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Channel Availability for East Coast High Frequency Surface Wave Radar Systems

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Channel Availability for East Coast High Frequency Surface Wave Radar Systems

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Abstract

In support of the operation of the east coast High Frequency surface wave radar (HFSWR) systems, we carried out a continuous measurement of noise and interference data in the frequency band of 3-6 MHz at Cape Race, Newfoundland in the period between August 1, 1998 and May 10, 2000. In [3], we presented an estimation of noise factors from the measured data. In this report, we study the channel availability, in terms of channel width and channel duration, by using the measured data. The aim of this study is to find the clear channels in which we can effectively operate the radar. The results of the study indicate: (1) channels with a bandwidth of 20 kHz are readily available, and (2) the number of available and non-overlapped channels decreases quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available.

Résumé

Dans le but de soutenir le fonctionnement des systèmes de radar haute fréquence à ondes de surface (HFSWR), des mesures continues du bruit et du brouillage dans la bande de fréquences 3-6 MHz ont été effectuées à Cape Race (Terre-Neuve) entre le 1er août 1998 et le 10 mai 2000. En [3], nous avons présenté une évaluation des facteurs de bruit établis à partir des mesures expérimentales. Dans ce rapport, nous étudions la disponibilité des canaux, du point de vue de la largeur et de la durée, en utilisant les mesures expérimentales. Cette étude a pour objet de déterminer les canaux libres dans lesquels le radar peut fonctionner avec efficacité. Les résultats de l'étude indiquent : (1) que des canaux à largeur de bande de 20 kHz sont aisément disponibles et (2) que le nombre des canaux disponibles et non superposés diminue rapidement à mesure que la largeur de bande augmente. À une largeur de bande de 100 kHz, aucun canal n'est disponible.

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Executive Summary

In collaboration with Raytheon Canada Limited, the Department of National Defence has recently installed two High Frequency surface wave radar (HFSWR) systems on the east coast of Newfoundland. The two radar systems, one at Cape Bonavista and the other at Cape Race, are operated in the frequency band between 3 and 6 MHz. These systems are capable of detecting ships and low-flying aircraft over a sea surface at distances that are well beyond the horizon of a microwave radar.

However, the frequency band is often congested with signals from radio broadcast stations and HF communication users. The radar systems often encounter the problem of co-channel interference. This problem is particularly severe at night when the ionosphere supports the propagation of radio signals in the frequency band over long distances.

In support of the operation of the two HFSWR systems, we carried out a continuous measurement of the noise and interference power level at Cape Race, Newfoundland, for the period between August 1, 1998 and May 10, 2000. In [3], we presented an estimation of noise factors from the measured data. In this report, we study the channel availability, in terms of channel width and channel duration, by using the measured data. The aim of this study is to find the clear channels in which we can effectively operate the radar.

From the study, we tabulated a list of contiguously and continuously available radio frequencies. The results of the study indicate:

1. Channels with a bandwidth of 20 kHz are readily available.

2. As channel bandwidth increases, the number of available and non-overlapped channels decreases quickly. At a bandwidth of 100 kHz, there is no channel available.

3. For ship detection, three channels are available contiguously and continuously in the lower end of the frequency band: 3.00-3.01, 3.05-3.07 and 3.45-3.47 MHz. These channels have bandwidths of 20, 30 and 30 kHz, respectively. In the past, the HFSWR systems have been operated at a RF between 3.1 and 3.3 MHz. For better radar performance, it is recommended that we move the radar operating frequency to one of the available channels.

4. For aircraft detection, the HFSWR systems could be operated in the same frequency band as for ship detection. However, it is probably better to operate the radar at a slightly higher radio frequency to take advantage of the larger radar cross-section (RCS) of the targets at these frequencies. For example, the radar systems could be operated in one of the four channels that are contiguously and continuously available: 4.10-4.11, 4.18-4.19, 4.37-4.39 and 4.68-4.69 MHz. The bandwidths of these channels are 20, 20, 30 and 20 kHz, respectively.

5. The bandwidth of the available channel dictates the choice of waveform for the radar. The results above indicate that the radar is likely restricted to pulse waveforms (coded or uncoded) if co-channel interference is to be avoided.

Leong, H and Dawe, B. 2001. Channel Availability for East Coast High Frequency Surface Wave Radar Systems. DREO TR 2001-104. Defence Research Establishment Ottawa.

Sommaire

En collaboration avec Raytheon Canada Limitée, le ministère de la Défense nationale a récemment installé deux systèmes de radar haute fréquence à ondes de surface (HFSWR) sur la côte Est de Terre-Neuve. Les deux systèmes, l'un à Cape Bonavista et l'autre à Cape Race, fonctionnent dans la bande de fréquences entre 3 et 6 MHz. Ces systèmes sont capables de détecter les navires et les aéronefs volant à basse altitude au-dessus d'une surface maritime, à des distances dépassant largement l'horizon d'un radar à micro-ondes.

Il arrive toutefois souvent que la bande de fréquences soit encombrée de signaux provenant de stations de radiodiffusion et d'utilisateurs de communications HF. Les systèmes radars sont souvent exposés au problème de brouillage dans le même canal. Ce problème est particulièrement grave la nuit, alors que l'ionosphère permet la propagation des signaux radio dans la bande de fréquences sur de grandes distances.

Dans le but de soutenir le fonctionnement des deux systèmes HFSWR, des mesures continues du niveau de puissance du bruit et du brouillage ont été effectuées à Cape Race (Terre-Neuve) entre le 1er août 1998 et le 10 mai 2000. En [3], nous avons présenté une évaluation des facteurs de bruit établis à partir des mesures expérimentales. Dans ce rapport, nous étudions la disponibilité des canaux, du point de vue de la largeur et de la durée des canaux, en utilisant les mesures expérimentales. Cette étude a pour objet de déterminer les canaux libres dans lesquels le radar peut fonctionner avec efficacité.

À partir de l'étude, nous avons dressé la liste des fréquences radio contiguës constamment disponibles. Les résultats de l'étude indiquent ce qui suit :

1. Des canaux à largeur de bande de 20 kHz sont aisément disponibles.

2. À mesure que la largeur de bande des canaux augmente, le nombre des canaux disponibles et non superposés diminue rapidement. À une largeur de bande de 100 kHz, aucun canal n'est disponible.

3. Pour la détection des navires, trois canaux contigus sont constamment disponibles dans la partie inférieure de la bande de fréquences : 3,00-3,01, 3,05-3,07 et 3,45-3,47 MHz. Ces canaux présentent respectivement des largeurs de bande de 20, 30 et 30 kHz. Par le passé, des systèmes HFSWR ont été exploités à une fréquence radio comprise entre 3,1 et 3,3 MHz. Afin d'améliorer les performances des radars, il est recommandé de déplacer leur fréquence de fonctionnement dans l'un des canaux disponibles.

4. Les systèmes HFSWR utilisés pour la détection des aéronefs pourraient utiliser la même bande de fréquences que pour la détection des navires. Cependant, c'est probablement mieux de faire fonctionner le radar à une fréquence radio légèrement supérieure afin de tirer profit de la plus grande surface équivalente radar (RCS) des cibles à ces fréquences. Par exemple, les systèmes radars pourraient fonctionner dans l'un des quatre canaux contigus constamment disponibles : 4,10-4,11, 4,18-4,19,

4,37-4,39 et 4,68-4,69 MHz. La largeur de bande de ces canaux est respectivement de 20, 20, 30 et 20 kHz.

5. La largeur de bande du canal disponible détermine le choix de la forme d'onde du radar. Les résultats ci-dessus indiquent que le radar est vraisemblablement limité à des ondes en forme d'impulsions (codées ou non codées) lorsque le brouillage dans le même canal est à éviter.

Leong, H et Dawe, B. 2001. Channel Availability for East Coast High Frequency Surface Wave Radar Systems. DREO TR 2001-104. Centre de recherches pour la défense Ottawa.

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Acknowledgements

The set-up and maintenance of the spectrum monitor described in this report was part of a long-term contract awarded to Northern Radar Systems Limited between 1998 and 2000 under the scientific authority of Dr. E. Hung. The authors would like to thank Dr. E. Hung for his long-term efforts in the management of the contract.

1. Introduction

In collaboration with Raytheon Canada Limited, the Department of National Defence has recently installed two High Frequency surface wave radar (HFSWR) systems on the east coast at Cape Bonavista and Cape Race in Newfoundland. The two radar systems are operated in the lower end of the HF band between 3 and 6 MHz. They are capable of detecting ships and low-flying aircraft over a sea surface at distances that are well beyond the horizon of a collocated microwave radar.

The radar systems, however, often encounter the problem of co-channel interference. During nighttime hours, the frequency band of 3 to 6 MHz is congested with signals from radio broadcast stations and HF communication users. Techniques such as the coherent sidelobe cancellation (CSL) [1, 2] can be used to alleviate the problem. However, the residual interference after cancellation could still degrade the performance of the HFSWR.

The presence of interference is influenced by the diurnal changes of the ionosphere. During daylight hours, the D layer in the ionosphere (altitude: 50-90 km) is ionized because of the strong influx of sunlight. The D layer absorbs signals in the lower end of HF band from interference sources at long ranges. Thus, the HFSWR systems experience little or no interference during daylight hours. During nighttime hours, however, the ionized layer in the D region is neutralized due to the absence of sunlight. The signals in the lower end of HF band penetrate through the D region and are refracted off the higher layers in the ionosphere (e.g., F layer). Thus, there could be many interfering signals during nighttime hours.

In support of the operation of the two HFSWR systems, we carried out a continuous measurement of the noise and interference power level at Cape Race, Newfoundland, for the period between August 1, 1998 and May 10, 2000. In [3], we presented an estimation of noise factors from the measured data. In this report, we study the channel availability, in terms of channel width and channel duration, by using the measured data. The aim of this study is to find the clear channels in which we can effectively operate the radar.

The report is organized as follows. In Section 2, we describe the spectrum monitor system and the data measurement process. In Section 3, we provide a preliminary analysis of the measured data, and point out some of the anomalies observed in the data. In Section 4, we review the noise estimation process and the results of the noise estimation. In Section 5, we describe the methodology used to study the channel availability and present the results of the study. Finally, in Section 6, we present the conclusions and recommendations. Here, it should be pointed out that, although the noise and interference measurement was made at Cape Race only, which is only about 226 km from Cape Bonavista, the results presented in this report should be valid for both radar sites.

2. Spectrum Monitor System

The spectrum monitor[1] was set up at the center of the radar site at Cape Race (Latitude=46.65° North, Longitude=53.08° West). Figure 1 shows the location of the spectrum monitor antenna relative to the main building of the radar site and the transmit and receive antennas of the radar. The spectrum monitor antenna was a 23 foot, Shakespeare model 33, SSB fiberglass covered monopole antenna, located at a distance of about 160 feet southeast from the back of the main building. The antenna was installed with a base of 32 copper radials (#12 wire, 15 m long) as a ground screen.

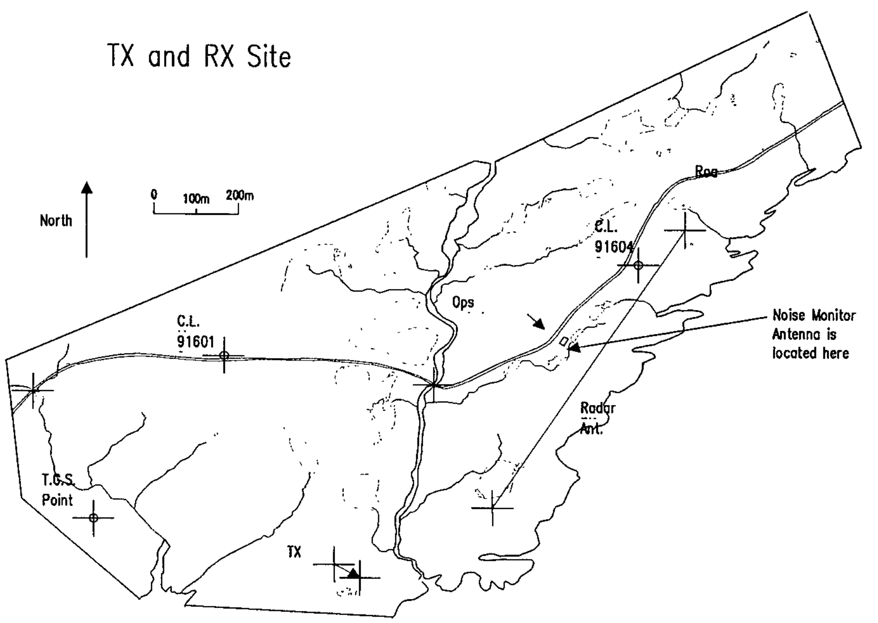

Figure 1 ***Location of Spectrum Monitor Antenna Relative to HFSWR Transmit and Receive Antennas***

Figure 2 shows the system configuration of the spectrum monitor. In addition to the 23 foot monopole antenna, the spectrum monitor system consisted of a high-pass filter, a pre-amplifier, a Rohde & Schwarz ESH3 receiver and a standard PC compatible computer system. The high-pass filter had a cut-off frequency of 1.8 MHz, and was used to reject the interference of low frequency broadcast radio signals. A mini-circuits ZHL-1A amplifier was connected as a pre-amplifier to improve the sensitivity of the spectrum monitor. The pre-amplifier provided an average gain of 18.5 dB so that the input to the Rohde & Schwarz ESH3 receiver was not internal noise-limited. The computer was connected to the ESH3 receiver using a GPIB interface, and the computer was then connected to an FTP server via an

[1] This was called noise monitor in [1] for historic reasons. Strictly speaking, it should be called a spectrum monitor as it measured both the noise and interference power level.

Ethernet interface. The measured noise data was thus available remotely from the FTP connection.

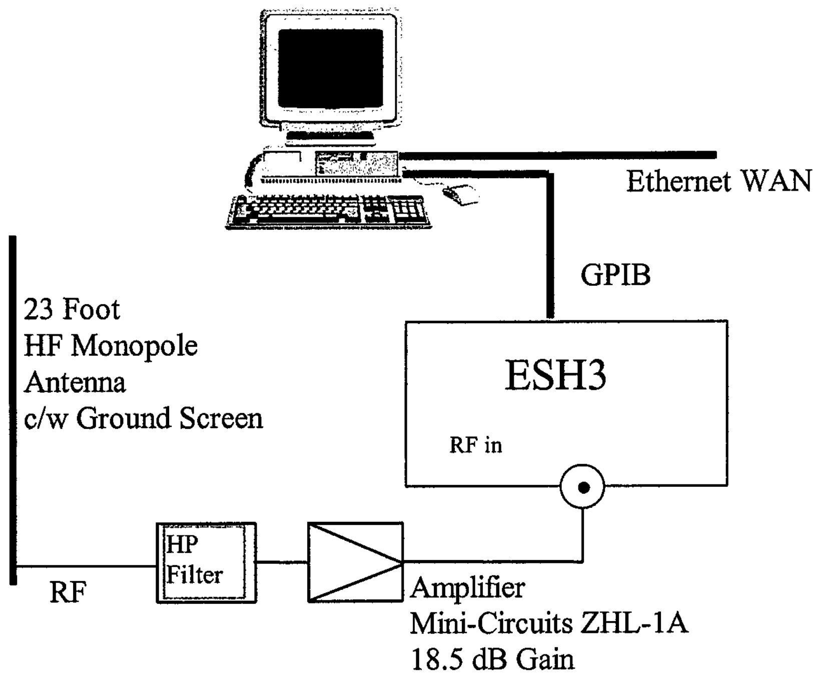

Figure 2 Spectrum Monitor -- System Configuration

The HFSWR systems at Cape Race and Cape Bonavista were nominally designed to operate at a radio frequency (RF) between 3.5 and 5.5 MHz. However, for ship detection, the radar systems were often operated at a RF between 3.1 and 3.3 MHz. In support of the operation of the radar systems, we limited the overall bandwidth of the spectrum monitor to an interval between 3 and 6 MHz. For each hour of a day, the spectrum monitor scanned the frequency band of 3 to 6 MHz with a frequency step-size of 10 kHz. Hence, we obtained an hourly measurement of the noise and interference power levels at the RFs of 3.00, 3.01, 3.02, ..., 6.00 MHz. The measurement bandwidth of the spectrum monitor was chosen to be 10 kHz. This measurement bandwidth is larger than the bandwidths of most communication signals present in the HF band. However, since the radar system has bandwidths typically in the order of tens of kilo-Hertz, it is small enough for the measurement to give an indication of the noise and interference power level expected at the radar receivers. For the measurement at each RF, the spectrum monitor used an integration time of 2 seconds, followed by a gap of 2 seconds before the measurement at the next RF. Therefore, the 301 measurements by the spectrum monitor across the frequency band required 1204 seconds or slightly more than 20 minutes. The spectrum monitor was originally scheduled to operate at the top of every hour. However, an ionosonde was later brought into operation at the radar site at Cape Race. To avoid the interference from the ionosonde, the ionosonde was then scheduled to operate at the top of the hour for about 5 minutes, and the spectrum monitor to activate at a quarter past the hour. In summary, the spectrum monitor scanned the band of 3-6 MHz once every hour and the computer automatically logged the noise and interference power measurement once per hour.

The spectrum monitor has been calibrated using a procedure described in Appendix A. This included the calibration of the monopole antenna and pre-amplifier, and the correction of the cable attenuation for different radio frequencies in the 3-6 MHz band. The output power from the spectrum monitor, p_{na}, depends on the measurement bandwidth. It can be converted into a power factor, f_a, that is independent of the measurement bandwidth by using Equation (1)

$$f_a = p_{na} / kT_0 b \tag{1}$$

where k = the Boltzmann's constant = 1.38×10^{-23} J/K
T_0 = standard temperature[2] = 290 K
b = bandwidth of the spectrum monitor = 10 kHz

In decibel scales, Equation (1) becomes

$$F_a = P_{na} - 10 Log(kT_0 b) \tag{2}$$

The output power p_{na} in Equation (1) is in Watts, and correspondingly, the output power P_{na} in Equation (2) is in dBW. The calibrated output power from the spectrum monitor is actually provided in dBmW. Hence, we need to convert it into dBW by subtracting 30 dB before we use Equation (2) to calculate the noise and interference power factor from the measured noise data.

Figure 3 shows typical plots of the Rodhe and Schwarz ESH3 scans at midday and midnight at Cape Race. In Figure 3 are the power factors, expressed in dB above kT_0b, vs. radio frequency (RF), measured on at midday and midnight on August 30, 1998. At midday, the D layer absorbs signals from other sources at long distances, and therefore, the radar operation environment is relatively quiet. At midnight, however, the D layer is absent, and signals in the HF band can propagate via skywave mode from other sources at long distances. Figure 3 clearly shows the presence of many interfering signals in the frequency band from the scan at midnight.

Figure 4 shows the hourly scans of the spectrum monitor over the 24-hour period on August 30, 1998. Here, we intentionally set all the vertical axes to the same scale. As shown in Figure 4, the radar operation environment was very quiet during daytime between 1000 and 1900 UTC. However, there were many interfering signals at night between 0000 and 0800 and between 2100 and 2300 UTC. Some interfering signals were also present during night-to-day and day-to-night transition hours at 0900 and 2000 UTC.

[2] There is a small difference in the temperature we use here and the temperature used by the International Radio Consultative Committee (CCIR) in [2]. CCIR uses a temperature of 288 K, whereas we use a standard temperature of 290 K. This difference, however, is really negligible, adding only about -0.03 dB to the measured data.

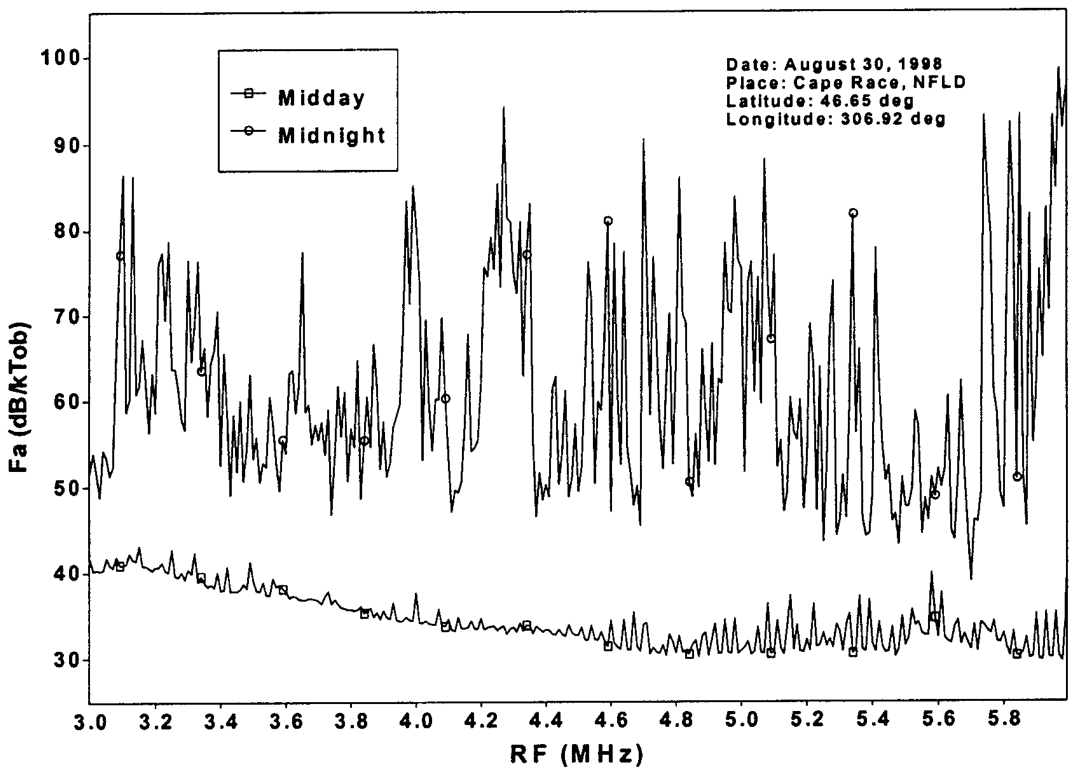

Figure 3 *Typical Plots of Spectrum Monitor Scans at Midday and Midnight at Cape Race, Newfoundland*

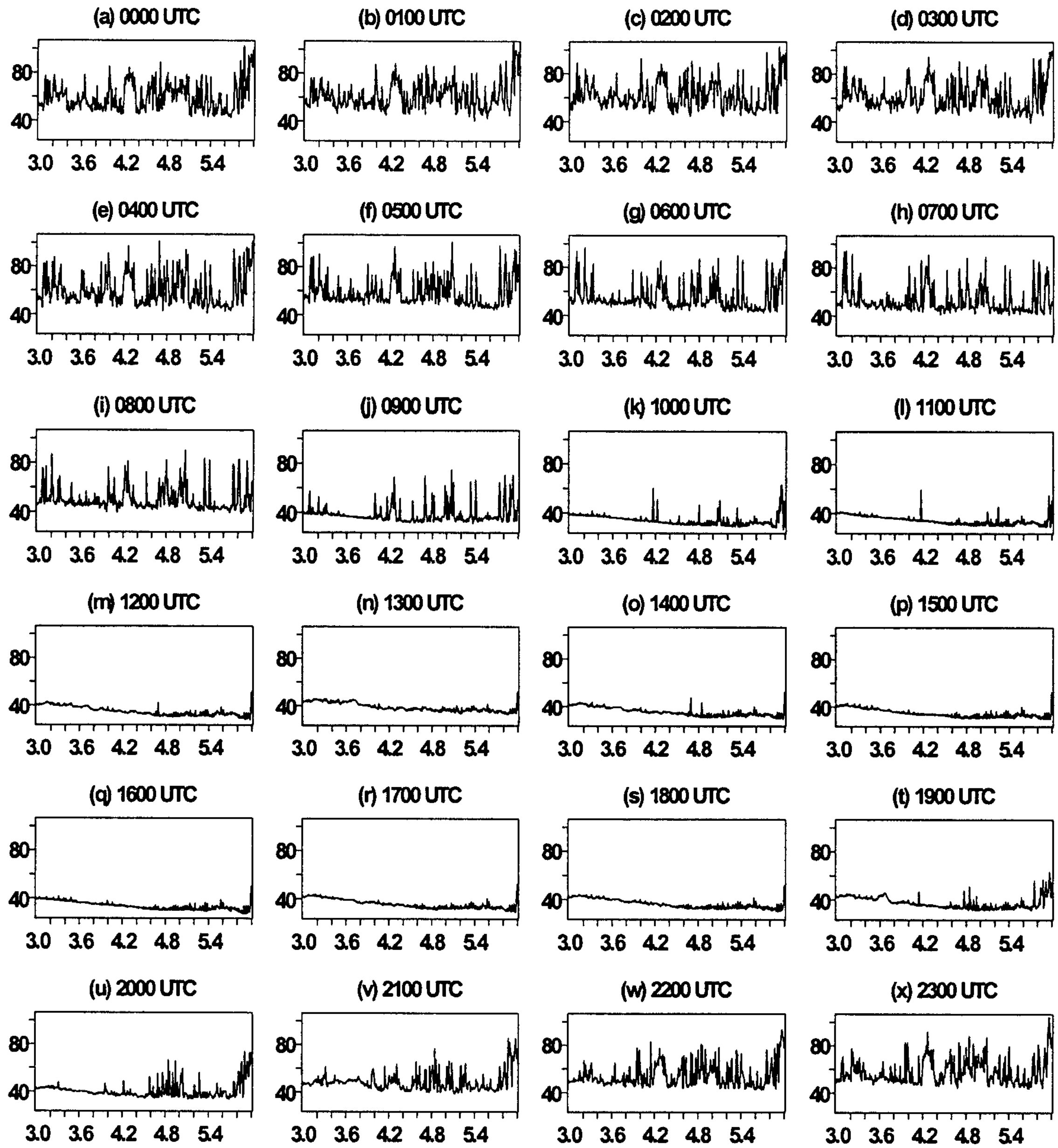

Figure 4 *Scans of Spectrum Monitor over 24 Hours on August 30, 1998 (Horizontal Axis: RF (MHz); Vertical Axis: Fa (dB/kT_0b); Vertical Axes Are All of the Same Scale.)*

3. Preliminary Analysis of Measured Data

One of the problems encountered while setting up the spectrum monitor was that the ESH3 receiver was initially internal noise-limited during daylight hours when the external noise power level was the lowest. The external noise level was simply too low to be observable in the original setup of the spectrum monitor. This problem was resolved with the addition of a ZHL-1A pre-amplifier. The pre-amplifier provided an averaged gain of 18.5 dB across the frequency band to boost up the input to the ESH3 receiver. Figure 5 shows the internal noise level of the ESH3 receiver measured with a matching 50-Ohm input resistor in replacement of the monopole antenna. This internal noise level is compared with the daytime noise level that was shown in Figure 3. As shown in Figure 5, the ESH3 receiver is now clearly externally noise-limited, and the daytime noise power level is well above the internal noise power level.

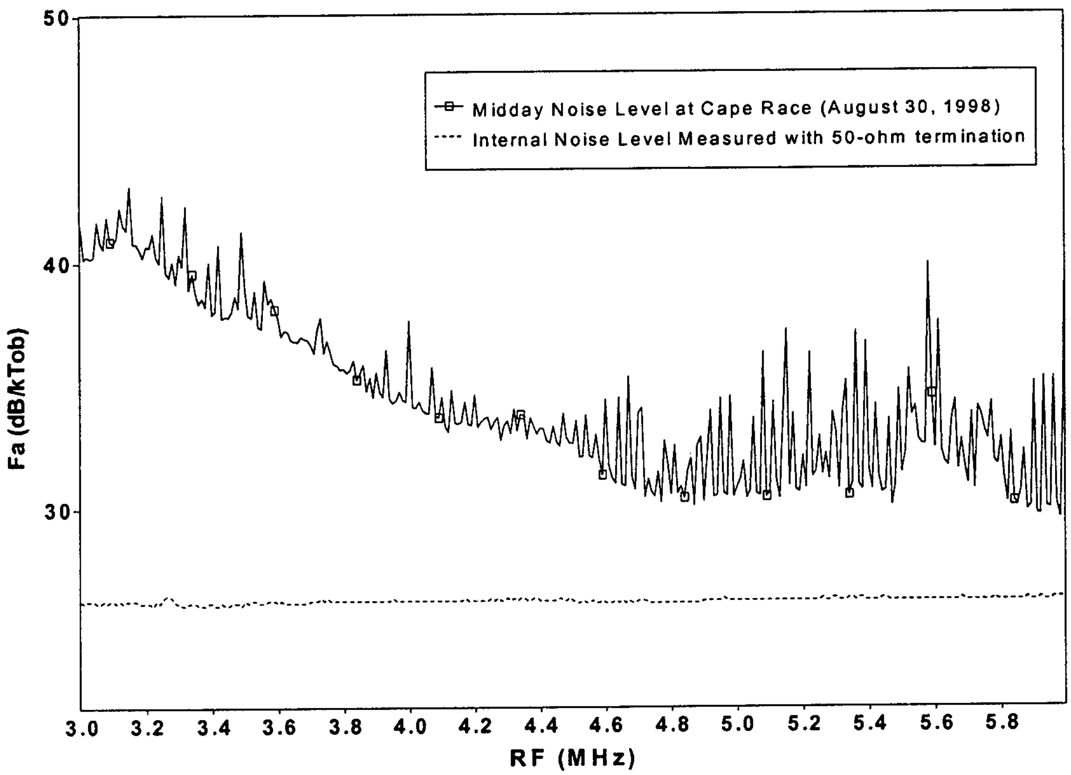

Figure 5 ***Comparison of Measured Daytime Noise Power Level with Internal Noise Power Level Measured with A 50-Ohm Input Resistor Termination***

The measured data were recorded in a computer file daily between August 1, 1998 and May 10, 2000, except during disruptions in the operation of the spectrum monitor. Disruptions could occur during power outages and testing of the radar and/or ionosonde and after damage to the system antenna due to lightning and/or thunderstorm. Occasionally, the operation of the spectrum monitor was also interrupted by hardware problems such as computer malfunction and pre-amplifier failure. The measured data had to be monitored regularly to detect all possible disruptions. In case there was damage to the antenna or other hardware problem, the spectrum monitor had to be re-calibrated after the problem was resolved. Because of the disruptions, the measured data were not available for certain dates. Table I lists the dates for which the measured data are available, together with comments on why the data are missing for the other dates.

Table 1 Spectrum Monitor Data Availability

Dates for Which Data Are Available	Number of Days for Which Data Are Available	Comments
Aug 01-23, 27-31, 1998	28	Power outage, Aug 23-27
Sept 01-24, 28, 1998	25	Hardware failure, Sept 25-27
Oct 01-13, 20-31, 1998	25	Computer and power failure, Oct 14-19
Nov 01-30, 1998	30	Temporary power outage, Nov 16 and 20
Dec 01-31, 1998	31	Antenna damaged Dec 08, 1998-Jan 13, 1999;
Jan 01-31, 1999	31	Damage detected and fixed on Jan 13, 1999.
Feb 01-28, 1999	28	
Mar 01-31, 1999	31	Power outage, Mar 19
Apr 8-9, 12-13, 28-30, 1999	7	Pre-amp failed.
May 01-31, 1999	31	
Jun 01-30, 1999	30	
Jul 01-31, 1999	31	
Aug 01-31, 1999	31	
Sept 01-18,20-21,24-25,27-30, 1999	24	Power outages
Oct 01-15, 1999	15	Pre-amp failed
Nov 03-30, 1999	28	
Dec 01-31, 1999	31	
Jan 02-31, 2000	30	Y2K shut down on Jan 01, 2000
Feb 01-29, 2000	29	
Mar 01-31, 2000	31	
Apr 01-30, 2000	30	
May 01-10, 2000	10	Operation stopped on May 10

In monitoring the data from the spectrum monitor, we observed several anomalies in the datasets. Some of these anomalies were due to the operation of the HFSWR at Cape Race at the radar operating frequencies. Others were probably due to the testing of the radar transmitter during its installation phase. Regardless their origins, we need to identify them before we carry out an estimation of noise factors and a study of channel availability with the measured spectrum data.

3.1 Anomaly Due to Radar Operation

The HFSWR at Cape Race has been operating since mid-November 1998. Initially, the radar was operated intermittently at one of the three RFs: 3.19, 3.29 and 4.09 MHz. Since November 30, 1998, the radar has been observed to operate mostly at a RF between 3.1 and 3.3 MHz. Figure 6 shows a scan of the spectrum monitor during midday (around 1515 UTC) on September 11, 1999. The radar signal could be observed at the RF of 3.20 MHz. Note that the peak at the RF of 3.5 MHz was likely a higher harmonic of the radar signal, and the strong peaks at the RFs of 5.10 and 5.22 MHz were likely radioteleprinter communication (RTTY) signals.

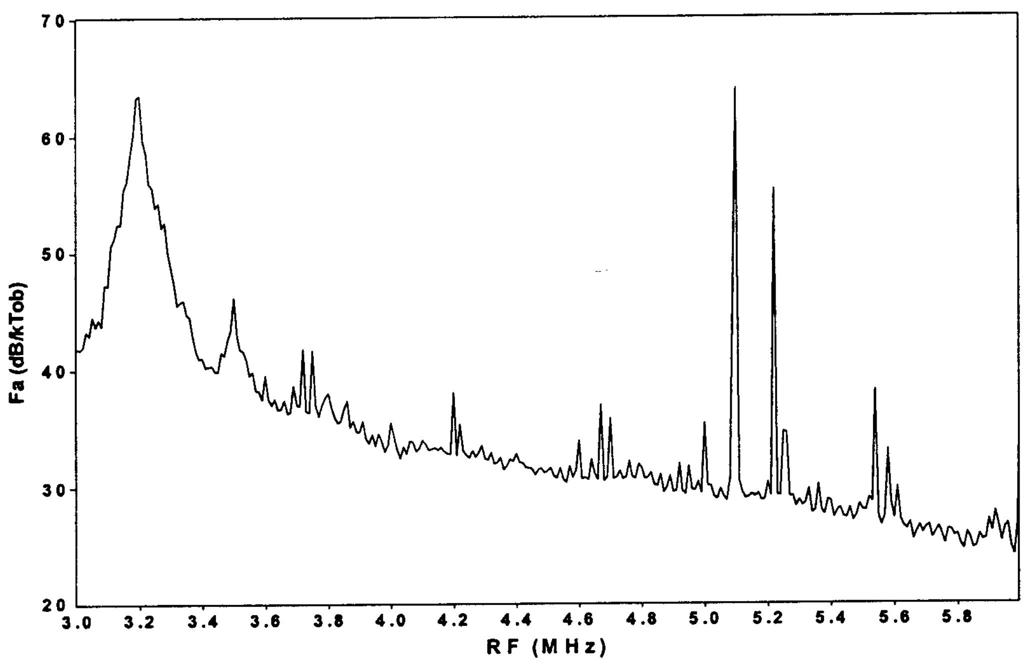

Figure 6 ***Spectrum Monitor Scan Showing Signal of HFSWR at Cape Race***

During night operation, the radar signal had to compete with interfering signals. Figure 7 shows the scans of the spectrum monitor over the 24-hour period of August 28, 1999. The radar signal could be clearly observed at the RF of about 3.29 MHz during daytime hours between 1015 and 2115 UTC. However, the radar signal was interfered with by many other signals during the nighttime hours between 0015 and 0915 UTC and between 2215 and 2315 UTC.

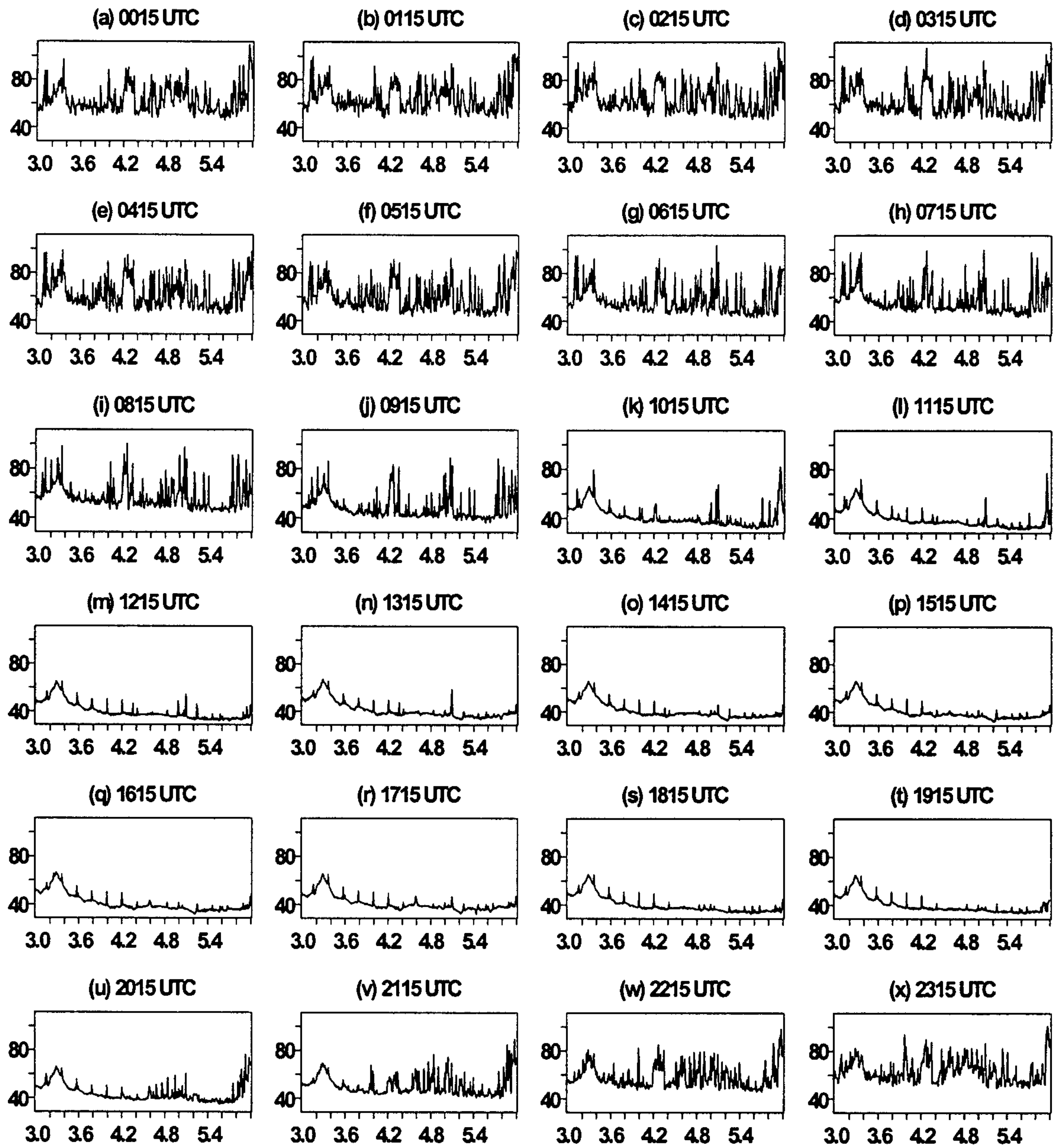

Figure 7 *Scans of Spectrum Monitor over 24 Hours on August 28, 1999 Showing Signals of HFSWR at Cape Race (Horizontal Axis: RF (MHz); Vertical Axis: Fa (dB/kT$_0$b); Vertical Axes Are All of the Same Scale.)*

3.2 Noise Spikes

Anomalous noise spikes could be observed during daytime when the external noise power level was low. In Figure 7, for example, noise spikes could be observed during the daytime hours between 1015 and 1915 UTC and at the day-to-night transition hour of 2015 UTC on August 28, 1999. While the spikes at the RF of 5.10 MHz in the scans between 1015 and 1315 UTC were verified as real RTTY signals, the others were considered as artifacts. These artifacts were thought to originate from the computer system that controlled the ionosonde. A test was carried out with the ionosonde computer system being turned off and on while the spectrum monitor was measuring data. Figure 8 shows the two consecutive scans of the spectrum monitor when the ionosonde computer was turned off and then turned on. In Figure 8(a), the noise spikes mostly disappeared when the ionosonde system was turned off. In Figure 8(b), a few noise spikes re-appeared when the ionosonde was turned on. Note that the RTTY signal at 5.10 MHz could be observed in both scans in Figure 8.

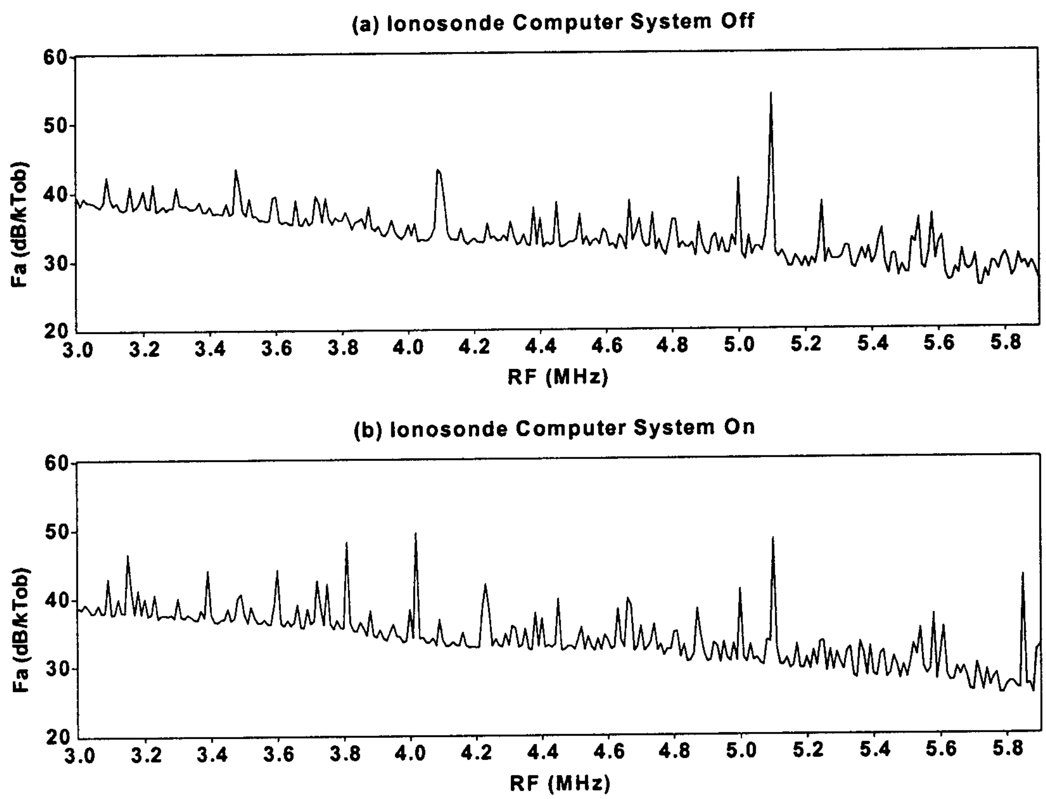

Figure 8 ***Spectrum Monitor Scans at 1515 and 1615 UTC on Dec 17, 1999 When the Ionosonde Was Turned Off and Then On***

The noise spikes may cause a bias in the estimation of noise factors, and introduce errors in the statistics of channel availability at the RFs of the noise spikes. However, since the noise spikes appear frequently in the datasets, it is unavoidable to have these bias and errors.

3.3 Anomaly Due to Radar Testing

Occasionally, broadband signals could be observed in the scan of the spectrum monitor. The appearance of these broadband signals was likely due to the testing of the radar transmitter at Cape Race. The radar transmitter was tested at that time because of its unexpectedly low gain. Figure 9 shows two scans of the spectrum monitor obtained on October 5, 1998 and May 13, 1999, respectively. In Figure 9(a), a broadband signal was observed between the RFs of 3.25 and 4.20 MHz. In Figure 9(b), two broadband signals were observed -- one between 3.08 and 3.5 MHz, and the other between 3.70 and 4.02 MHz.

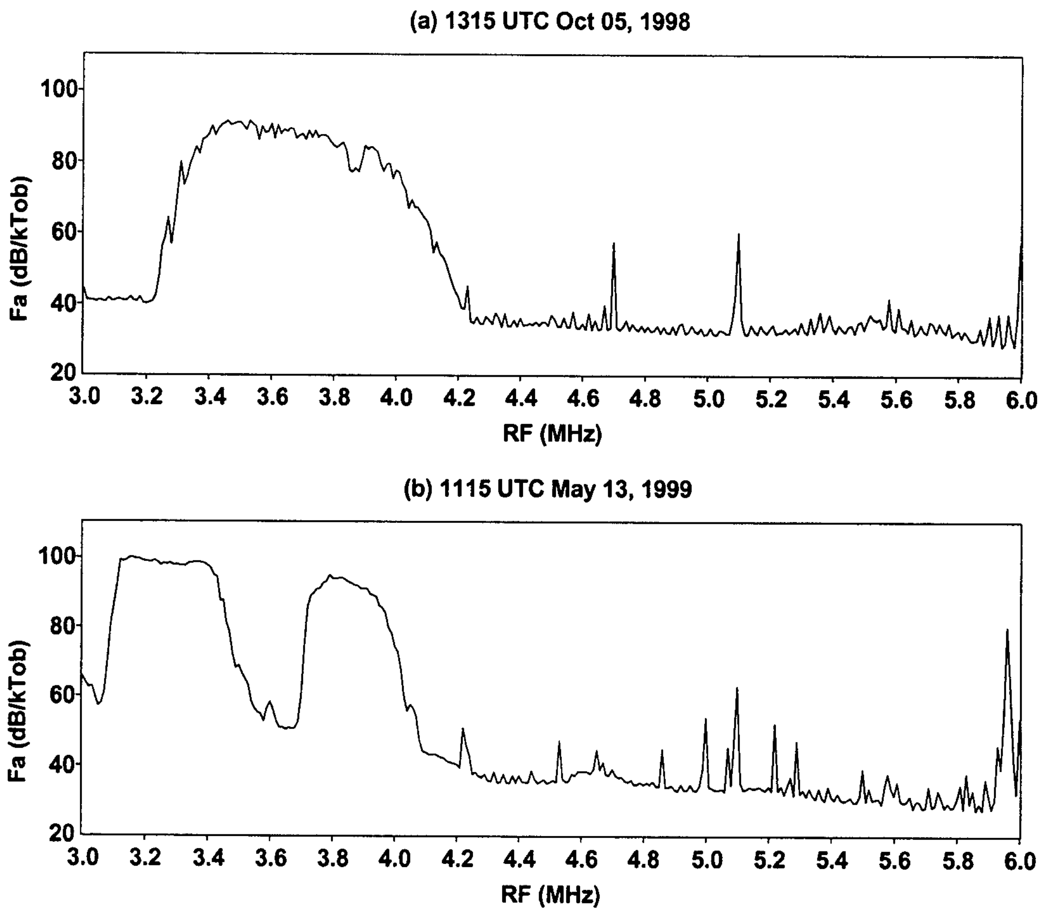

Figure 9 *Spectrum Monitor Scans Showing Spurious Broadband Signals*

The appearance of broadband signals was actually very rare in the datasets. In the estimation of noise factor and the subsequent study of channel occupancy, we could simply exclude the few datasets that contain the broadband signals. Hence, the broadband signals should not have an effect on the noise factor estimation and the channel occupancy study.

4. Noise Factor Estimation

The estimation of noise factors from the measured data has been reported in [3]. This estimation uses a procedure called the "minimum of median", which consists of two steps:

1. Obtain the median of the measured data at each frequency bin and at each hour of a day over a specified season of a year;

2. Take the minimum of the median over a specified frequency interval (bandwidth) to estimate the noise figure at the upper bound of that interval.

The following is the rationale for the procedure. The noise power level is known to have significant diurnal changes. Hence, we maintain the hourly variation of the noise data, and we take the median of the measured noise data at each frequency bin and at each hour of a day over a specified season of a year. By taking the median at each radio frequency bin, we also maintain the variation of the noise and interference power levels across the frequency band. However, since the interference normally dominates the external noise, and some interfering signals may appear on a nightly basis in certain frequency bins, the median would not provide a true representation of the noise floor. In order to provide a better estimate of the noise floor, we take the minimum of the median over selected frequency intervals.

In [3], we chose a bandwidth of 1 MHz for the frequency interval, i.e., we took the minimum of the median over the frequency interval of 3-4, 4-5 and 5-6 MHz, and we obtained the noise estimates at the radio frequencies of 4, 5, and 6 MHz. Here, we are more interested in the variation of the noise factor with radio frequency. Therefore, we further divide the bandwidth. We take the minimum of the median over the frequency interval of 3.0-3.5, 3.5-4.0, 4.0-4.5, 4.5-5.0, 5.0-5.5 and 5.5-6.0 MHz, and we obtain the noise estimates at the radio frequencies of 3.5, 4.0, 4.5, 5.0, 5.5 and 6 MHz.

Traditionally, the season of a year is classified as spring from March to May, summer from June to August, fall from September to November, and winter from December to February. According to this classification, we have six complete seasons of data available from Cape Race: fall and winter, 1998, and spring, summer, fall and winter, 1999.

Figure 10(a-f) shows, respectively, the estimated noise factors from the measured data for the six RFs in the six different seasons in 1998 and 1999. For all the six seasons, the noise estimates exhibit a marked variation between daytime and nighttime hours. The noise level is significantly higher at night, and drops by as much as 20 dB during daytime. Note that, in Figure 10, the time axis (horizontal axis) is expressed in universal time code (UTC), or Greenwich time. The local Newfoundland time is 3.5 hours behind Greenwich time, except during the summer daylight saving time when the local time is only 2.5 hours behind.

Here we should point out that the estimated noise factor at 3.5 MHz was biased because of the presence of the radar signal at the RF between 3.1 and 3.3 MHz. The radar at Cape Race has been operating since mid-November 1998. During daytime, the radar signal dominates over the frequency band between 3.1 and 3.3 MHz. Figure 10 shows that the daytime noise factor at 3.5 MHz was significantly higher than the other noise factors for all but the season of fall 1998. This much higher noise factor was due to the bias caused by the radar signal.

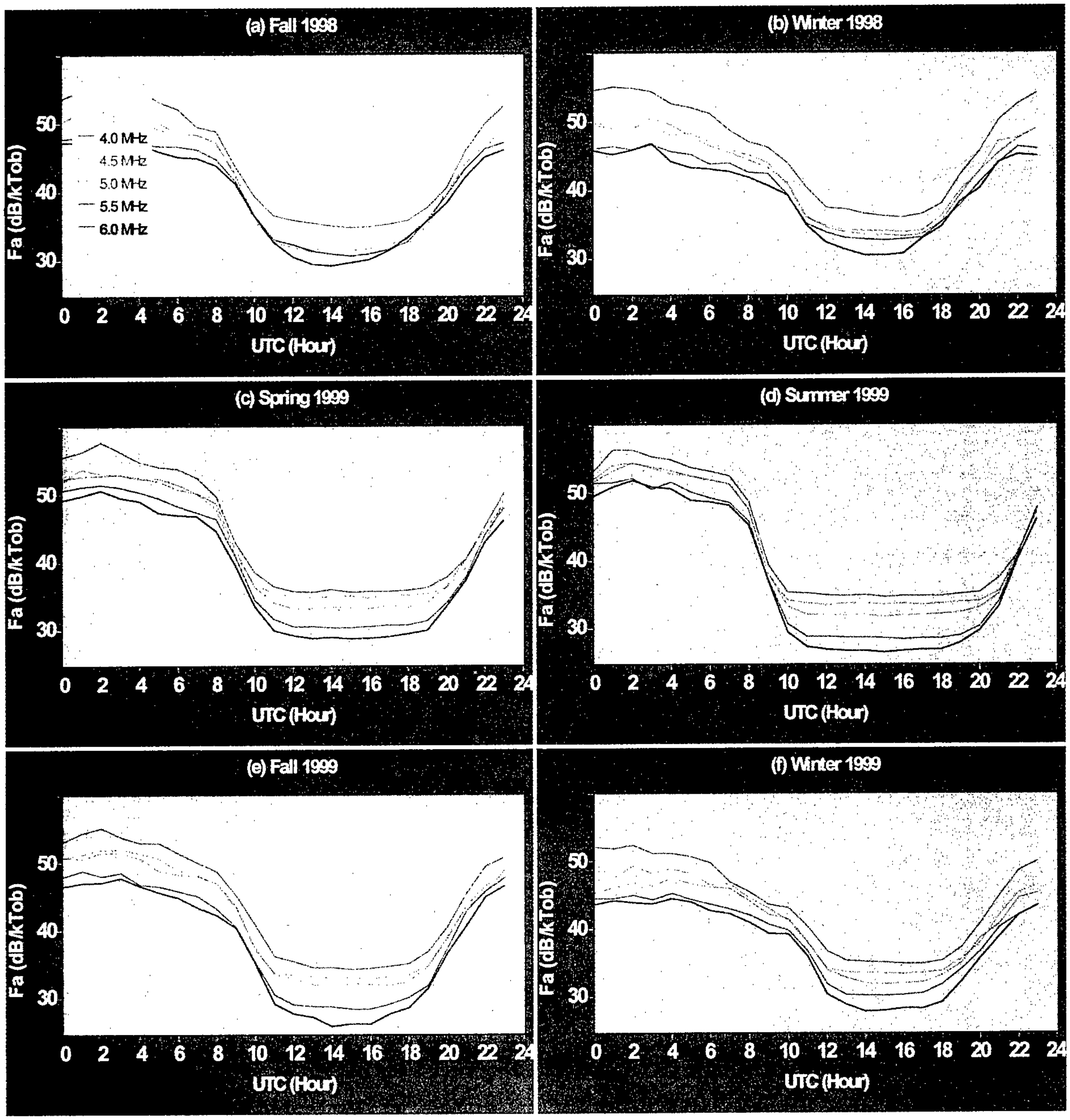

Figure 10 ***Estimated Noise Factors at the RFs of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0 MHz over Six Consecutive Seasons in 1998 and 1999 at Cape Race, Newfoundland***

5. Channel Availability

Given the noise estimates in Figure 10, we are now ready to evaluate the channel availability in the frequency band of 3-6 MHz, using the measured noise and interference data from Cape Race.

5.1 Decision Rule

At a given time (hour) of a day, we define that the channel is occupied if the measured noise and interference level is 6 dB higher than the estimated noise level (i.e., by a factor of 4). The channel width here is 10 kHz, the same as the measurement bandwidth. In Section 4, we obtained the noise estimates at the RFs of 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0 MHz. Here, we linearly interpolate the estimates between the adjacent frequencies, and use the interpolation as the estimate of the noise level at a selected frequency bin. In the frequency interval between 3.0 and 3.5 MHz, we have only one noise estimate. Hence, we simply use this estimate for the entire frequency interval.

For each season of a year, we count the number of days on which the channel is occupied. We define the probability of the channel being occupied as:

$$P_{OCC} = \frac{N_C}{N_T} \tag{3}$$

where N_C is the number of days on which the channel is occupied in a season and N_T is the total number of days on which the measured data are available in that season. Here, we exclude from N_T the days when the measured data were unavailable, the days when there were power outages or hardware failures, and the days when there were anomalous broadband signals in the scans of the spectrum monitor.

Figure 11 shows this probability of channel occupancy in the frequency band of 3 to 6 MHz at midnight and midday hours (0315 UTC and 1515 UTC) for each of the four different seasons in 1999. In Figure 11(a), we can observe that the frequency band at midnight was very much congested. Many of the channels had a probability of occupancy as high as 1. In Figure 11(b), the frequency band was mostly clear, except the peak in the lower end of the frequency band between 3.1 and 3.4 MHz and the sporadic spikes across the frequency band. The peak was due to the presence of the radar signal and the sporadic spikes were thought to originate from the interference from the ionosonde computer system. The peak and most of the spikes were really artefacts in the study of channel occupancy.

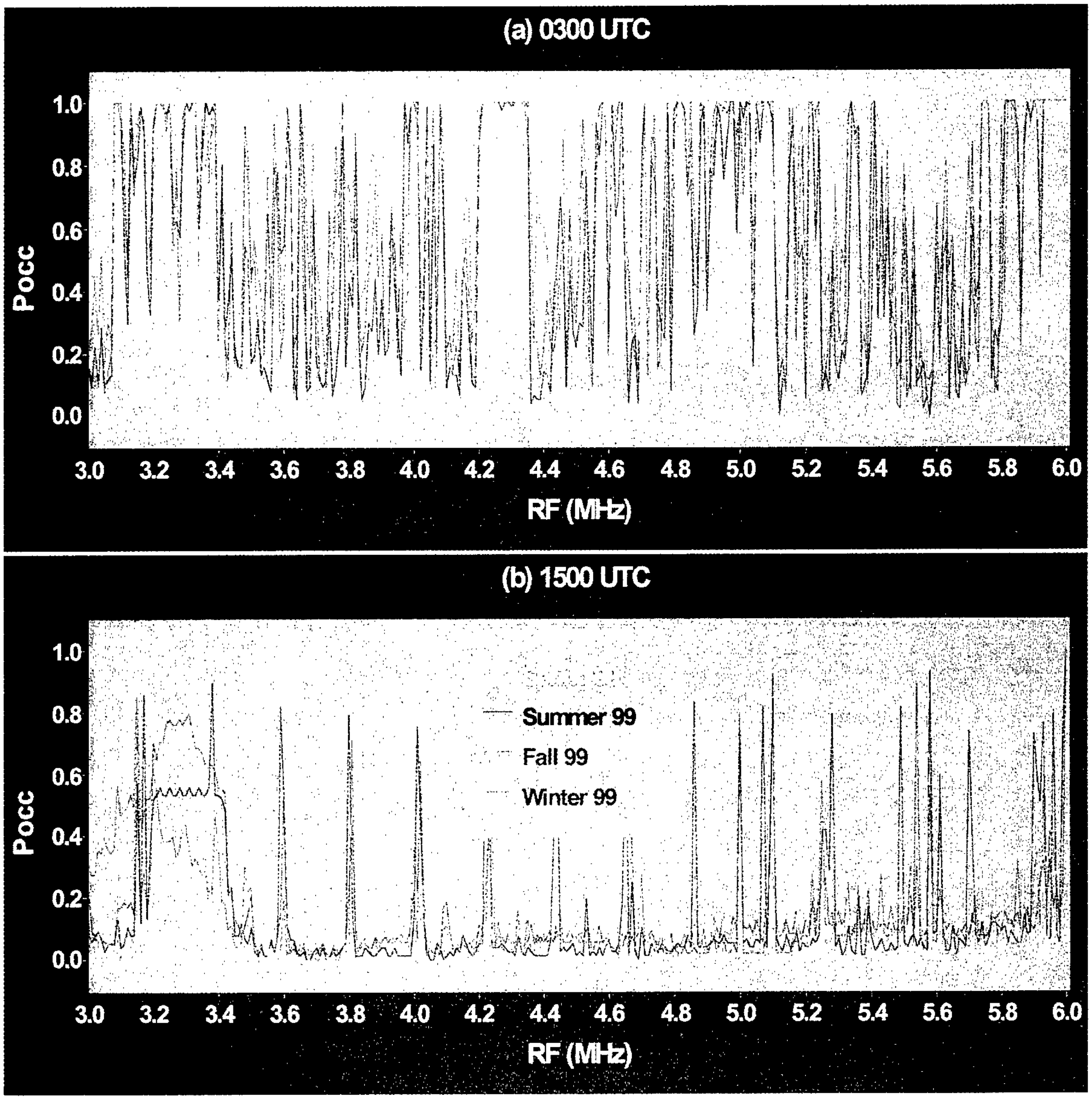

Figure 11 ***Probability of Channel Being Occupied at Midnight (~0315UTC) and Midday (~1515 UTC) over Four Different Seasons in 1999***

The probability of a channel being occupied was computed for each and every hour of a day over each of the six seasons in 1998 and 1999. To summarize the statistics, we count the number of hours for which the channel is available in a day for each of the six seasons. We define that the channel is available if $P_{OCC} < 0.5$. Figure 12 shows the number of hours for which the channel is available in any given day for each of the six seasons. From Figure 12, we can then tabulate the radio frequencies that are available continuously for 24 hours in a given day for each season. Table 2 lists these radio frequencies for the six different seasons.

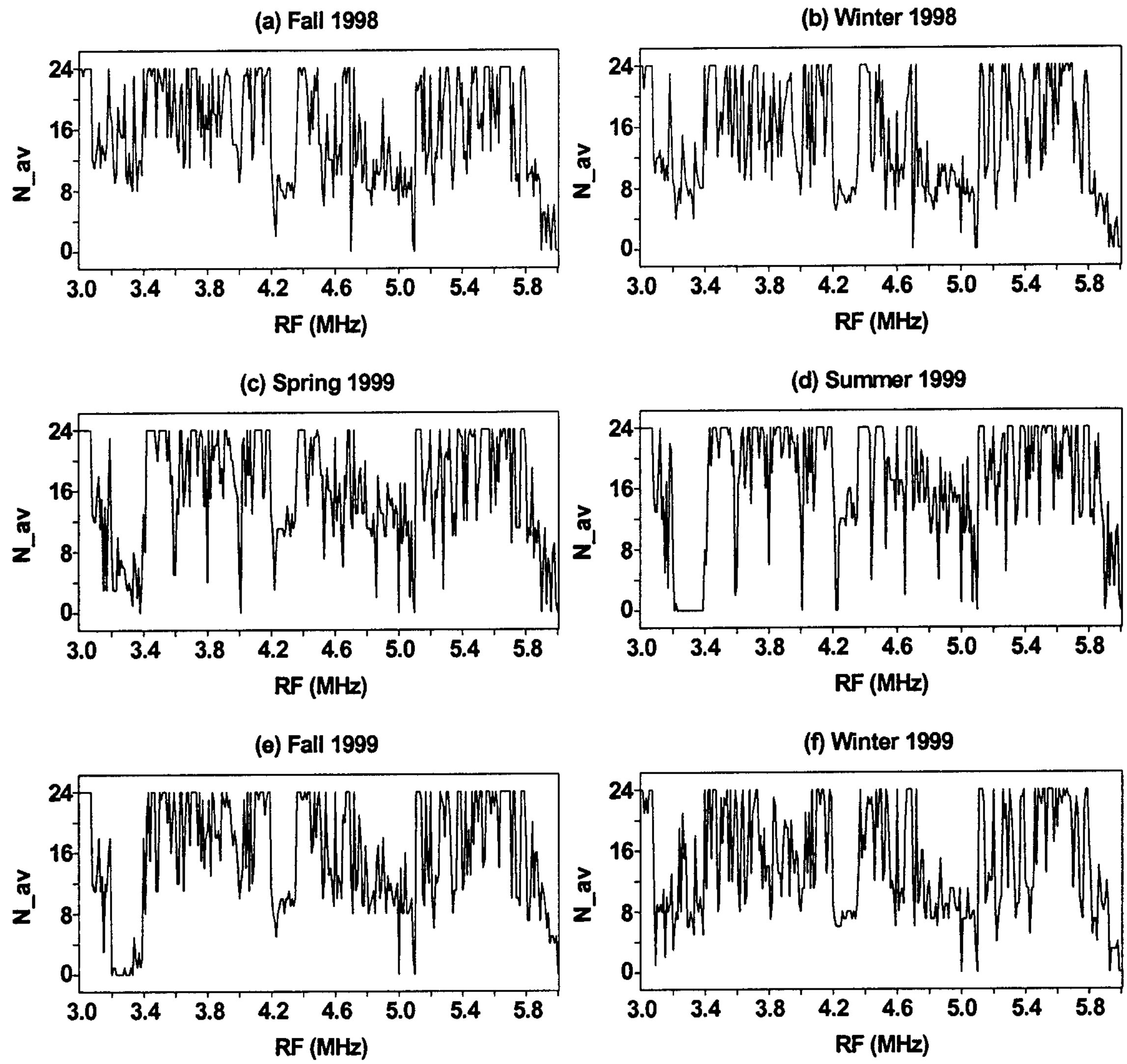

Figure 12 ***Number of Channel-Available Hours (N_av) in a Day over Six Different Seasons in 1998 and 1999***

Table 2 *Continuously Available Radio Frequencies (MHz) over Six Different Seasons in 1998 and 1999*

Fall 1998:
3.00-3.01 3.03-3.07 3.18 3.40 3.43-3.44 3.46-3.47 3.49 3.53-3.54 3.56
3.59 3.67-3.68 3.70-3.73 3.83 3.92 4.05 4.07 4.10 4.12-4.14 4.18-4.19
4.37-4.38 4.40-4.41 4.49 4.66 4.68-4.69 4.72 5.16 5.26 5.30-5.31
5.37-5.38 5.46 5.48-5.49 5.54-5.57 5.59 5.64-5.70 5.78-5.79
Winter 1998:
3.00-3.01 3.03-3.07 3.40 3.43-3.47 3.54 3.56 3.59 3.64 3.71-3.73
4.02-4.03 4.07 4.10-4.11 4.14 4.18-4.19 4.37-4.41 4.49 4.69 4.72
5.12-5.13 5.18 5.20 5.26 5.28 5.30 5.38 5.46 5.48-5.49 5.54-5.55 5.57
5.59 5.62 5.64 5.66-5.67 5.69-5.70
Spring 1999:
3.00-3.07 3.42-3.47 3.50-3.54 3.56 3.63-3.64 3.70-3.73 3.76 3.81 3.83
3.87 3.91-3.92 4.05 4.07 4.10-4.14 4.17-4.19 4.37-4.41 4.49 4.68-4.69
4.72 5.11-5.14 5.20 5.26 5.32 5.37-5.38 5.42 5.45 5.48 5.52-5.57 5.59
5.64 5.66-5.67 5.69 5.70 5.72-5.73 5.77-5.79
Summer 1999:
3.00-3.07 3.12 3.43 3.45-3.47 3.50-3.54 3.56 3.64 3.67-3.68 3.70-3.73
3.75-3.76 3.81 3.83 3.85-3.87 3.90-3.92 3.94 4.02 4.05 4.07 4.10-4.14
4.17 4.18-4.19 4.36-4.42 4.47-4.51 4.60 4.66-4.69 4.72 5.11-5.14 5.20
5.29-5.32 5.37-5.39 5.42 5.44 5.46-5.48 5.51-5.52 5.54-5.57 5.59 5.64
5.66 5.69 5.72 5.73 5.77-5.80
Fall 1999:
3.00-3.07 3.43 3.45-3.47 3.50 3.52-3.56 3.59 3.63-3.64 3.67-3.68
3.70-3.73 3.75 3.83 3.89 3.92 4.05 4.07 4.10-4.15 4.18-4.19 4.36-4.38
4.41 4.43-4.44 4.47 4.50 4.54 4.60 4.67-4.69 4.72 5.11-5.13 5.17 5.20
5.26 5.30-5.31 5.37-5.39 5.42 5.46 5.48 5.49 5.51-5.52 5.55-5.57 5.59
5.61 5.64-5.70 5.72 5.73 5.77-5.79
Winter 1999:
3.00-3.01 3.05-3.07 3.40 3.42-3.43 3.45-3.47 3.54 3.56 3.59 3.64 3.68
3.72-3.73 4.07 4.10-4.11 4.13-4.14 4.18 4.37 4.47 4.49-4.50 4.53 4.60
4.66-4.69 4.72 5.11-5.13 5.20 5.26 5.30 5.39 5.46 5.48 5.51-5.52
5.54-5.59 5.61 5.64 5.66 5.78-5.79

5.2 Channel Width

The channel width discussed above is 10 kHz only. The channel width required by the HFSWR systems is typically in the order of tens of kilo-Hertz, depending on the waveform used by the radar. For a pulse Doppler radar (coded or uncoded), the required bandwidth is generally around 20 kHz. For a frequency-modulated continuous waveform (FMCW) or a frequency-modulated-interrupted continuous waveform (FMICW), the required bandwidth is generally in the order of 100 kHz. Hence, when we consider the channel availability for the radar systems, we have to look for the contiguous channels available from the spectrum monitor system.

From Table 2, we can extract these contiguously and continuously available channels. Table 3 lists all these channels. From Table 3, we can then count the number of available channels for different bandwidth requirements by the radar systems. Here, we consider non-overlapped channels only. Table 4 lists the numbers of non-overlapped channels available for the bandwidth requirements of 20, 40, 60, 80 and 100 kHz. Table 4 shows that 20 kHz channels are readily available. However, the number of available and non-overlapped channels drops off quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available.

Table 3 ***Contiguously and Continuously Available Radio Frequencies (MHz) over Six Different Seasons in 1998 and 1999***

```
Fall 1998:
3.00-3.01 3.03-3.07 3.43-3.44 3.46-3.47 3.53-3.54 3.67-3.68 3.70-3.73
4.12-4.14 4.18-4.19 4.37-4.38 4.40-4.41 4.68-4.69 5.30-5.31 5.37-5.38
5.48-5.49 5.54-5.57 5.64-5.70 5.78-5.79
Winter 1998:
3.00-3.01 3.03-3.07 3.43-3.47 3.71-3.73 4.02-4.03 4.10-4.11 4.18-4.19
4.37-4.41 5.12-5.13 5.48-5.49 5.54-5.55 5.66-5.67 5.69-5.70
Spring99:
3.00-3.07 3.42-3.47 3.50-3.54 3.63-3.64 3.70-3.73 3.91-3.92 4.10-4.14
4.17-4.19 4.37-4.41 4.68-4.69 5.11-5.14 5.37-5.38 5.52-5.57 5.66-5.67
5.72-5.73 5.77-5.79
Summer 1999:
3.00-3.07 3.45-3.47 3.50-3.54 3.67-3.68 3.70-3.73 3.75-3.76 3.85-3.87
3.90-3.92 4.10-4.14 4.18-4.19 4.36-4.42 4.47-4.51 4.66-4.69 5.11-5.14
5.29-5.32 5.37-5.39 5.46-5.48 5.51-5.52 5.54-5.57 5.77-5.80
Fall 1999:
3.00-3.07 3.45-3.47 3.52-3.56 3.63-3.64 3.67-3.68 3.70-3.73 4.10-4.15
4.18-4.19 4.36-4.38 4.43-4.44 4.67-4.69 5.11-5.13 5.30-5.31 5.37-5.39
5.51-5.52 5.55-5.57 5.64-5.70 5.77-5.79
Winter 1999:
3.00-3.01 3.05-3.07 3.42-3.43 3.45-3.47 3.72-3.73 4.10-4.11 4.13-4.14
4.49-4.50 4.66-4.69 5.11-5.13 5.51-5.52 5.54-5.59 5.78-5.79
```

Table 4 ***Number of Available Non-Overlapped Channels for Different Bandwidth Requirements***

Season \ Bandwidth	20 kHz	40 kHz	60 kHz	80 kHz	100 kHz
Fall 1998	22	4	1	0	0
Winter 1998	16	3	0	0	0
Spring 1999	27	9	3	1	0
Summer 1999	31	11	2	1	0
Fall 1999	27	6	3	1	0
Winter 1999	15	2	1	0	0

5.3 Nighttime Channel Occupancy

The channel occupancy and availability discussed above is derived from data collected over both daytime and nighttime hours in a day. However, the dominant radar signal and the sporadic spikes in the spectrum scans during daytime hours may cause a bias in the statistical data. In the following, we consider the channel occupancy and availability for the nighttime hours only. Specifically, we examine the data collected in the 12-hour period between 2200 and 0900 UTC (Approximately between 18:30 and 0530 local time), inclusively.

Figure 13 shows the number of hours for which the channel is available over the 12-hour period in each of the six seasons. From Figure 13, we can tabulate the radio frequencies that are available continuously for the 12 hours at night. Table 5 lists these radio frequencies for the six different seasons. From Table 5, we can then extract the contiguously and continuously available channels, and these channels are listed in Table 6.

From Table 6, we can count the numbers of available channels during the nighttime hours for the different bandwidth requirements. Again, we consider non-overlapped channels only. Table 7 lists these numbers of non-overlapped channels for the bandwidth requirements of 20, 40, 60, 80 and 100 kHz during the nighttime hours. By comparing Table 7 with Table 4, we observe that there are actually more channels available when we consider the nighttime data only. This indicates that the artifacts did cause some bias in the daily channel availability data.

One may question here whether the operation of the radar at Cape Race has also caused a bias in the channel availability in the frequency band of 3.1 to 3.3 MHz during the nighttime hours. To answer this question, we may simply look at the spectrum data measured in the fall of 1998, which includes the months of September, October and November. The radar system at Cape Race has been operational only since November 10, 1998. At the beginning, the radar was mostly operated at 4.09 MHz. Only for four afternoons in November 1998, the radar was operated at a RF between 3.1 and 3.3 MHz. Hence, there was no radar signal in the frequency band between 3.1 and 3.3 MHz in the nighttime data measured in the fall of 1998. Table 6 shows that there were no contiguously and continuously available channels in that frequency band during the nighttime hours in the fall of 1998, regardless of whether the radar was operating or not. This indicates that the channels in that frequency band were not likely available for the radar.

Similar to Table 4, Table 7 shows that channels with a width of 20 kHz are readily available. However, the number of available and non-overlapped channels also drops off quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available.

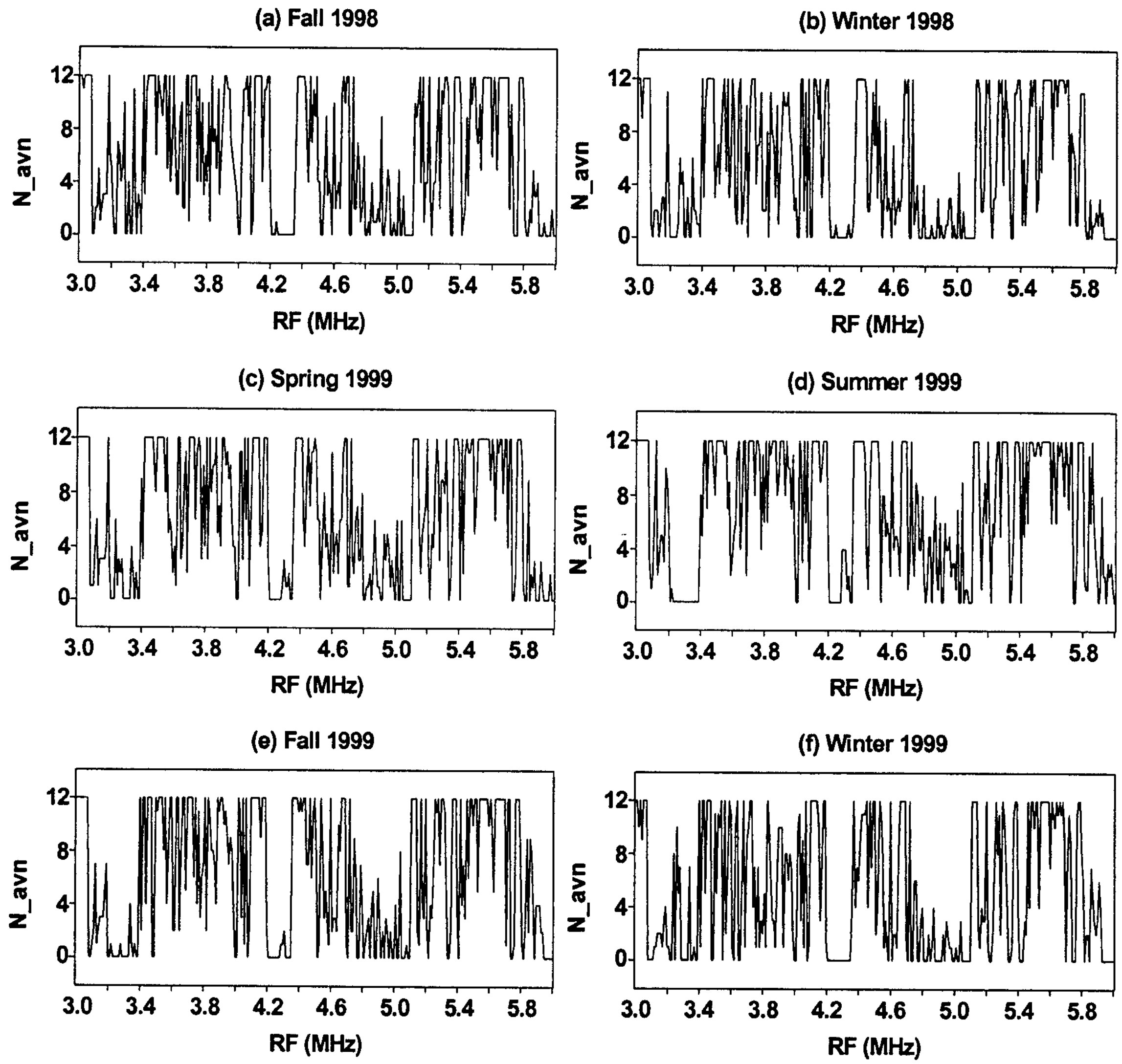

Figure 13 ***Number of Channel-Available Hours (N_avn) at Night between 2200 and 0900 UTC over Six Different Seasons in 1998 and 1999***

Table 5 ***Continuously Available Radio Frequencies (MHz) at Night between 2200 and 0900 UTC over Six Different Seasons in 1998 and 1999***

Fall 1998:
3.00-3.01 3.03-3.07 3.18 3.40 3.43-3.47 3.49 3.53-3.56 3.59 3.67-3.68
3.70-3.73 3.83 3.91-3.92 4.05 4.07 4.10-4.14 4.18-4.19 4.37-4.41 4.45
4.49 4.66 4.68-4.69 4.72 5.14 5.16 5.20 5.26 5.30-5.31 5.36-5.39 5.46
5.48-5.49 5.54-5.59 5.61 5.64-5.70 5.77-5.79
Winter 1998:
3.00-3.01 3.03-3.07 3.40 3.43-3.47 3.54 3.56 3.59 3.64 3.71-3.73
4.02-4.03 4.07 4.10-4.11 4.14 4.18-4.19 4.37-4.42 4.49 4.67 4.69 4.72
5.12-5.13 5.18 5.20 5.26 5.28 5.30 5.38-5.39 5.46 5.48-5.49 5.54-5.59
5.61-5.62 5.64-5.67 5.69-5.70
Spring 1999:
3.00-3.07 3.19 3.42-3.47 3.50-3.54 3.56 3.63 3.64 3.70-3.73 3.76 3.81
3.83 3.87 3.91-3.92 4.05 4.07 4.10-4.14 4.17-4.19 4.37-4.41 4.45 4.49
4.68-4.69 4.72 5.11-5.14 5.20 5.26 5.32 5.37-5.39 5.42 5.45 5.48-5.49
5.52-5.59 5.61 5.64 5.66-5.67 5.69-5.70 5.72-5.73 5.77-5.79
Summer 1999:
3.00-3.07 3.12 3.42-3.43 3.45-3.47 3.50-3.54 3.56 3.64 3.67-3.68
3.70-3.73 3.75-3.76 3.81 3.83 3.85-3.87 3.90-3.92 3.94 4.02 4.05 4.07
4.10-4.14 4.17-4.19 4.36-4.42 4.47-4.51 4.60 4.66-4.69 4.72 5.11-5.14
5.20 5.26-5.27 5.29-5.31 5.32 5.37-5.39 5.42 5.44 5.46-5.48 5.51-5.52
5.54-5.59 5.61 5.64-5.66 5.69 5.72-5.73 5.77-5.80 5.86
Fall 1999:
3.00-3.07 3.40 3.42-3.43 3.45-3.47 3.50 3.52-3.54 3.56 3.59-3.60 3.63
3.64 3.67-3.68 3.70-3.73 3.75 3.81 3.83 3.89 3.91-3.92 4.02 4.05 4.07
4.10-4.15 4.17-4.19 4.36-4.39 4.41 4.43-4.44 4.47 4.50 4.54 4.60
4.67-4.69 4.72 5.11-5.14 5.17 5.20 5.26 5.28 5.30-5.31 5.37-5.39 5.42
5.46 5.48-5.49 5.51-5.52 5.54-5.59 5.61 5.64-5.70 5.72 5.73 5.77-5.79
Winter 1999:
3.00-3.01 3.03 3.05-3.07 3.40 3.42-3.43 3.45-3.47 3.54 3.56 3.59 3.64
3.68 3.72-3.73 3.83 4.07 4.10-4.14 4.18-4.19 4.37 4.45 4.47 4.49-4.50
4.53 4.60 4.66-4.69 4.72 5.11-5.14 5.20 5.26 5.30 5.38-5.39 5.46
5.48-5.49 5.51-5.52 5.54-5.59 5.61 5.64 5.66 5.68 5.78-5.79

Table 6 ***Contiguously and Continuously Available Radio Frequencies (MHz) at Night between 2200 and 0900 UTC over Six Different Seasons in 1998 and 1999***

```
Fall 1998:
3.00-3.01 3.03-3.07 3.43-3.47 3.53-3.56 3.67-3.68 3.70-3.73 3.91-3.92
4.10-4.14 4.18-4.19 4.37-4.41 4.68-4.69 5.30-5.31 5.36-5.39 5.48-5.49
5.54-5.59 5.64-5.70 5.77-5.79
Winter 1998:
3.00-3.01 3.03-3.07 3.43-3.47 3.71-3.73 4.02-4.03 4.10-4.11 4.18-4.19
4.37-4.42 5.12-5.13 5.38-5.39 5.48-5.49 5.54-5.59 5.61-5.62 5.64-5.67
5.69-5.70
Spring 1999:
3.00-3.07 3.42-3.47 3.50-3.54 3.70-3.73 3.91-3.92 4.10-4.14 4.17-4.19
4.37-4.41 4.68-4.69 5.11-5.14 5.37-5.39 5.48-5.49 5.52-5.59 5.66-5.67
5.69-5.70 5.72-5.73 5.77-5.79
Summer 1999:
3.00-3.07 3.42-3.43 3.45-3.47 3.50-3.54 3.67-3.68 3.70-3.73 3.75-3.76
3.85-3.87 3.90-3.92 4.10-4.14 4.17-4.19 4.36-4.42 4.47-4.51 4.66-4.69
5.11-5.14 5.26-5.27 5.29-5.31 5.37-5.39 5.46-5.48 5.51-5.52 5.54-5.59
5.64-5.66 5.72-5.73 5.77-5.80
Fall 1999:
3.00-3.07 3.42-3.43 3.45-3.47 3.52-3.54 3.59-3.60 3.67-3.68 3.70-3.73
3.91-3.92 4.10-4.15 4.17-4.19 4.36-4.39 4.43-4.44 4.67-4.69 5.11-5.14
5.30-5.31 5.37-5.39 5.48-5.49 5.51-5.52 5.54-5.59 5.64-5.70 5.77-5.79
Winter 1999:
3.00-3.01 3.05-3.07 3.42-3.43 3.45-3.47 3.72-3.73 4.10-4.14 4.18-4.19
4.49-4.50 4.66-4.69 5.11-5.14 5.38-5.39 5.48-5.49 5.51-5.52 5.54-5.59
5.78-5.79
```

Table 7 ***Number of Available Non-Overlapped Channels for Different Bandwidth Requirements during Nighttime Hours***

Season \ Bandwidth	20 kHz	40 kHz	60 kHz	80 kHz	100 kHz
Fall 1998	28	9	2	0	0
Winter 1998	22	5	2	0	0
Spring 1999	30	10	3	2	0
Summer 1999	38	11	4	1	0
Fall 1999	33	8	4	1	0
Winter 1999	20	4	1	0	0

5.4 Channel Availability for Ship Detection

For ship detection, the HFSWR systems are normally operated in the frequency band between 3 and 4 MHz to take advantage of the low propagation attenuation. However, the second half of this frequency band, between 3.5 and 4 MHz, is allocated as an amateur band, and hence, cannot be used for daily radar operation. In the first half of the frequency band, between 3 and 3.5 MHz, we have to look for available channels from the nighttime availability data as the daytime measured data are biased due to the operation of the radar at Cape Race. Normally that portion of the frequency band is unoccupied during daytime hours. Hence, if a channel in that band is available during nighttime hours, it should be available for the entire day. From Table 6, we found that the following channels were available contiguously and continuously at night over each of the six seasons:

```
Fall 1998 --        3.00-3.01 3.03-3.07 3.43-3.47 MHz
Winter 1998 --      3.00-3.01 3.03-3.07 3.43-3.47 MHz
Spring 1999 --      3.00-3.07 3.42-3.47 MHz
Summer 1999 --      3.00-3.07 3.42-3.47 MHz
Fall 1999 --        3.00-3.07 3.42-3.43 3.45-3.47 MHz
Winter 1999 --      3.00-3.01 3.05-3.07 3.42-3.43 3.45-3.47 MHz
```

The above data indicate that three channels were available contiguously and continuously throughout the six seasons: 3.00-3.01, 3.05-3.07 and 3.45-3.47 MHz. These channels had a bandwidth of 20, 30 and 30 kHz, respectively.

In the past, the HFSWR systems have been operated at a RF between 3.1 and 3.3 MHz. Unfortunately, this was not one of the available channels. For better radar performance, it is recommended that we move the radar operating frequency to one of the available channels.

Here we should point out that the above available channels are parts of the frequency bands between 3.025 and 3.155 MHz and between 3.400 and 3.500 MHz that are allocated for aeronautical mobile communications by the Federal Communications Commission (FCC) [4]. It is not clear whether we are allowed to operate the radar systems in these frequency bands, although we have been using these bands for the radar systems for some time.

5.5 Channel Availability for Aircraft Detection

For aircraft detection, the HFSWR systems could be operated in the same frequency band as for ship detection. However, it is probably better to operate the radar at a slightly higher radio frequency, say, between 3.5 and 5 MHz, to take advantage of the larger radar cross-section (RCS) of aircraft targets at these frequencies. Excluding the amateur band, the contiguously and continuously available channels from Table 6 are:

```
Fall 1998 --        4.10-4.14 4.18-4.19 4.37-4.41 4.68-4.69
Winter 1998 --      4.02-4.03 4.10-4.11 4.18-4.19 4.37-4.42
Spring 1999 --      4.10-4.14 4.17-4.19 4.37-4.41 4.68-4.69
Summer 1999 --      4.10-4.14 4.17-4.19 4.36-4.42 4.47-4.51 4.66-4.69
Fall 1999 --        4.10-4.15 4.17-4.19 4.36-4.39 4.43-4.44 4.67-4.69
Winter 1999 --      4.10-4.14 4.18-4.19 4.49-4.50 4.66-4.69
```

The above data indicate that four channels were available contiguously and continuously throughout the six seasons: 4.10-4.11, 4.18-4.19, 4.37-4.39 and 4.68-4.69 MHz. These channels had a bandwidth of 20, 20, 30 and 20 kHz, respectively.

The first two of the four channels are parts of the band allocated for maritime mobile communications (4.063-4.438 MHz). The third channel is part of the band allocated for fixed and mobile except aeronautical mobile communications (4.438-4.660 MHz). The fourth channel is part of the band allocated for aeronautical mobile communications (4.650-4.700 MHz). Special permission may be required in order to operate the radar in these bands.

5.6 Channel Width and Waveform Selection

The width of available channels is likely to dictate the choice of waveform for the radar if the radar is to avoid co-channel interference. The results above indicate that twenty kHz channels are readily available, but the number of available and non-overlapped channels drops off quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available. Hence, it is unlikely for the radar to have FMCW or FMICW types of waveforms without getting co-channel interference as these waveforms normally requires bandwidths in the order of 100 kHz. It is more likely that the radar has pulse waveforms (coded or uncoded) without getting co-channel interference as these waveforms normally require bandwidths only in the order of 20 kHz.

6. Conclusions and Recommendations

In support of the operation of the east coast HFSWR systems, we carried out a study of channel occupancy in the frequency band between 3 and 6 MHz using the data measured with a spectrum monitor at Cape Race, Newfoundland. From the study, we tabulated a list of contiguously and continuously available radio frequencies. The results of the study indicate:

1. Channels with a width of 20 kHz are readily available.

2. The number of available and non-overlapped channels drops off quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available.

3. For ship detection, three channels are available contiguously and continuously in the lower end of the frequency band: 3.00-3.01, 3.05-3.07 and 3.45-3.47 MHz. The bandwidths of these channels are 20, 30 and 30 kHz, respectively. In the past, the HFSWR systems have been operated at a RF between 3.1 and 3.3 MHz. For better radar performance, however, it is recommended that we move the radar operating frequency to one of the available channels.

4. For aircraft detection, the HFSWR systems could be operated in the same frequency band as for ship detection. However, it is probably better to operate the radar at a slightly higher radio frequency to take advantage of the larger RCS of the targets at these frequencies. For example, the radar systems could be operated in one of the four channels that are contiguously and continuously available: 4.10-4.11, 4.18-4.19, 4.37-4.39 and 4.68-4.69 MHz. The bandwidths of these channels are 20, 20, 30 and 20 kHz, respectively.

The width of the available channels dictates the choice of waveform for the radar if the radar is to avoid co-channel interference. The results above indicate that it is unlikely for the radar to operate with FMCW or FMICW waveforms without getting co-channel interference as these waveforms normally require bandwidths in the order of 100 kHz. It is more likely that the radar uses one of the pulse waveforms (coded or uncoded), as these waveforms normally require a bandwidth only in the order of 20 kHz.

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[1] H. Leong, "Adaptive Suppression of Interference in HF Surface Wave Radar Using Auxiliary Horizontal Dipole Antennas", DREO Technical Report, TR 1998-1336, Defence Research Establishment Ottawa, September 1998.

[2] H. Chan and E. Hung, "An Investigation in Interference Suppression for HF Surface Wave Radar", DREO Technical Report, TR 2000-028, Defence Research Establishment Ottawa, December 2000.

[3] H. Leong, B. Dawe and D. Power, "Noise Measurements At Cape Race in Support of East Coast High Frequency Surface Wave Radar", DREO Technical Memorandum TM 2000-089, Defence Research Establishment Ottawa, November 2000.

[4] Federal Communications Commission, "United States Table of Frequency Allocation", 47CFR2.105, National Archive and Records Administration, October 1, 1999.

Appendix A Calibration of Spectrum Monitor

1. Antenna Calibration

The antenna used for the Cape Race spectrum monitor was a Shakespeare model 393, 23 foot SSB fibreglass antenna with no loading coil. It was installed with 32 base copper radials (#12 wire, 15 m long) as a ground screen.

A proper antenna analysis requires the consideration of an equivalent circuit for the antenna. Figure 1 shows the equivalent circuit used by Northern Radar [1]. This circuit contains the following parameters:

R_a = Antenna radiation resistance
R_g = Ground resistance
X_a = Antenna reactance to ground
R_b = base resistance
X_b = base reactance
Z_b = base impedance = R_b+jX_b
R_L = receiver resistance (50 Ohms)

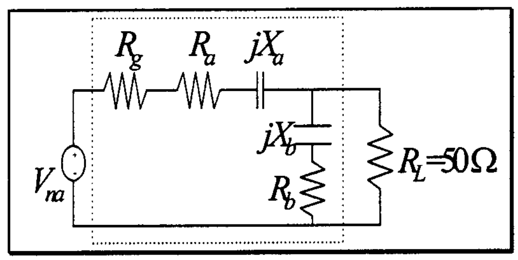

Figure 1. Equivalent Antenna Circuit

The antenna input impedance, Z_{in}=R_{in}+jX_{in}, is the parallel connection of Z_b with $Z_a = R_a + R_g + jX_a$. Using an impedance analyser, the input impedance, as well as the base impedance Z_b, can be measured. The measurement of Z_b can be achieved by simply disconnecting the lead to the antenna. The antenna impedance, Z_a, can be extracted from Z_{in} by subtracting the base susceptance, $Y_b = 1/Z_b$, from the input susceptance, $Y_{in} = 1/Z_{in}$, i.e.,

$$Y_a = 1/Z_a = Y_{in} - Y_b \tag{A1}$$

Figures 2, 3 and 4 show the above described impedances for the 23 foot whip antenna. In Figure 2 are the base resistance and reactance, in Figure 3 are the antenna input resistance and radiation resistance plus the ground resistance, and in Figure 4 are the input reactance and the antenna reactance. These measured values are used in the calibration procedure described below.

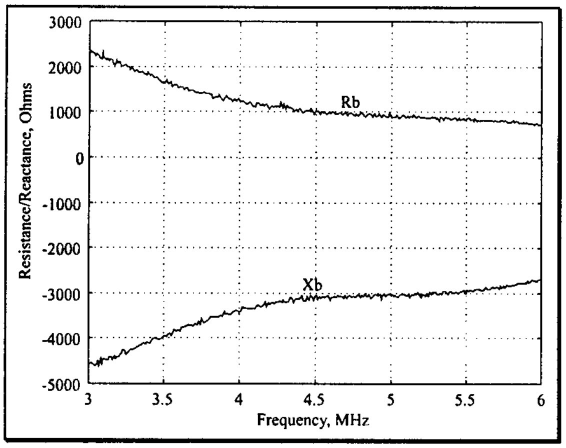

Figure 2. Base Impedance

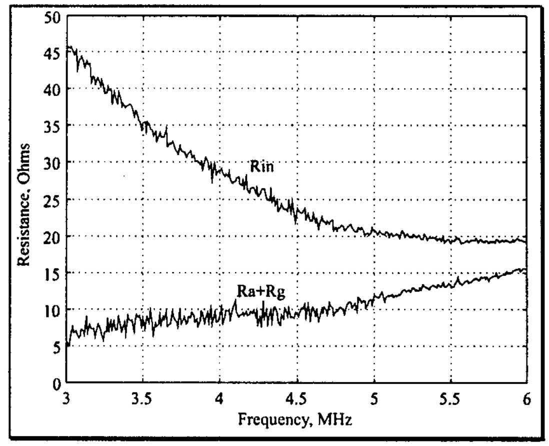

Figure 3. Input and Antenna Resistances

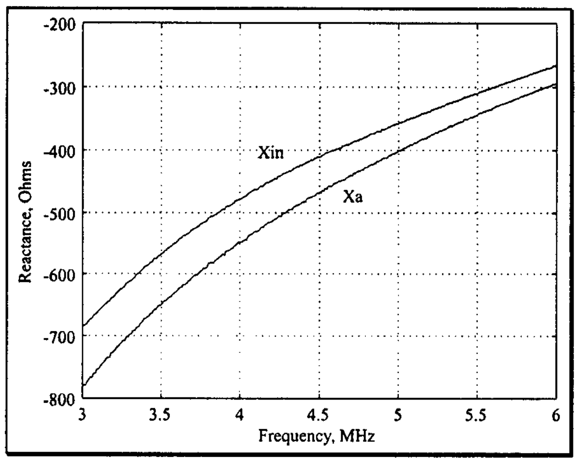

Figure 4. Input and Antenna Reactances

Calibration Procedure

The whip antenna can be calibrated by using the equivalent antenna circuit. The available root-mean-square noise voltage (open circuit) can be measured at the base of the antenna and is given by the following [2]:

$$V_{na} = 2\sqrt{KT_a R_a B} \tag{A2}$$

where T_a is the equivalent antenna noise temperature (K), K is Boltzmann's constant (J/K), R_a (Ohms) is the antenna radiation resistance and B (Hz) is the measurement bandwidth. The voltage across the load (receiver) resistor, V_L, can be calculated using a voltage divider:

$$V_L = \frac{Z_{eq} V_{na}}{R_a + R_g + jX_a + Z_{eq}} = \frac{Z_{eq} V_{na}}{Z_a + Z_{eq}} \quad \text{(A3)}$$

where Z_{eq} is the parallel impedance of R_L and Z_b:

$$Z_{eq} = Z_b R_L / (Z_b + R_L) \quad \text{(A4)}$$

Therefore, the noise power to the receiver is given by

$$P_L = |V_L|^2 / R_L = \frac{4R_a}{R_L} \left| \frac{Z_{eq}}{Z_a + Z_{eq}} \right|^2 (KT_a B) \quad \text{(A5)}$$

Note that if matched lossless conditions exist (R_L=R_a, R_g=0, X_a=0, X_b=R_b=∞) then the power to the receiver is

$$P_L = \frac{4R_a}{R_a} \left| \frac{R_a}{2R_a} \right|^2 (KT_a B) = KT_a B = P_{na} \quad \text{(A6)}$$

which equals the noise power from a lossless, perfectly matched antenna. Note that the noise factor, f_a, is defined [3] as:

$$f_a = \frac{P_{na}}{KT_0 B} = \frac{KT_a B}{KT_0 B} = \frac{T_a}{T_0} \quad \text{(A7)}$$

where T_0 is standard temperature (290 K) and T_a is the antenna noise temperature.

We use the following notation in the case of a lossy, unmatched antenna, such as the 23 foot whip antenna at Cape Race:

$$P_L = MP_{na} \quad \text{(A8)}$$

where M is the loss factor given by

$$M = \frac{4R_a}{R_L} \left| \frac{Z_{eq}}{Z_a + Z_{eq}} \right|^2 \quad \text{(A9)}$$

2. Amplifier Calibration

The gain of the pre-amplifier (ZHL-1A) has been measured with a vector network analyser and the linear gain of the pre-amplifier is plotted Figure 5. Note that the average gain of the pre-amplifier is 18.5 dB.

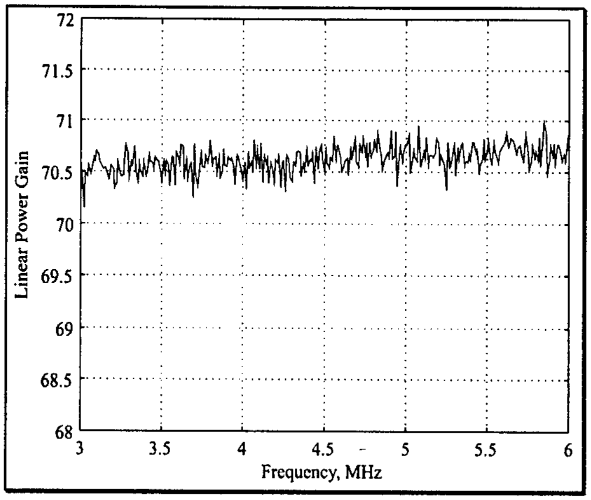

Figure 5. Power Gain Of Pre-Amplifier ZHL-1A

The internal noise floor of the spectrum monitor, P_{nr}, can be obtained by placing a 50 Ohm resistor at the amplifier input. This produces the matched conditions, from which the system noise, P_0, can be measured. This system noise consists of the internal receiver noise P_{nr} and the amplified 50 Ohm resistor noise $P_{ar} = AKT_0B$, where A is the amplifier gain. We can determine the internal receiver noise level by subtracting the amplified resistor noise from the measured system noise P_0:

$$P_{nr} = P_0 - P_{ar} = P_0 - AKT_0B \tag{A10}$$

At the bandwidth of 10 kHz, the system noise P_0 is -108 dBm.

The total noise power received by the system when it is connected to the antenna is given by

$$P_{n0} = AP_L + P_{nr} = AMP_{na} + P_0 - AKT_0B \tag{A11}$$

The quantity that we require is the external noise power, P_{na}. By solving the equation above, we have:

$$P_{na} = \frac{1}{M}\left[\frac{P_{n0}}{A} - \left(\frac{P_0}{A} - KT_0B\right)\right] \tag{A12}$$

which we can then use in Equation (A7) to calculate the noise factor

$$f_a = \frac{P_{na}}{KT_0B} = \frac{1}{M}\left[\frac{P_{n0} - P_0}{AKT_0B} + 1\right] \tag{A13}$$

3. Cable Attenuation Correction

The cable out to the antenna is approximately 160 feet long and introduces an attenuation that must be corrected. This cable attenuation has been measured and is plotted in Figure 6.

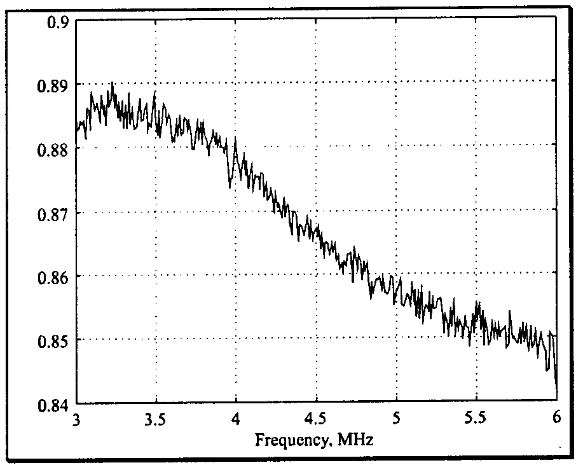

Figure 6. Cable Attenuation, L_C

To account for this cable loss, we simply replace the loss factor M in Equation (A9) with the following:

$$\widetilde{M} = ML_C \tag{A14}$$

Where L_C is the cable loss factor and $\widetilde{M}$ is the corrected loss factor.

References

[1] Northern Radar, "Verification of the Performance of the Cape Race Transmitting and Receiving Antennas, Technical Report Number NR-AF00A-R01, December 1997.

[2] R. E. Colin, "Antennas and Radiowave Propagation", McGraw-Hill Book Company, 1985, pp 312-315.

[3] International Radio Consultative Committee, "Characteristics and Applications of Atmospheric Radio Noise Data", CCIR Report 322-3, International Telecommunication Union, Geneva, 1988.

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In support of the operation of the east coast High Frequency surface wave radar (HFSWR) systems, we carried out a continuous measurement of noise and interference data in the frequency band of 3-6 MHz at Cape Race, Newfoundland in the period between August 1, 1998 and May 10, 2000. In [3], we presented an estimation of noise factors from the measured data. In this report, we study the channel availability, in terms of channel width and channel duration, by using the measured data. The aim of this study is to find the clear channels in which we can effectively operate the radar. The results of the study indicate: (1) channels with a bandwidth of 20 kHz are readily available, and (2) the number of available and non-overlapped channels decreases quickly as channel bandwidth increases. At a bandwidth of 100 kHz, there is no channel available.

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