channel. Indeed, without an ability to evaluate the properties of the ionosphere fairly continuously across the HF band, the accuracy of communication channel assessments at discrete frequencies between 2 and 27.5 MHz will be degraded. This degradation will render real-time spectrum management techniques far less effective.

To understand this principle, it must be recognized that the chirp waveform is utilized to develop a representation of ionospheric properties over a large area of potential communication service. The Chirpsounder® may be considered a sensor which provides detailed information about the HF channel over a geometrical path of fixed length. A complete Chirpsounder® constellation may include a large number of such paths, and these Chirpsounder paths may or may not be collinear with those of the communication paths. Many paths are rather distended such that the largest frequency for the sensor path, known as the Maximum Observable Frequency (MOF), will be somewhat greater than the communication frequencies which are available to be used. An array of sensor MOFs may be converted to an array of ionospheric properties from which we may derive the communication path MOFs as well as the Lowest Observable Frequencies (LOFs). This cannot be done accurately if our sensor has a skeletonized view of the ionosphere.

An example is instructive. Consider that we have an ionosonde station pair located at a separation distance of 4000 km, suitable for a 1-hop analysis. Suppose that the value of foF2 is 10 MHz, a typical maximum value for the ionosphere during the daytime. For a path of this length the ray zenith angle φ is rather large and the secant factor (i.e., sec φ) will approach a value of 3. The MOF $\approx$ sec φ foF2= 30 MHz, say. Suppose now that we have a communication path with the same ionospheric midpoint but having a length of 1250 km. In this case, the value of foF2 would still be 10 MHz, but the value of sec φ might be reduced to approximately 2.0 by virtue of the increased elevation angle of the communication path. Thus the MOF would be estimated to be 20 MHz. This suggests that the highest frequency that can possibly be useful for service over the communication path would be 20 MHz, which enables all maritime-mobile

bands except 22000-22885, 25070-25210, and 26100-26175 kHz to be considered. Specifically, we would not eliminate from consideration those frequencies in the range: 18780-18980 and 19680-19800 kHz. This is all well and good. Unfortunately, if our Chirpsounder were to be "clipped" at 27.5 MHz, we wouldn't know that the MOF over the sensor path was 30 MHz, so we could only guess at the MOF for the communications path. Our guess might typically be 27.5 MHz since we can't sense any higher than that. Using the correct secant factor (i.e., 3.0) with the incorrect value of MOF gives an erroneous value of ≈ 9 MHz for the midpath foF2 rather than 10 MHz (i.e., the correct value). So we predict that the upper limit of communication for our communication path will be 9 x 2.0 = 18 MHz rather than 20 MHz. As a consequence, we would not recommend frequencies within the sub-bands: 18780-18900 kHz and 19680-19800 kHz, frequencies which are allocated from maritime-mobile services in regions 1-3 in the RRs. Regrettably, these band would be near optimum, and should be considered.

There are additional reasons for enabling FMCW-ALE Chirp sounding in the extended frequency range. One of these has to do with the process of communication forecasting and assessment. Spectrum management of an adaptive HF network demands apriori estimation of the list of frequencies which are best for operation throughout the network. Enhancements in circuit MOFs may be encountered under a number of conditions. These include: increases in the foF2 during the positive phase of magnetic storms, the expansion of the auroral oval into midlatitude domains as magnetic activity becomes enhanced, the advance of the solar terminator at the eastern boundary of the service area, and the encroachment of the equatorial anomaly crest into lower midlatitude domains coincident with an enhanced Equatorial electrojet current. The magnitude and extent of these enhancements are quite variable and a precise measurement is required to provide accurate estimates of the eventual impact in the service region at later times. As a essential ingredient for successful prediction, we must be able to monitor enhanced MOFs with the highest frequencies which have already been designed into the Chirpsounder® system.

Another factor worthy of note is the use of TCI/BR technology by the aeronautical mobile community. Chirpsounder® technology is the basis for a resource and frequency management system being developed in support of the HF Data Link system. This system, Dynacast®, will provide basic frequency lists and optimum ground stations for air-to-ground communications in near-real-time. The use of the 2-30 MHz frequency range for sounding is a necessary property of the Dynacast® methodology. Other applications of the FMCW-ALE chirp waveform are envisioned. Specifically, it is possible to organize scan lists of FED-STD-1045 ALE radios with the Chirpsounder®-based Dynacast methodology. This will reduce harmful interference which may arise from excessive in-band channel probing, a feature of the FED-

STD-1045 protocol which is required to organize netted operation. Other features of the 2-30 MHz chirp waveform are being translated into engineering concepts for HF skywave communication systems.

3.0 Conclusion

TCI/BR has developed a Chirpsounder system® which complies with the main features of the proposed FCC rule outlining the nature of FMCW-ALE signaling. While the proposed FCC rule limits FMCW-ALE chirp signaling to the range 2-27.5 MHz, the TCI/BR instrument operates within the stated range plus an extended frequency range 27.5-30 MHz. In this paper we have provided information which justifies allowance for transmission over the extended frequency range as well. The positive features of the allowance for use over the extended range includes the following:

1. Improved Frequency Management for Adaptive HF Systems
2. Improved Resource Management for Adaptive HF Networks
3. Greater Accuracy in Forecasting
4. Greater Synergy with Other Services and Applications

For all these reasons TCI/BR recommends that allowance be made for chirp transmission in the extended frequency range. Further justification for this recommendation derives from the fact that other systems and services which operate in bands higher than those allowed in the maritime-mobile service have need of the Chirpsounder® information in the extended range for their own spectral management requirements

References

Goodman, J.M., 1992, *HF Communications: Science & Technology*, Van Nostrand Reinhold, New York.

Draft New Recommendation: "Methodology for Frequency Management of Adaptive Radio Systems and Networks in the HF Fixed and Mobile Services", Working Paper USWP9C/4, USSG9, USWP9C.

ITU-R FACT SHEET

Date July 9, 1996

USWP 9C
Doc. USWP 9C/4

Ex Parte Presentation
PR Docket No. 92-257
Two copies provided to the Secretary.

Document Title: DRAFT NEW RECOMMENDATION: METHODOLOGY FOR FREQUENCY MANAGEMENT OF ADAPTIVE RADIO SYSTEMS AND NETWORKS IN THE HF FIXED AND MOBILE SERVICES

Author: John M. Goodman
Organization: TCI/BR Communications
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Purpose/Objective:

To provide the basis for a draft new recommendation (DNR) for use in the design and operation of adaptive HF communications systems employed in the HF Fixed and mobile services. A practical methodology for near-real-time management of network resources based upon proven technology is introduced. Through experimental methods, it is shown that knowledge of the ionospheric channel, achieved through use of modernized unobtrusive sounding, will provide for a substantial increase in the adaptive HF systems and networks. An general approach for enhancement of adaptive HF operations, including the performance of ALE systems and networks, is provided. The contribution is directly responsive to Question ITU-R 147/9. It is also important in the consideration of Question ITU-R 204/1 and Recommendation 720 (GT PLEN B).

Abstract:

As part of the development of technology to support an HF data link (HFDL) communication service to support the aeronautical-mobile community, a comprehensive study of multiple ionospheric paths was conducted. These data were obtained nearly simultaneously over selected paths enabling path and frequency diversity to be examined. The technology used to develop the unique data base is the familiar oblique-incidence sounding system using a chirp waveform. This type of system was deployed by the US military, the MOD-UK, NATO and other organizations in the 1970s and 1980s for purposes of frequency management in the period prior to the development of many adaptive HF methods. It was highly successful. This DNR provides the summary of a comprehensive analysis of propagation data obtained between December 1994 until the Spring of 1996. Over 700,000 ionograms and 40 path-years of data have been collected and are archived for detailed analysis. Special attention is directed toward the evaluation of data sets obtain in 1995 at four designated sites corresponding to different propagation regimes. The results provide estimates of link and star-net communication availabilities under a variety of frequency and station diversity conditions. Consolidated long-term availability estimates are also provided; and the guidance is provided in the areas of network topology and frequency management. The most important lesson which may be derived from the analysis is that ionospheric channel information is essential in the optimization of availability and capacity of adaptive HF nets. Secondly, it is possible to greatly improve the efficiency of ALE nets if external sounding methods may be utilized to assist in the frequency management function. The reasons include: (a) a reduction in the amount of overhead which is assigned for channel sounding over impossible or marginal channels, (b) the improvement in network efficiency achieved by utilization of the data for communication rather than getting organized, and (c) an improvement in regional and global coordination of frequency plans and scan lists. The approach also reduces the potential for self-jamming within the adaptive HF networks, since channel sounding is reduced, or eliminated in some cases. In short, we are recommending that consideration be given to non-organic methods, including the sounding methods described in the recommendation, in the development of versatile and unobtrusive schema for regional and global management of adaptive HF systems and networks.

Documents
Radiocommunication
Study Groups
Period: 1995-1997

Document USWP 9C/4
9 July 1996
Original: English

Received:
Subject: Question ITU-R 204/9, ITU-R 204/1: Recommendation 720 (GT PLEN B)

UNITED STATES OF AMERICA

DRAFT NEW RECOMMENDATION

METHODOLOGY FOR FREQUENCY MANAGEMENT OF ADAPTIVE RADIO SYSTEMS AND NETWORKS IN THE HF FIXED AND MOBILE SERVICES

1. Introduction

The purpose of this contribution is to advance a draft new recommendation (DNR) for use in the design and operation of adaptive HF communications systems employed in the HF Fixed and mobile services. This DNR provides the summary of a comprehensive analysis of propagation data obtained between December 1994 until the Spring of 1996. Over 700,000 ionograms and 40 path-years of data have been collected and are archived for detailed analysis. Special attention is directed toward the evaluation of data sets obtain in 1995 at four designated sites corresponding to different propagation regimes. The results provide estimates of link and star-net communication availabilities under a variety of frequency and station diversity conditions. Consolidated long-term availability estimates are also provided; and the guidance is provided in the areas of network topology and frequency management. The contribution is responsive to Questiion ITU-R 147/9. It is also important in the consideration of Question ITU-R 204/1 and Recommendation GT PLEN B.

2. Methodology

The proposed Recommendation is found in Attachment 1. The basis for the Recommendation is provided in Annex 1, a summary of a comprehensive experimental data collection and analysis effort.

ATTACHMENT 1

DRAFT NEW RECOMMENDATION

Methodology for Frequency Management of Adaptive Radio Systems and Networks in the HF Fixed and Mobile Services

(Question ITU-R 147/9; also Question ITU-R 204/1; Recommendation 720 [GT PLEN B])

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 imposed by the time-varying ionosphere, which further limits the number of the number of useful frequency bands within the available spectrum;

d) the fact that modern HF systems have been improved to allow for use of automatic and adaptive frequency management schemes, including periodic frequency changes and sharing of frequencies within a network;

e) that experimental studies outlined in Annex A indicate the substantial gains to be achieved through exploitation of frequency and space diversity;

f) that full-band sounding, belonging to a class of Real-Time Channel Evaluation (RTCE) schemes, provides an unequivocal assessment of all HF channels associated with sounded paths in a network environment, and may form the basis for an improved frequency management capability when used in a real-time scenario;

g) that there exists an independent full-band chirp sounding technology which does not produce harmful interference to users of the spectrum, and which, being independent of the communication network to be served, will eliminate any potential reductions in system capacity necessitated by excessive in-band channel sounding during stressed conditions;

h) that WRC-97 is recommended to consider improvements in the regulation and frequency management of fixed services (and some mobile services) between 1.6 and 28 MHz;

recommends:

that for adaptive HF networks in the fixed and mobile services, the information contained in Annex A be considered as provisional guidance for:

- general spectrum planning
- network topology analysis

and that full-band 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 programs;
- 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 Automatic Link Establishment (ALE) and Automatic Radio Control Systems (ARCS).

[Working Draft 7-9-96]

Annex A: A Long-Term Investigation of the HF Communication Channel

1.0 Introduction

A comprehensive experimental investigation of the potential of frequency and path diversity has been carried out during the 1993-1996 time frame, a period of moderate to low solar activity. This investigation was directed toward thesolution of many of the problems which have long plagued HF communication systems and have hindered its effectiveness. These activities have been supportive of the U.S. Government and industry efforts to identify and examine various issues which are vital to the development of a truly effective HF communication system, with special emphasis on automatic digital data commuinication. While the original intent of the investigations was to develop a data base which could be utilized in an analysis of an aeronautical-mobile data link application at HF, the resultant data, being derived from a fixed constellation of HF transmitters and receivers, is more directly supportive of resource and frequency management strategies for the HF fixed service. The issues include radio propagation, frequency management, and system architecture. While the results have application to voice communication, the primary motivation is directed toward the improvement in reliability for conveyance of digital data. Paths which we have examined have been within the polar cap, auroral zone, high-latitude trough, as well as midlatitude channel environments. For some of the experiments during which various aspects of frequency reuse were examined, long-haul transequatorial, transauroral, and midlatitude paths were monitored concurrently. In this paper data sets which have been derived during a year-long campaign called the "Northern Experiment" are stressed.

Any practical system design for HF data communications includes a specification of the number of ground stations and frequencies to provide service on a worldwide basis. As HF practitioners are well aware, a variation in network topology or a change in the frequency list will lead to differing levels of link and network performance. This situation is also quite region-specific. While data have been obtained for all geophysical regions including midlatitudes and some transequtorial paths, the most critical region was deemed to be the high latitudes for several reasons. For example, it is an area for which satellite connectivity might be vulnerable or non-existent, and therefore a region for which HF data communication service might be of critical importance. There are also a number of fixed-service applications; and it also constitutes a major air route corridor, a factor of importance to the aeronautical-mobile community. In addition to the issues note above, propagation studies have addressed station diversity gain, and methodologies for dynamic frequency management.

Figure 1 is a map of all sounder sites, including transmitters and receivers. Given the fact that many ionospheric phenomena are best organized by magnetic rather than geographic coordinates, an overlay of magnetic latitude contours is given. The magnetic latitude is related to the magnetic dip by the relation $\tan \theta = 0.5 \tan I$ where θ is the magnetic latitude and I is the dip angle. More than 700,000 ionograms and 40 path-years of data are included in the data base. Table 1 is a listing of sounder sites including their geographic and geomagnetic coordinates.

Table 1

Transmitter and Receiver Locations for the Propagation Experiments

Name of Station	Operating Mode: Transmit (TX) Receive (RX)	Geographic Latitude (Degrees)	Geographic Longitude (Degrees)	Magnetic Latitude (Degrees)
Churchill	RX	58.75 N	094.00 W	73
Fairbanks	RX	64.83 N	147.83 W	65
Iqaluit	TX, RX	63.75 N	068.50 W	74
Inverness	TX	57.67 N	003.57 W	54
Jan Mayen	TX	71.00 N	008.05 W	67
North Carolina	RX	36.45 N	077.67 W	49
Pene Grande	TX	40.52 N	003.75 W	35
Puerto Rico	TX	18.45 N	067.07 W	30
Reykjavik	TX, RX	64.15 N	021.97 W	63
San Francisco (Palo Alto)	TX	36.43 N	122.17 W	42
San Francisco (Santa Cruz)	RX	37.12 N	122.15 W	42
Stockholm	RX	59.60 N	017.07 W	55
St. Johns	TX, RX	47.57 N	052.68 W	57
Vancouver	TX	49.08 N	122.40 W	55
Wainwright	TX	52.83 N	110.85 W	62
Winnipeg	RX	49.88 N	097.17 W	62

2.0 Data Collection and Measurement Procedures

The sensors utilized for obtaining the propagation data obtained in this document were sounders employing the FMCW chirp waveform. Transmissions and receivers are time synchronized to achieve a processing gain which is exploited to enable the lowest possible power to be transmitted over the sampled paths. Complete ionograms were obtained over the 2-30 MHz HF spectrum, along with other signal parameters throughout the HF spectrum within 500 Hz sub-bands. These data were collected at a number of receiver stations and retreived for detailed statistical analysis.

The sounder receivers used in the eperiments measure the Signal plus Noise (S+N) and Noise (N) in a 500 Hz bandwidth in 100 kHz steps throughout the 2-30 MHz HF spectrum. Specifically, the S+N and N are sampled and averaged over the upper 50 kHz of each 100 kHz slice of spectrum. As the

sounder transmitter is sweeping through each 100 kHz. which takes 1 second, the sounder receiver is performing two different measurements in time sequence. All the measurements are divided into one second time frames that correspond to 100 kHz of frequency sweep. During the first 0.5 second that it takes to sweep 50 kHz, the sounder receiver is offset turned to sweep the upper half of the 100 kHz frequency spectrum while the sounder transmitter is sweeping the lower half of this 100 kHz spectral region; thus the receiver does not receive signals from the sounder transmitter during this first 0.5 second. Rather, during this time the receiver is measuring HF noise as well as interference from unwanted stations. We refer to this as noise, even though it truly represents noise plus interference. During the second 0.5 second of each frame, the receiver is synchronized with the remote transmitter and a measurement of S+N is made.

In the analysis of S+N and N, four independent samples are taken, spaced 0.1 second or 10 kHz apart. The sample amplitudes thus represent averages over the 500 Hz bandwidth, and these values are stored for subsequent analysis. Ultimately the measurements are related to a bandwidth of 3 kHz. After the 2-30 MHz sweep is completed, the resulting 280 measurements of averaged S+N and N are transferred to a personal computer and stored on a magnetic diskette.

In order to relate the sounder measurements of Signal-to-Noise Ratio (SNR) to a particular application, it is necessary to stipulate properties of some generic receiver and translate the sounder results to be consistent with that set of properties. In the analysis, which is specific to an HF Data Link communication system under development, the requisite SNRs for passing error-free data at data rates of 300, 600, 1200, and 1800 bps have been determined for a particular modem using on-air tests and with a Watterson simulator. The specific modem selected for the study typically passed 300 bps data error-free with a 0 db SNR in actual trials while the simulator results suggested that a SNR of 4 dB was required. The on-air test results have been used as a basis for the study. Since all sounder data have been preserved, and are independent of the modem selected for comparison, it is possible to look at other modems and receiver characteristics. For the modem selected for consideration herein the various thresholds used with specifies sounder transmitter power levels and data rates are summarized in Table 2.

Table 2

HF System Data Rates Associated with SounderTransmitter Power Levels and Requisite Values of (S+N) /N Measured by the Sounder receiver

Data Rate (bps)	Sounder Transmitter Power Level (Watts)	(S+N)/N Threshold Level (dB)
1800	100	18
1200	100	14
300	100	8
1800	10	8
1200	10	5
300	10	3

3.0 Method for Estimation of Link and Star-Net Availability

To evaluate the fractional unavailability (U) of a channel under prescribed conditions one evaluates the number of number of instances for which the SNR thresholds described in Section 2 are not exceeded and divides this value by the number of opportunities over the reckoning period. The availability (A) is thus given by 1-U. To estimate the impact of frequency diversity over the specified channel, account is taken of one or more frequencies before the exceedence measure is made. This may be carried out using preselected frequency bands selected from a particular service, or a subset of these frequencies as determined by operational constraints. The highest possible link availability is deduced under the assumption that all frequencies within a particular service are allowable for use.

The impact of station diversity may be deduced from the data base through examination of selected star-nets which are defined by a central receiver node (i.e., clusterhead) and two or more connecting paths from distant transmitters. Candidate clusterheads are those in Table 1 which have the operational designation RX. From Figure 1, the associated links for each clusterhead may be seen. Experience has shown that station diversity gain increases monotonically with the number (N) of transmitting stations serving a clusterhead but with diminishing returns. Provided transmitting nodes are distributed over widely separated paths, a strategy with reduces the correlation of the SNR fluctuations, it is found that a practical value for N is 3 or 4. Accordingly the present analysis has fixed the largest value of N to be 4. This is convenient, since the data collection procedure involved the sampling of up to 4 paths at each clusterhead with a duty cycle of twice per hour.

4.0 Experimental Conclusions

There are a number of conclusions which have been reached based upon the data collected during the Northern Experiment, and the analyses which have been carried out. The major conclusions are given below. Some flow directly from axiomatic principles of HF propagation and the ionospheric interaction.

4.1 <u>On Spectrum</u>: Adequate spectrum must be available to achieve optimum connectivity, whereas the conditions for adequacy will ultimately depend upon factors such as traffic loading. Present studies have shown that communication availabilities approaching 100% may be achieved provided one has access to four widely-separated ground stations, and can select from among a pool of frequencies residing in a sufficient number of bands distributed across the HF spectrum, wherein the selections are dynamic, based upon real-time sounding. The studies indicate that 8 frequencies are generally adequate, and this should apply directly to the fixed service, since the measurements were derived from a fixed constellation of sounders. However, the condition for adequacy may require additional frequencies during disturbed conditions, and most certainly when the number of diversity paths is reduced, or whenever ionospheric correlation distances are increased. Similar arguments obtain for the mobile services, although mobility may enhance diversity advantage as a result of the temporal variation of propagation geometry. Since there are 11 aeronautical-mobile bands and only 8 maritime-mobile bands, it is clear that the achievement of maximum availabilities using frequency diversity is more limited in a maritime-mobile environment than in an aeronautical-mobile environment. However, this disadvantage is generally restricted to periods of increased ionospheric variability.

4.2 <u>On Network Topology</u>. Star networks have been examined in considerable detail. In the following discussion it is assumed that each node in the network is comprised of transmission and reception

capability. Based upon the principle of space diversity, it is found that HF connectivity between a central node (i.e., clusterhead) and the sorrounding cluster of external nodes is improved substantially if the cluster population is increased. Conditions will modulate the numerical size of the cluster but it has been shown that four stations are fairly optimum if the geometry is specified properly. In the data collection campaign which served as the basis for the study, the clusterheads are receivers and the external nodes are transmitters. Propagation reciprocity is assumed.

The cluster (i.e., network) connectivity is enhanced if the correlation between the paths linking the clusterhead and the other nodes in the cluster is low. The other condition is that the paths being cross-correlated are viable, since low correlation is always possible if one or both of the paths do not permit propagation. This principle suggests the following strategy for selection of cluster members: (a) association of paths having widely separated control points, (b) 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. This suggests, for four circuits in the cluster, that the region defined by great circle paths connecting the transmitting nodes should be selected to "box-in" 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, one should strive for specification of equatorward circuits with as much diurnal separation as possible. Two or more separated equatorward circuits might be part of the mix. The poleward (or northward, in the case of the Northern hemisphere) path may be of any length, while the equatorward path should be as long as possible without coming too close to the equatorial anomaly crest.

An overall regional or global network may consist of an assembly of subnets or clusters. Ionospheric properties at the clusterheads and at other nodes in each cluster are evolving. For fixed services, in which the clusterhead is stationary, the evolution results from ionospheric variability. For mobile services, the clusterhead may be in motion, and this make the situation more complicated. Frequencies which were once optimum will not remain so for very long. The outage duration for paths in the Northern Experiment has been monitored and these data indicate persistence which increases with magnetic activity; this might be troublesome unless steps are taken to enhance the level of space diversity. It also points to the importance of dynamic management of network resources, including the swapping 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 Es is recognized as a summer daytime phenomenon for midlatitudes, Northern Experiment data shows that Es bands due to the auroral zone may be used to circumvent F region propagation disturbances.

4.3 <u>On Midlatitude Implications</u>: The characteristics and principles described above will lead to performance of an HF data communication system approaching 100% for midlatitude subnets (i.e., star-nets) provided the following is true: that 4 external nodes are potentially available for each clusterhead, that 8-11 frequencies uniformly distributed throughout the HF band are specified, that frequency pooling is allowed, and that dynamic frequency management is utilized. This has been shown experimentally for a midlatitude cluster of circuits which exhibited sufficient diversity to overcome the effects of a large magnetic storm. It is clear that the presence of sporadic E will be a major deterrent to communication outage at midlatitudes during ionospheric storms, for which the F-region is greatly denuded, and a successful frequency management subsystem must account for Es dynamically.

4.4 <u>On High Latitude Implications</u>: For high latitudes, the principles which have been identified in 1-4 above apply equally well. However, the underlying unavailability statistics for individual links may be

unsatisfactory in this environment. While station diversity was certainly useful in increasing the network availability in the midlatitude region, it is clearly essential at high latitudes. Using full-band sounding as a driver for dynamic frequency management decisions, one may derive a solution which approaches the optimum. Unavailabilities based upon 4-circuit clusters are generally unacceptable if predictions are used to drive the frequency selections in the face of disturbed conditions. If full-band sounding is employed, worst-case unavailabilities of roughly 5% were observed for high latitude clusters even though the SPs which were specified do not appear to be optimized. It is anticipated that long-term average availabilities approaching 100% may also be achieved if diversity is used in an optimal fashion, and if dynamic station and frequency management strategies are employed. Sporadic E appears to be a persistent feature of the high latitude region, and it generally operates as a positive influence on the communication performance. Available models provide only limited guidance in connection with sporadic E presence, and this implies that observation must be employed to take advantage of the phenomenon.

4.5 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 MOF (viz., the maximum observed frequency for a specified circuit) from the MUF (i.e., the predicted median value of the maximum frequency for the same circuit). Enhancements in the MOF are associated with the initial positive phase of the magnetic storm, while longer lasting diminutions in the MOFs are closed associated with the negative phase of the magnetic storm. It is the longer term MOF diminutions which are the most deleterious as far as HF communication is concerned. These storm-time effects are most pronounced at midlatitudes. Because magnetic storm effects occur over such a vast area and 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.

While magnetic storms give rise to obvious MOF variations, there are also identifiable MOF fluctuations associated with elevated values of magnetic activity as represented by indices such as Ap, the planetary magnetic activity index. These may be associated with an increase in the number and magnitude of Traveling Ionospheric Disturbances (TIDs) which originate in the neighborhood 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 oblique-incidence sounders.

It is also well known that magnetic activity is correlated with a descent of the various circumpolar features, including the midlatitude trough and the auroral oval. The oval thickens and moves equatorward as Ap increases, and these features contract as Ap becomes smaller. This is important since a fixed circuit may alternatively be defined as trans-polar, trans-oval, trans-trough, or some combination of these based upon the time-varying location of the indicated features. The significance in these definitions lies in the fact that the propagation effects, and hence the variability of the circuits for the different regions, are associated with different geophysical regimes. In sum, the impact of magnetic activity may be to modify the geophysical regime, and thus the variability profile, for a fixed circuit. The rules whereby one translates the location of the circumpolar features based upon a specified value of Ap, for example, is not precise. Again, the use of real-time ionospheric specification (RTIS) such as oblique-incidence 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 will involve the marriage of a constellation of sounders, selected

solar-terrestrial data from utility programs such as SPIDR, and other RTIS resources available over the World Wide Web. 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.

4.6 Advantages of Real-Time Sounding over Prediction Methods. Prediction methods have long been used to specify frequency lists for adaptive HF systems. Programs such as IONCAP and other derivatives are examples of methods which have been used. Since these codes represent only the median behavior of propagation parameters, there are variations between actual observation and the model predictions. Because of this, there has developed a cottage industry in which models are improved by the application of "updates". Early methods used vertical and oblique sounder data sets. So-called pseudoflux methods have been used with some success, and there now exist schema 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: (a) the time interval between measurement and application of result, and (b) the proximity of the updated model result to region of interest. The latter factor is dependent upon the density of update sources, while the latter is dependent upon the response time of the network upon receipt of frequency management information. That updates lose value rapidly is well-known. We would normally prefer to apply updates within an hour or less to achieve the maximum benefit, although this value varies with the state of variability. After several hours, an update process yields limited if any improvement over median representations for which updates have not been applied. Thus prediction methods may be used if the system response time is very slow. However if the response time is immediate, there are clear great advantages to the application of Real-Time Channel Evaluation methods (RTCE), a general methodology which contains oblique sounding as a subset.

Figure 2b clearly illustrates the advantages of RTCE (viz., oblique sounding) over prediction methods. The simulated service was HF data link, and the required SNR for a stipulated grade of service was specified. (See Section 2 above.) The example shows how IONCAP performs as compared with actual observation derived from an oblique sounder system. Both frequency management systems had access to eleven frequency bands, and communication was deemed to be a success if the measured SNR 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 oblique sounder identified a viable frequency band not included among the three selected by the prediction system.

5.0 Long-Term Availability Determinations

The following discussion refers to a consolidation of availability assessments for a period of time between December 1994 through October 1995. These availabilities correspond to a rate of 300 bps, which is the baseline rate considered in the analysis. Four clusters have been examined in some detail. These are represented by clusterheads at Churchill, Iceland, Tors Cove, and a site in North Carolina. From Figure 1, we can see to which four external nodes the clusterheads are connected. The four clusterheads which have been selected involve an admixture of paths. For convenience, we may characterize the clusterheads and their associated clusters of paths as polar, auroral, trough, and midlatitude, assignments which are based upon representative geophysical regimes which may be

involved. It should be noted that no cluster is characterized by the admixture of paths in a single geophysical regime. This is intentional, since a well-designed system is one for which diversity is to be stressed. Accordingly, Churchill, Iceland, Tors Cove, and North Carolina may represent polar, auroral, trough, and midlatitudes respectively; but association of a specific cluster with a geophysical regime does not imply that all of the paths correspond to that regime, only that the clusterhead is located at a position characterized by that regime.

The average availability is deduced under the following condition. It is asserted that connectivity is established if any one of eleven preselected bands will pass a prescribed SNR test reckoned at the clusterhead for passage of 300 bps messages over any one of the four paths in the star-net or cluster. One is really deducing service availability. Figure 3 is a chart showing the monthly-average availabilities and composite service availability for each of the selected clusters of paths. It is seen that that the least reliable cluster is Churchill (polar) with gradually improving availability arising for Iceland (auroral), Tors Cove (trough), and North Carolina (midlatitude). There are also certain months with low availabilities for selected sites. For example, the lowest value for Churchill is in December 1994, the lowest for Iceland is in May, the lowest value for Tors Cove is in October, and the lowest value for North Carolina is in June. Thus we see little seasonal consistency in the data base.

Despite the fact that there appears to be no seasonal pattern in the data base, it is reassuring to see that the network or cluster-average service availabilities obey a simple rule of monotone improvement with decreasing geomagnetic latitude. Still one might have expected a cluster labeled "auroral" to exhibit somewhat poorer performance than a cluster labeled "polar". A strictly polar communication path should exhibit fairly stable availability despite the generally lower MOFs, except in the presence of polar cap absorption events. However, a major reason that the Churchill cluster has a lower availability than the Iceland cluster is that the former generally consists of three transauroral and 1 polar-polar path whereas the Iceland cluster consists of 2 midlatitude and 2 transauroral paths. The Tors Cove cluster is generally represented by a trough-auroral path, a trough-trough path, a transauroral path and a midlatitude path. The North Carolina cluster is generally represented by 3 midlatitude paths and 1 transauroral path. Again, we must emphasize that the geophysical regime representations depend upon time of day, magnetic activity, and other factors which relate to the dynamic nature of the various circumpolar features.

It is observed that the Churchill cluster never exhibits a month in which the service availability is 100%. Iceland exhibits 3 months out of the 11 analyzed for which the availability is 100%. Tors Cove exhibits 4 months having 100% availability out of 9 analyzed, and North Carolina exhibits 5 months with 100% availability out of 10 analyzed. It is noteworthy that August provided the highest composite availability: 100% for North Carolina, Tors Cove and Iceland, and the highest computed monthly value for Churchill: 0.9993. The overall composite availability for August for all four sites was 0.9998.

Given the low values for unavailability (i.e., 1-A), individual outages have been examined. Almost all the outages were in the 0500 to 1300 LMT sector (reckoned at the clusterhead). In fact there were only 5 outages in all of the data collection interval for the period 0500-1300 LMT. The availability in the 16-hour period 1300 to 0500 is approximately 0.99993 based upon the number of possibilities for failure during this temporal epoch. On the other hand, the composite average availability for the 8-hour period from 0500-1300 LMT is reduced to about 0.988 Clearly this will have important implications for frequency management for the ultimate HF data communication system

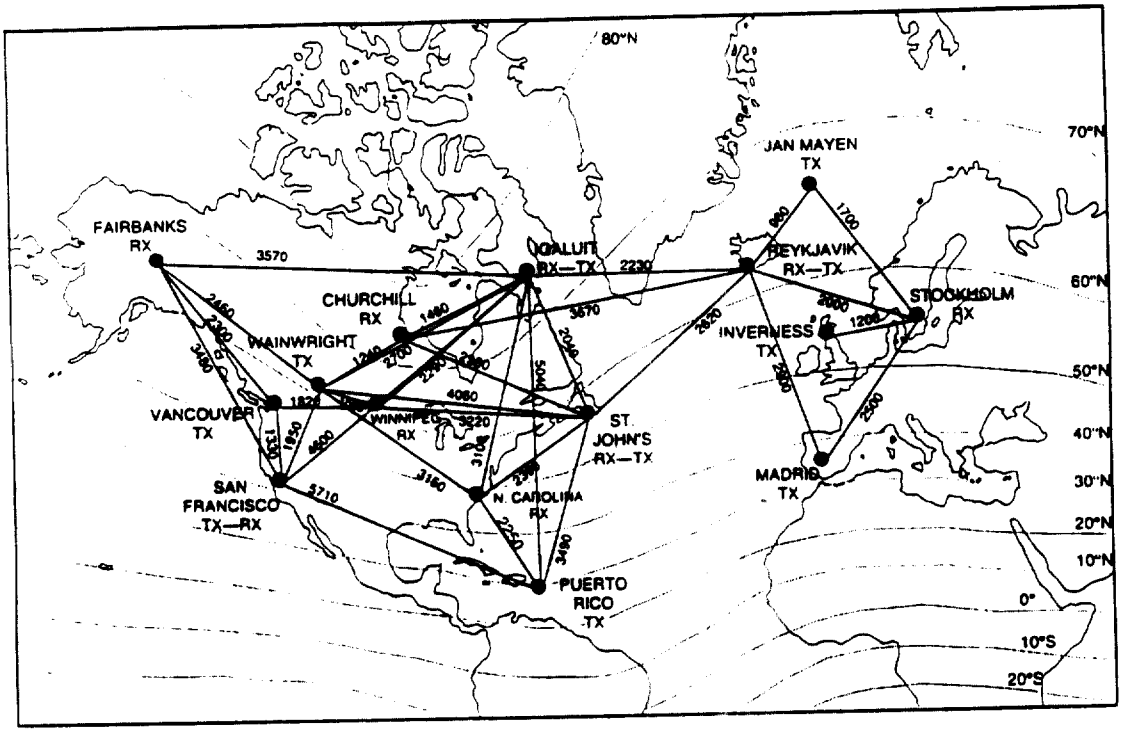
6.0 Real-Time Dynamic Map of the Ionosphere for HF Communication Assessment and Forecasting

A dynamic ionospheric map and HF propagation forecasting capability is being developed based upon near-real-time data extracted from oblique sounder instruments. However, the general concept embodied within the method is not dependent upon the exact form of the ionospheric data which is used for updating specified baseline climatological predictions, the process which turns predictions into forecasts and/or assessments , as the case may be. It is anticipated that this capability could be the driver for a real-time resource and frequency management subsystem for a variety of rergional or global HF communication systems. The system builds upon existing climatological models but incorporates data from a variety of other sources in formulating real-time maps of HF parameters. In short, the suggested forecasting scheme provides current information about ionospheric weather, whereas models such as IONCAP and VOACAP provide information about ionospheric climate. Planned deliverables include frequency assignments and related resource management data derived from real-time ionospheric assessment, and short-term forecasts based upon tailored algorithms for spatial and temporal extrapolation of data. Data sources include, but will not be limited to the following: the terrestrial network of oblique sounders, the complement of solar-terrestrial data from NOAA via the Internet, and MOF data from sounder receivers deployed on a variety of mobile platforms.

7.0 Summary

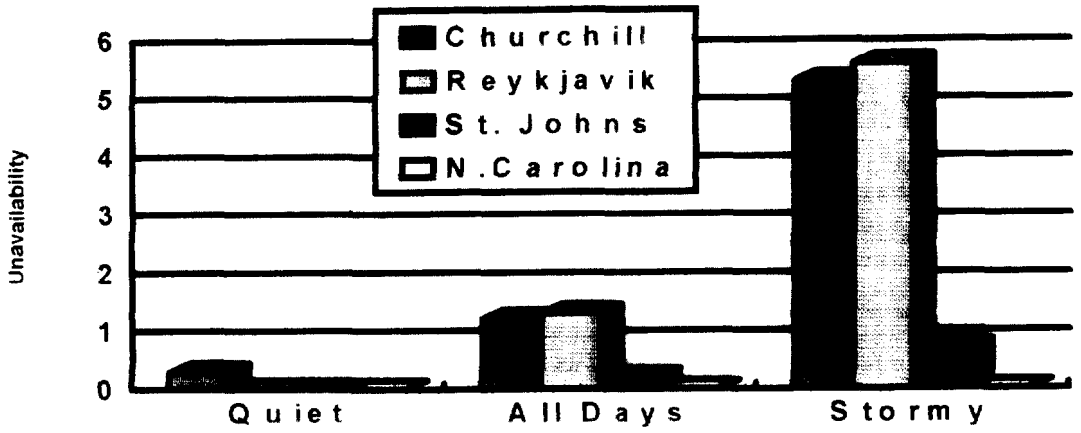
A study of link and network availability has been carried out based upon oblique sounder observations over an extensive region in the Northern hemisphere for approximately a year. The measured propagation conditions have been applied in an analysis of HF digital data link performance based upon a specific system design specification. Nevertheless the general conclusions will not change. It has been concluded that space and frequency diversity will enable the normally unsatisfactory ensemble of HF channels to be be utilized effectively to provide an HF communication service with long-term average availabilities approaching 100%. It is observed that average availabilities decrease as the network clusters migrate to higher geomagnetic latitudes. Daily and monthly variations are observed as well. There is also a striking diurnal influence on average availability, with very little limit on the performance for netted HF data communication service between 1400-0400 LMT at the clusterhead position.

It is emphasized that this result represents the very best that may be achieved under conditions for which full-band sounding is available to drive a dynamic nowcasting and forecasting subsystem for resource management. Frequency sharing and dynamic reallocation is a requisite condition, but it may not be sufficient. A full suite of frequencies populating all of the allowable bands is needed to exploit the dynamic forecasting capability. The reader is also reminded that these data sets were obtained during a period of low solar activity, with only a few episodes of enhanced magnetic substorms. The resource management challenges will become more daunting as the solar activity approaches its maximum, and this will surely necessitate some greater consideration of real-time failure mode assessment and mitigation.



(DISTANCES IN KILOMETERS)

Fig.1: Geometry of the Propagation Experiments



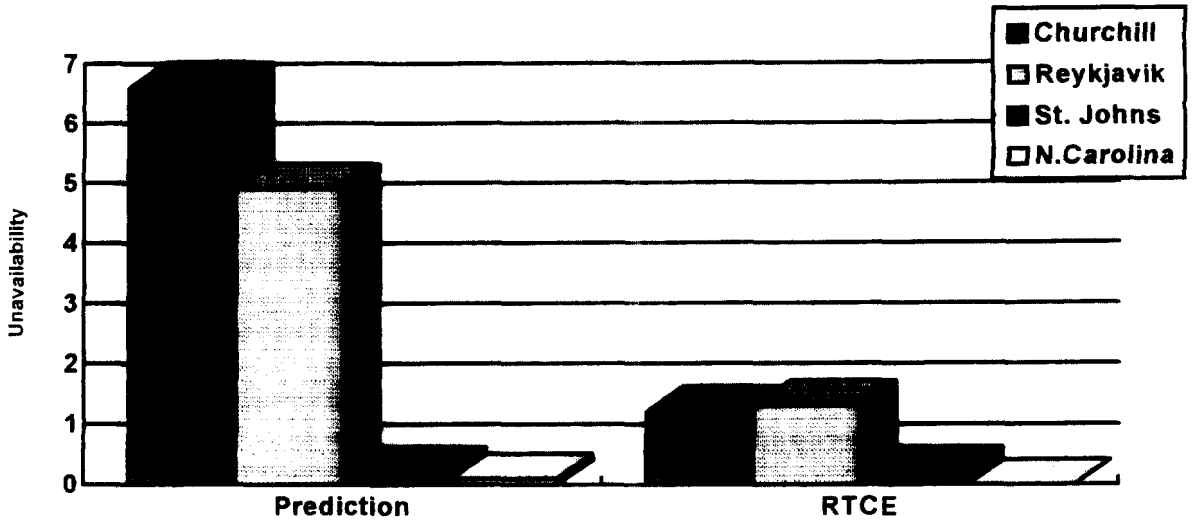


Figure 2a. (Top) The unavailability of communication as a function of magnetic activity conditions for four star-net clusters during April of 1995, a month a wide-ranging variation in the magnetic activity parameter Ap. The clusterheads are located at Churchill, Reykjavik, St. Johns, and North Carolina, 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 8, and is termed "quiet".

Figure 2b. (Bottom) The unavailability under two frequency management schemes. The scheme labelled "prediction" corresponds to the condition whereby IONCAP is utilized to preselect the three most likely frequencies for consideration. The second scheme labelled "RTCE" (viz., real-time channel evaluation) corresponds to the best frequency derived from real-time sounder measurement.

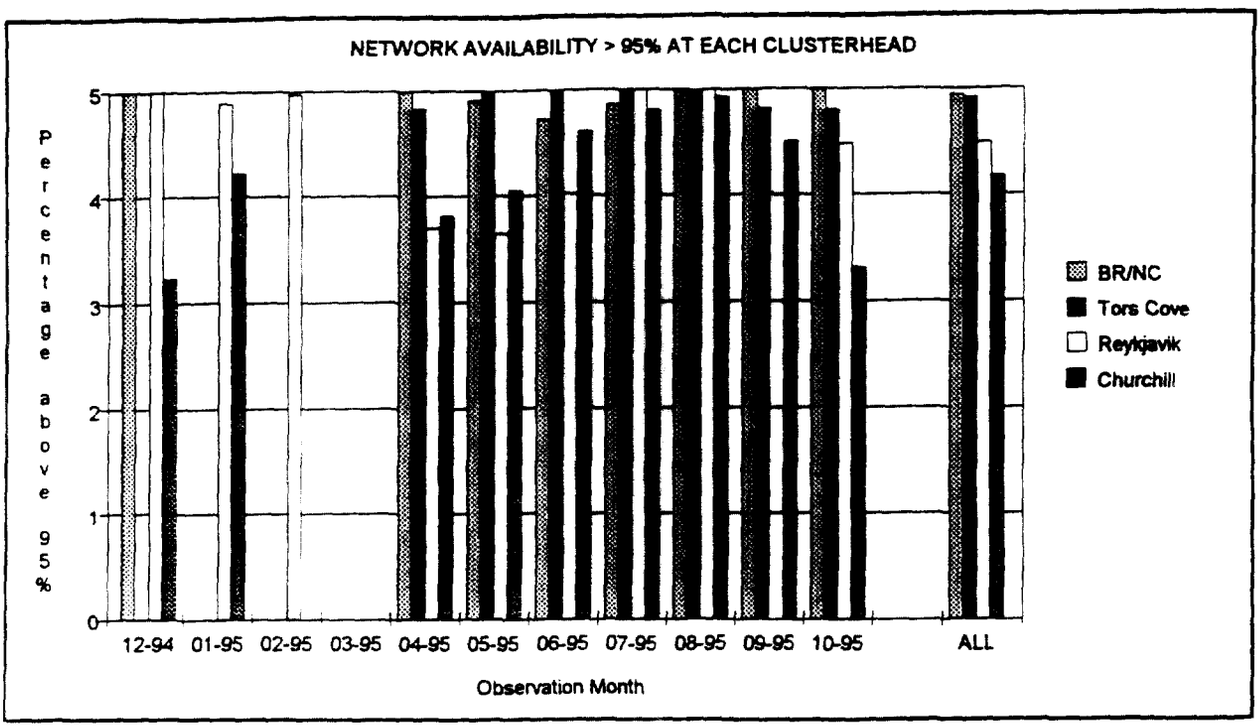


Fig. 3: Graphs of the link cluster availabilities for the Northern Experiment. The clusterheads may represent aircraft, ship, or fixed site positions, but in fact are locations of Chirpsounder® receivers. At these locations, we obtain data from four paths representing HF communication links. The clusterheads we have considered in this study are: (1) a site in northeastern North Carolina (BR/NC), (2) a site near St. Johns, Newfoundland (Tors Cove), (3) a site at Reykjavik, Iceland, and (4) a site located at Churchill, Canada. The links to each clusterhead may be determined from Figure 1. Churchill is connected to Iqaluit, Wainwright, St. Johns, and Reykjavik. Reykjavik is connected to Jan Mayen, Iqaluit, St. Johns, and Churchill. St. Johns is connected to Iqaluit, Reykjavik, Puerto Rico, and Wainwright. BR/NC is connected to Puerto Rico, St. Johns, Wainwright, and Iqaluit. Other possible clusterheads include: Iqaluit, Stockholm, San Francisco, and Fairbanks, but these four have not been considered in the current study. We have selected Churchill, Reykjavik, St. Johns, and BR/NC respectively as clusterheads for non-redundant representation of polar, auroral, trough, and midlatitude regimes, where these terms are based upon climatological average (i.e., not precise) positions. The "ALL" corresponds to a composite average availability for the entire period of observation for each cluster of links. The reader should note that the plotted availability must be added to 95% to get the total value. Thus a plotted value of 4% corresponds to 95 + 4 or 99%.