

A PROGRAMMABLE RECEIVER FOR MONITORING LF/MF/HF SIGNALS FROM REMOTE SITES

E. Olsen*, A. Weatherwax*, F. Dailami[†], and J. LaBelle*

Abstract

Although many studies of radiowave propagation have been performed at 0.1–10 MHz, relatively few systematic surveys have been made of natural emissions in this band [see reviews by Ellyett, 1969; LaBelle, 1989]. The predominance of man-made signals in this band requires a receiver of specialized capabilities which can be operated from a remote site. In this paper, we describe an instrument designed to meet these criteria and show data obtained from the first few weeks of its operation at a remote site in Alaska.

1 Introduction

Radio emissions arising from natural processes in the Earth’s ionosphere and magnetosphere have long captured the interest of both experimental and theoretical space scientists. Such emissions have provided clues about the plasma physics processes occurring in space and have served as probes of the parts of the ionosphere underlying their source. The most-studied band for terrestrial emissions is undoubtedly the VLF [see, for example, Helliwell, 1965]. The lower frequency ELF and ULF bands have also received a fair amount of attention [e.g., Jones, 1974].

However, from the Earth’s surface, the LF, MF, and lower HF bands (roughly 0.1–10 MHz) remain relatively unexplored as far as natural emissions are concerned. There are two main reasons for this. First, from the beginning of the radio age, these frequencies have been popular for man-made signals, since they can be efficiently transmitted with modest-sized antennas, they can easily carry audio information, and, at least at night, they reflect efficiently from the ionosphere and hence can propagate long distances over the horizon. It is hard to find a site today which is radio quiet below 10 MHz, and as a result, any natural emissions are difficult or impossible to detect beneath the massive man-made background.

**Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire*

[†]*Department of Electrical Engineering, Utah State University, Logan, Utah*

A second reason why 0.1–10 MHz terrestrial emissions have not been much studied is that, particularly at the low end of this range, these frequencies lie below the critical frequency of the ionosphere. This somewhat restricts the sources of waves one might observe from the ground. In particular, waves originating on the topside of the ionosphere would not in general penetrate to the ground, unless the critical frequency is exceptionally low (as sometimes occurs in the wintertime polar ionosphere), unless they propagate in the whistler mode, or unless a tunneling (‘radio window’) effect allows them to get through. The belief that relatively special conditions may be required to generate LF signals observable on the ground, and the general lack (until recently) of theoretical grounds for the existence of such signals, explains why so few attempts have been made to systematically monitor this band for natural terrestrial emissions.

Nevertheless, there is no reason to believe that natural signals could not be observed from the ground in the LF–HF band, and indeed there have been a number of reports of such observations from time to time over the last forty years [Ellyett, 1969; LaBelle, 1989]. Interest in the subject has revived with the discovery of intense LF emissions beamed upward away from the Earth on auroral field lines [Gurnett, 1974], and with recent observational [Benson et al., 1988; Benson and Desch, 1991] and theoretical [Wu et al., 1990; Ziebell et al., 1991] indications that less powerful versions of these LF emissions are observable from the ground under the right conditions. Although the amount of energy in such radio emissions may be small compared to the total energy of the aurora, the study of these emissions could provide important clues to auroral dynamics—in analogy to the way that solar radio bursts have provided tremendous insight to the dynamics of the solar corona, even though the radio energy is a tiny fraction of the energy released in a solar flare.

Although our experiment is designed to detect natural auroral emissions, the fact that this part of the spectrum is saturated with many man-made signals will require us to complement our study by investigating propagation characteristics of man-made signals over extended periods of time. The known location and frequencies of local and distant AM radio stations throughout the state of Alaska will allow us to correlate both ground and sky wave propagation characteristics with auroral activity. Not only is this study of man-made signals scientifically interesting, but it also provides a calibration and check of our instrument.

A receiver which operates at 0.1–10 MHz over a long period of time (months or years) requires some form of data compression, because at these frequencies it is unreasonable to record all the information about the waveform, which would require data rates in excess of 20 megasamples/second. In compressing the data one has the choice of recording a handful of frequencies continuously with high time resolution, or of recording all the information about the waveform, but at a very low duty cycle, or a combination of both. The first strategy has an advantage at LF since the background man-made signals usually (though not always) occur at discrete, readily-identifiable frequencies. By sampling relatively narrow-band channels and selecting frequencies carefully (and unevenly) to avoid interference, one can achieve effectively higher sensitivity while at the same time reducing the amount of data to be recorded. This can be augmented by only recording data for certain times or by recording only interesting events as recognized by certain criteria.

In addition, any radio receiver intended to measure natural LF emissions must be operable from a remote site, since only remote sites are removed from nearby sources of man-made interference. This requirement implies that the instrument must use a minimum of space and power, and must need only occasional intervention by people. Fortunately, small computers and microprocessors available today allow this to be achieved, though at a cost in complexity and in possibilities for self-interference of the instrument, namely the computer.

In Section 2 we describe a receiver which has been designed to meet these criteria. It incorporates a narrow bandwidth to optimize signal-to-noise by looking ‘in-between’ man-made interference signals. It switches rapidly between arbitrary frequencies in order to build up a spectrum quickly and step around interference signals. It stores about ten days worth of data without operator attention, and can be easily modified to store data for periods of months without intervention. In Section 3, some initial data from this instrument, taken at a remote site in Alaska, are displayed and discussed.

2 Instrument description

Figure 1 shows a block diagram of the Programmable Frequency Receiver (PFR). The receiver itself consists of six superheterodyne type receivers, each covering one octave of frequencies and together covering the range 0.15–9.6 MHz. The six receivers are controlled by a 8085 microprocessor system consisting of a Q85 microprocessor card and a modified QBOARD interface card from QSI Corporation. The microprocessor system (QSI) also collects data from the receivers and sends it over the RS-232 link to the PC where it is stored. Since the low-level control is handled by the QSI, the PC is relatively under-utilized, and will eventually be used for data compression.

Turning to the first elements of the block diagram (Figure 1), various antenna and preamplifiers could be made to work with the PFR. The present version of the instrument uses two non-resonant dipole antennas; one is vertical and the other is horizontal. The reason that non-resonant antennas are used rather than resonant antennas is that they can operate over a wide frequency range without requiring constant adjustment (‘trimming’) by an operator. This is of course essential for unmanned operation. While the non-resonant antenna is in some sense fundamentally less sensitive than a resonant antenna, this does not seem to be a problem at these frequencies since the sensitivity is determined by the environmental noise rather than by the instrument. The dipoles are not very directional and sense essentially the whole sky; directional antennas, as well as multiple antennas of different orientations, could easily be incorporated. The use of different orientations has been suggested as a means of discriminating man-made noise, which might under some circumstances be linearly polarized, from natural signals, which would not be linearly polarized.

Each antenna has its own preamplifier. These utilize high impedance and low noise ($6 \text{ nV}/\sqrt{\text{Hz}}$) FET’s as a first stage. They operate over a 10 MHz bandwidth with a gain of 10 in order to accommodate for cable losses between the preamplifier, which is placed at the antenna, and the receiver itself, which is preferably placed at least 250 feet from the

PFR RADIO SYSTEM

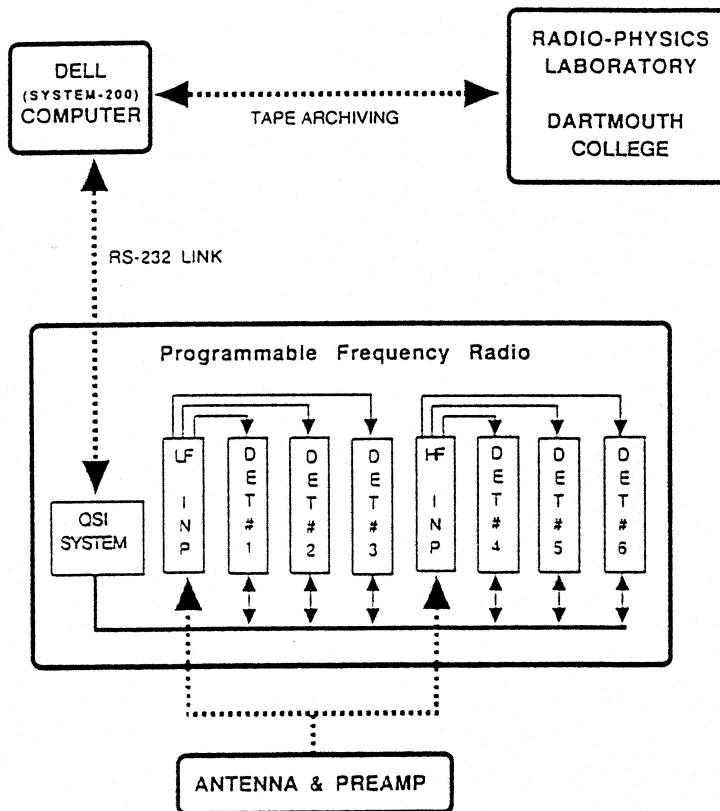


Figure 1: A block diagram of the PFR system is shown. A signal from the antenna/preamplifier is directed into one of six super-heterodyne type receivers. Each receiver covers one octave of frequencies, together covering the range 0.15–9.6 MHz. The analog output is converted to a digital signal via an 8-bit A/D, and the computer stores the data until it is backed up onto tapes, which are subsequently mailed back to Dartmouth College for analysis.

antenna to reduce self-generated interference from the computer. The preamplifiers have a dynamic range of 90 dB, larger than that of the receiver. Power (100 mA at 10 Volts) is provided to the preamplifier on the same conductor as the RF output signal. Finally, the preamplifiers are insulated with at least one inch of styrofoam and are heated by an ohmic heater which turns on whenever the temperature drops below 0° F.

Before the receiver, the preamplified RF signals may optionally be passed through one or more passive notch filters. These may be adjusted in frequency to eliminate the most severe local sources of interference at known discrete frequencies. The preamplifier gain can then be increased without overdriving the receiver, enhancing sensitivity. This trick works because the preamplifier dynamic range is greater than that of the receiver.

As mentioned above, the PFR actually consists of six receivers, each tuned over an octave of frequencies: 0.15–0.3 MHz, 0.3–0.6 MHz, and 0.6–1.2 MHz, henceforth referred to as LF; and 1.2–2.4 MHz, 2.4–4.8 MHz, and 4.8–9.6 MHz, henceforth referred to as HF. The LF and HF signals come in from the antenna and are routed to separate input cards before being mixed and detected. These input stages include high pass filters (set at 100 kHz for the LF and 1 MHz for the HF), gain to accommodate for the band-limiting and

splitting of the signals, power splitters which split both the LF and HF signals three ways to produce six signals (one for each receiver), and low pass filters which are different for each of these six signals and are cut off at the top edge of each octave (0.3, 0.6, 1.2, 2.4, 4.8, and 9.6 MHz). Extremely sharp (11-pole) passive low pass filters are used in this final filtering stage, because the mixing scheme requires that the signal at three times the frequency of interest be attenuated since it can be mixed to the same frequency as the fundamental by odd harmonics of the local oscillator, which are hard to suppress.

Each of the six filtered and preamplified signals, corresponding to six octaves in frequency range, is connected to its own receiver/detector card. These six receivers are identical in design except for their frequency range, and all are controlled by a single microprocessor via a 16-line bus. In each detector card, the RF signal is mixed once with a local oscillator tuned to the frequency to be measured. A simple RC filter removes the high frequency product, and the product near DC is band-pass filtered and detected. There are two choices for the bandwidth and detection time constant: Bandpass cutoffs of 300 and 1200 Hz, implying a total bandwidth of 2400 Hz, followed by an integrator with 3 ms time constant; or bandpass cutoffs of 300 and 600 Hz, implying a total bandwidth of 1200 Hz, followed by a peak detector which locks onto the highest value the signal attains during a 6 ms detection interval. The selected output is sampled at a time determined by the microprocessor.

The local oscillator signal is generated on each receiver/detector card by a Voltage-Controlled-Oscillator (VCO), whose input voltage is set by the microprocessor via the 16-line control bus and a digital-to-analog converter (DAC) on each receiver. In this manner, the microprocessor can change the frequency of a single receiver virtually instantaneously by re-setting the 12 input data bits of the DAC; the 12-bit resolution of the DAC assures sufficient frequency resolution for the octave covered by the receiver. The DAC-VCO combination is not as stable a frequency source as a phase-locked loop, but the slow lock-on time for the phase-locked loop at these frequencies and frequency resolution would limit the overall sampling rate of the receiver. In the DAC-VCO scheme, high stability is provided by a digital feedback loop: During each measurement, a counter controlled by the microprocessor is used to measure the actual frequency of the VCO; if the frequency is too low, the DAC is adjusted upwards the next time that particular frequency is set, and if the frequency is too high, the DAC is adjusted downward. Each time the set of frequencies to be detected is changed, the DAC-VCO system must be given about ten minutes of operation (approximately 30 cycles through every frequency) to calibrate itself, but after that time it appears to be quite stable. Gradual changes in the VCO or its tank circuit, due to run time or temperature, are compensated naturally by the digital feedback.

The QSI microprocessor is programmed in assembly language to cycle through 1536 selected frequencies (256 for each of the six receiver/detectors). The QSI ensures a constant flow of data back to the PC, over the RS-232 link, by interleaving in time the data collection process of each receiver; this process consists of setting DACs, resetting and reading the frequency feedback counters, waiting for detection to occur, selecting and sampling the detection circuits, and resetting the detection circuits. Additionally the QSI must keep track of the DAC settings for the 1536 frequencies and adjust them to incorporate

the results of the feedback, in order to be sure to detect the correct frequency.

The microprocessor's program is presently loaded over RS-232 from the PC at the beginning of each data taking session. The selected frequencies are loaded onto the microprocessor at the same time from a specified file on the PC's hard disk. This file contains 1536 frequencies in ASCII characters and is easily edited manually or with a program. To change frequency selections, the operator need only create a new frequency file and specify it when re-loading the microprocessor's program.

Alternatively, the PC contains a 'scheduler' program which automatically re-loads the microprocessor program at specified dates and times using specified frequency files. The scheduler also enables data to be recorded on disk for selected hours on selected dates; data from outside the specified times are received over RS-232 from the microprocessor but are simply not recorded on disk; this is done in order to keep the PFR locked onto the correct frequency. The scheduler therefore enables a full year of data-taking to be programmed into the PC and executed automatically. The PC is also programmed to automatically restart the data-taking process any time that data taking ceases due to a loss of power, and entries from the appropriate date and time in the scheduler file are used to re-start the program. The PC creates a separate data file for each data-taking interval, each file being labeled with distinct date and time stamps.

Only two forms of operator input are required in the current version of the PFR. First, the PC fills its 60 MB disk about once every ten days based on nearly 24-hour operation. When this happens, the operator must copy the contents of the disk to tape and clear it. A sub-program does this automatically, but the tape must be loaded by the operator. In the future, data compression programs on the PC should be able to compress the data files significantly and make operator input necessary only once every few months rather than once every ten days. Use of a larger disk and larger capacity tape would also extend the data-taking time in between operator intervention. A second form of operator input involves calibrating the clock of the PC from time to time. The operator runs a sub-program to set the clock to a WWV-generated time code monitored by telephone.

3 Initial results

Since the primary scientific objective of the PFR is to measure auroral emissions, a site was selected near Fairbanks, Alaska, at the optimal geomagnetic latitude for auroral observations. Fairbanks also has the advantage of having many complementary geophysical experiments. An even greater advantage is that some previous measurements of LF noise from the aurora were conducted there in 1986 [Benson et al., 1988]. At that time, these investigators made measurements at a large number of potential sites around Fairbanks and identified a quiet site about 20 miles northeast at Two Rivers, Alaska [R. F. Benson, personal communication, 1988]. We decided to take advantage of their previous work by operating from the same site.

The PFR was installed in early November, 1990. During the first few months, problems with power at the remote site caused the data-taking to be sporadic, but after February

1, data were collected for 20 hours per day. Figure 2 shows a spectrum measured on 7 December, 1990, at 1300 LT (2200 UT). At this time, the PFR was in a high frequency-resolution mode. The spectrum shown consists of 45 minutes of data averaged together. A number of peaks can be identified in this figure. The lowest octave (Figure 2*b*) is dominated by a local airport beacon at 256 kHz. Note that at the lowest frequencies, for which the frequency resolution in this mode is better than the inherent width of the channels, each discrete peak manifests itself as a double peak due to the zero-frequency IF and the resulting double humped response function of the radio. (This effect could be removed by deconvolution if desired, since the response function is known.) The signal levels are clipped at $10\ \mu\text{V}/\text{m}$ due to the limited dynamic range of the instrument. The broadcast band contains a number of discrete peaks, which correspond to local AM radio stations. Below the broadcast band several peaks occur which are identified with known RF beacons. In the HF, there is a peak at 3 MHz, which arises from some source of local interference which we have not identified. (Moving the instrument away from local buildings reduced the 3 MHz peak considerably.) Near 1.8 MHz there is a broad enhancement in the spectral density, which did not always occur, and the origin of which is unknown but under investigation.

Aside from the peaks in the spectrum, whose identification serves as a check that the PFR is working, the background noise can be determined from Figure 2. The actual maximum sensitivity of the instrument, as measured in the laboratory, lies a factor of 2–9 (depending on frequency) below the lowest levels of background noise shown in Figure 2. In other words, the noise level is determined by the environment. The least detectable signal measured in the laboratory varied from $0.3\text{--}2\ \mu\text{V}$ at the input to the preamplifier, while the actual observed noise level corresponds to about $3.5\ \mu\text{V}$ at the preamplifier. Note that one of the six receivers, corresponding to the 600–1200 kHz octave, was damaged early in the data-taking period during a temporary loss of heat in the building; as a consequence, its signal level is known relatively but not absolutely, and we cannot compare its background level to that in the other channels.

Figure 3 shows the diurnal variation of the observed signals in a gray scale format. The time interval displayed is 15:45:00 to 18:25:00 LT on 20 November, 1990. Only a portion of the observed spectrum is shown (600–1200 kHz). On this day, the sunset on the ground occurred at 15:29:00 LT, and sunset at the ionosphere somewhat later. The figure shows the enormous difference at these frequencies between daytime and nighttime observations. During the day, only local AM transmitter and beacons are observed, while after dark, many nonlocal sources appear. In the example shown, the only additional nighttime signatures occur at discrete frequencies and hence represent most likely distant AM transmissions. At other times, different types of emissions are seen. Eventually, the PFR will be programmed to avoid known man-made discrete signals and concentrate on quiet bands in between them in order to identify natural emissions.

Figure 4 depicts the occurrence of ‘strong’ signals as a function of local time for two different nights. Strong signals are defined to be signals that would appear as a black line in the grayscale shown in Figure 3. Grayscales like Figure 3 were examined during each one hour interval and the number of discrete strong signals was recorded. Figure 4 plots the statistics for for two typical evenings out of fifteen studied to date. The frequency

12/07/90 - Frequency vs. Signal Strength - Two Rivers, Alaska

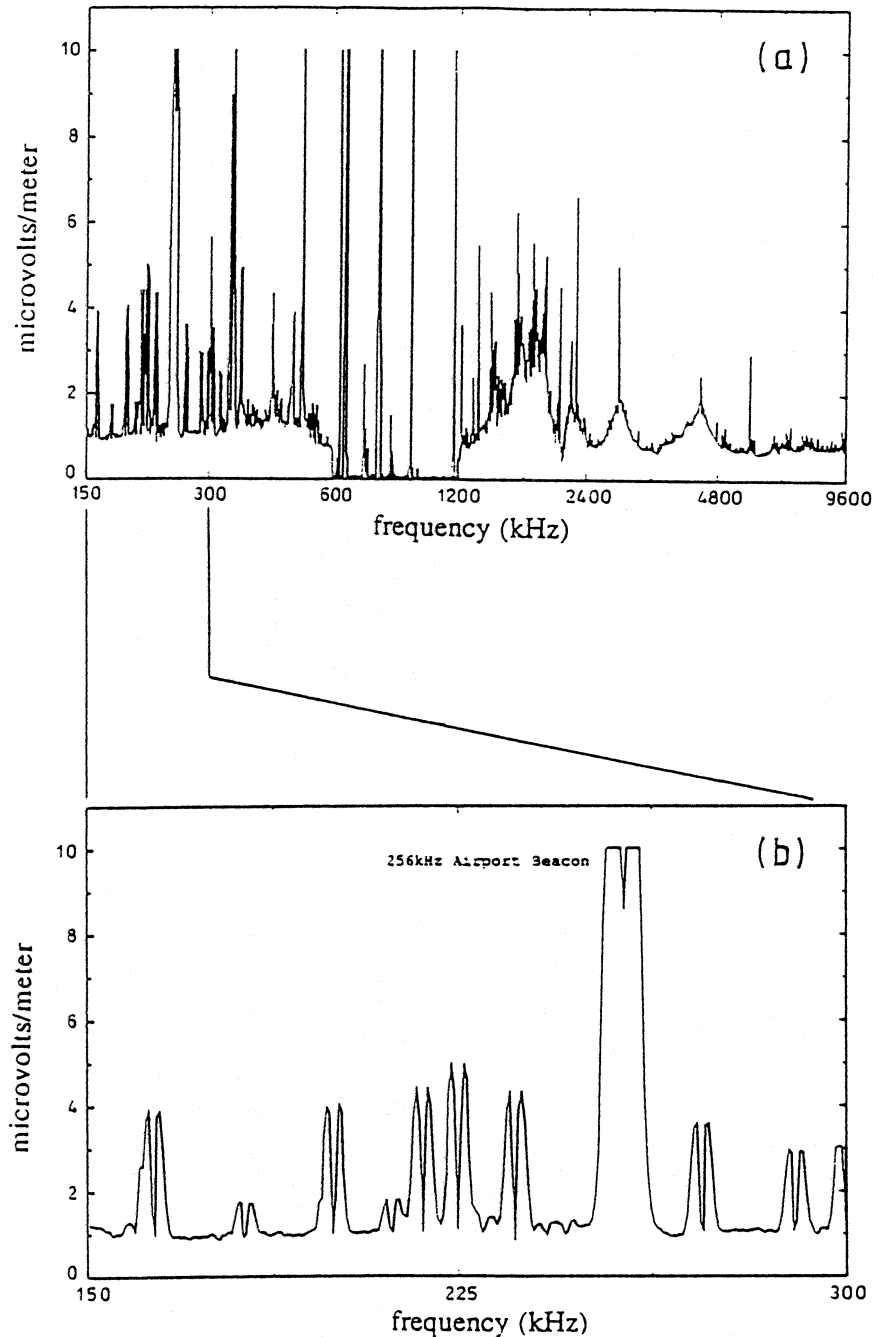


Figure 2: (a) A typical spectrum (signal strength versus frequency) recorded at Two Rivers, Alaska on December 7, 1990. All six of the receivers were calibrated and normalized with the exception of receiver 3, for which only relative measurements were available. Peaks in the spectrum correspond to known local sources, mostly AM radio stations, except for the peak at 3 MHz which represents interference from the experiment computer. The lower panel (b) shows an expanded view of 150–300 kHz. Each peak manifests itself as a double peak, due to the double humped response function of the receiver.

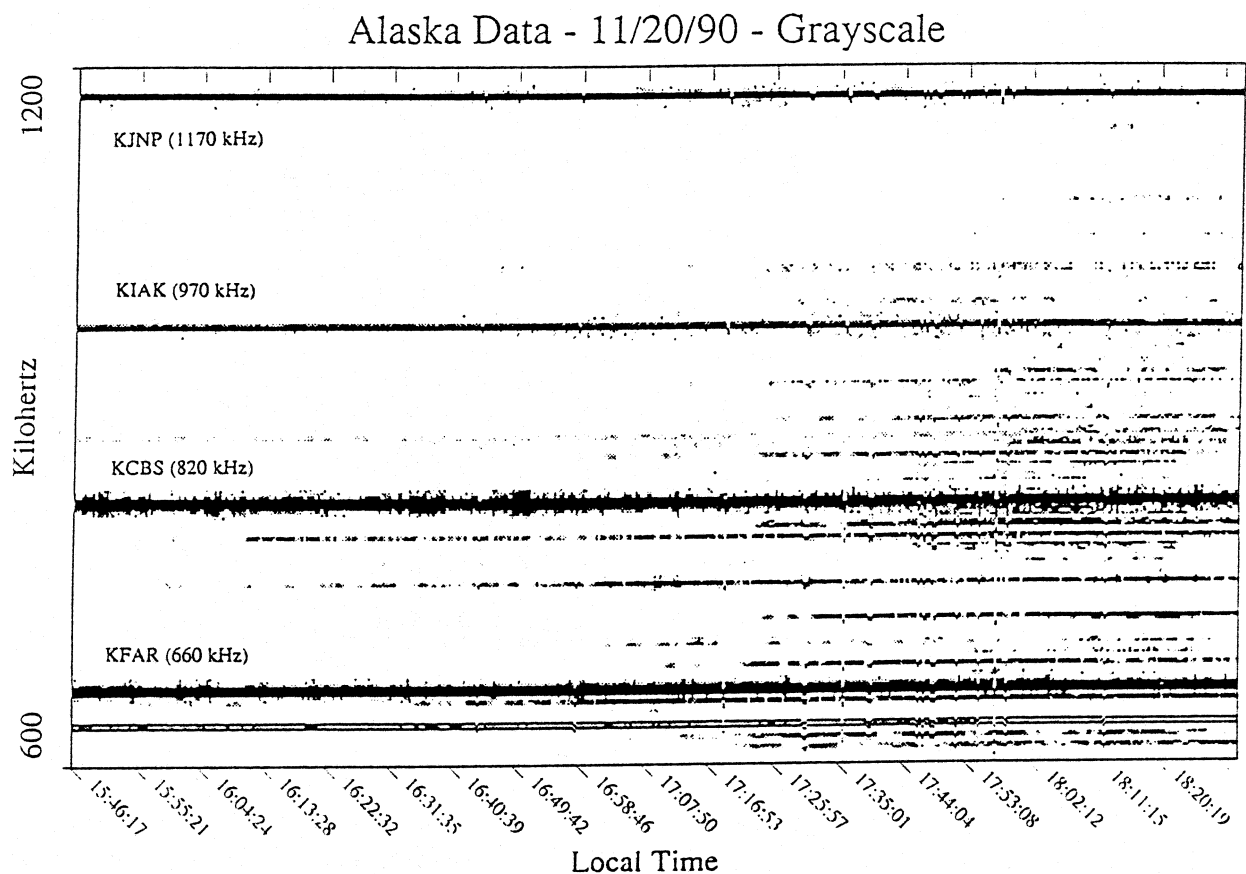
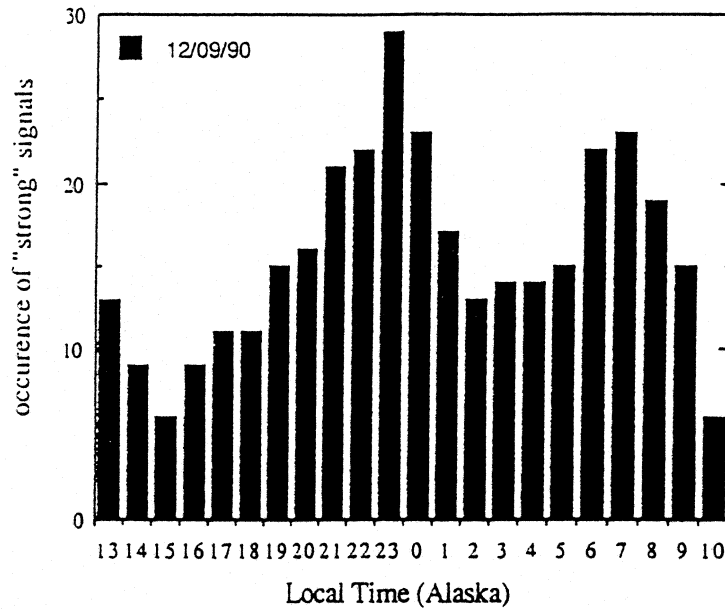


Figure 3: A typical dynamic spectrogram recorded at Two Rivers, Alaska on November 20, 1990. Notice that as sunset begins (15:20 LT on the ground, later in the ionosphere), distant radio stations and other signals increase in strength. Local radio stations are marked.

range 600–1200 kHz was used to generate Figure 4 because it falls in the heart of the AM broadcast band and contains many discrete strong signals, improving the statistics. The occurrences of strong signals favors the nighttime, as expected, with 2–3 times as many strong signals occurring near midnight as during the day. The number of strong signals tends to peak just before midnight, but it displays an interesting ‘double-humped’ distribution, consisting of the pre-midnight peak, a dip near 0300 LT, and a secondary peak near 0600–0700 LT. The significance of these features is not clear from the meager statistics in Figure 4 alone, but the pattern is repeated day after day.

A previous study monitoring the intensities of fifteen radio stations from Fairbanks over several years indicated a local time dependence of their intensities with some features similar to Figure 4 [R. D. Hunsucker, personal communication]. Though this feature may arise naturally, the effect could be purely artificial. For example, as is well known, radio waves propagate much greater distances with less attenuation after sunset, which could explain enhanced nighttime occurrence of strong signals. However, many stations cease transmission in the midnight to early morning timeslot. This coupled with the fact that many of these stations may originate from time zones east of Alaska could explain the observed distribution of strong signals.

12/09/90 - Histogram - Two Rivers, Alaska



12/11/90 - Histogram - Two Rivers, Alaska

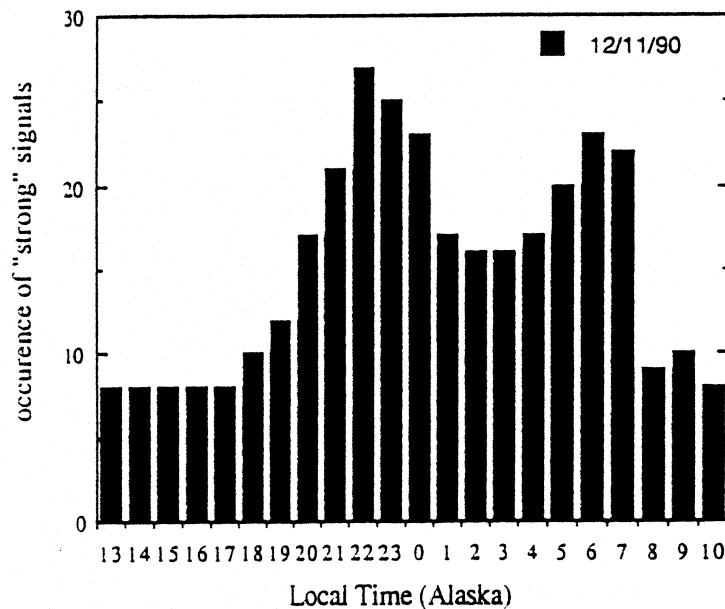


Figure 4: The number of discrete strong signals observed during one hour as a function of local time (LT), for two typical nights in December, 1990. The occurrence of strong signals is significantly greater at night than during the day; there is a peak somewhat before midnight, followed by a dip and a secondary peak near 0600–0700 LT. This effect may be of purely artificial origin, as discussed in the text.

4 Summary

A programmable frequency receiver has been designed and built for the specialized purpose of investigating natural radio emissions in the LF–HF band (0.15–9.6 MHz). The receiver uses a programmed VCO rather than a swept system for flexibility in selecting frequencies, which need not be evenly spaced. Also, any combination of frequency and time resolution can be programmed. The receiver also uses digital feedback rather than analog feedback (phase-locked loop) in order to lock on to frequencies faster. The relatively narrow bandwidth selections of the receiver (1.2 or 2.4 kHz) with steep rejection to the sides allows quiet frequencies to be monitored within the midst of noisy frequencies. Finally, the operation of the radio is handled by a microprocessor, freeing up the higher level computer for data logging and data compression.

The next step is to make the PFR a completely unmanned instrument for periods of up to one year by incorporating data compression and by using a larger disk drive. We also plan to incorporate more than two antennas into future versions in order to attempt to use polarization to distinguish natural from artificial signals. Eventually, magnetometer or other complementary geophysical data may be logged onto the PFR computer and could be used by the computer to determine favorable conditions for running the instrument.

As shown above, preliminary work involving radio station propagation raises interesting questions and provides a check of the instruments' operation. Besides this work, two types of studies focusing on natural emissions are underway. The first involves an extension of the study conducted by Benson et al. [1988], in which only four frequencies were monitored (150, 291, 500 and 700 kHz). We plan to re-do their experiment within the framework of ours; when signatures similar to theirs are identified, the higher frequency resolution available in our observations may settle the question of whether the emissions are man-made or natural in origin. A second study involves investigating several candidate emissions which we believe could be natural in origin. Correlation with magnetometer and all-sky camera data is an important component of this study.

Acknowledgments: We would like to thank the following people and institutions for their help on the development of this instrument: At Utah State University, SDL for the use of their CAD design equipment, Kay Baker, Jay Ballard, Joe Doupnik and Earl Pound; at Dartmouth College, Mike Trimpi, Rick Cook and Dave Collins; in Alaska, Eldon Thompson and Bob Hunsucker. Finally, we acknowledge support from Data I/O Corp. and Motorola Corp.

References

- Benson, R. F., M. D. Desch, R. D. Hunsucker, and G. J. Romick, Ground level detection of low and medium frequency auroral radio emissions, *J. Geophys. Res.*, **93**, 277, 1988.

- Benson, R. F., and M. D. Desch, Wideband noise observed at ground level in the auroral region, *Radio Sci.*, **26**, 943, 1991.
- Ellyett, C. D., Radio noise of auroral origin, *J. Atmos. Terr. Phys.*, **32**, 671–682, 1969.
- Gurnett, D. A., The Earth as a radio source: Terrestrial Kilometric Radiation, *J. Geophys. Res.*, **79**, 4227–4238, 1974.
- Helliwell, R. A., Whistlers and Related Ionospheric Phenomena, Stanford University Press, Stanford, Calif., 1965.
- LaBelle, J., Radio noise of auroral origin: 1968–1988, *J. Atmos. Terr. Phys.*, **51**, 197–211, 1989.
- Jones, D. L., Extremely low frequency ionospheric radio propagation studies using natural signals, *IEEE Trans. Comm.*, **22**, 477, 1974.
- Wu, C. S., P. H. Yoon, and H. P. Freund, A theory of electron cyclotron waves generated along auroral field lines observed by ground facilities, *Geophys. Res. Lett.*, **16**, 1461, 1990.
- Ziebell, L. F., C. S. Wu, and P. H. Yoon, Kilometric radio waves generated along auroral field lines observed by ground facilities: A theoretical model, *J. Geophys. Res.*, **96**, 1495, 1991.