PART I

Background

Chapter 1

Introduction

INVESTIGATIONS of communications by way of the ionosphere have been ongoing since the late 19th century. There are still many unknowns in this field despite one-hundred years of research. This chapter describes the motivation for investigating the topics in this thesis. Investigations are instigated by issues arising out of the development of an advanced HF receiver at Ebor Computing—issues important for HF communications.

1.1 Research Motivation

Long distance radio-communications became practical in the early-1900s with the experiments and inventions of Guglielmo Marconi (1909). Marconi was able to demonstrate the feasibility of long-distance wireless communications because, as later deduced from a theoretical perspective, ionized gases in the upper atmosphere (the ionosphere) cause refraction of high-frequency (HF) signals (nominally 2 MHz to 30 MHz). Such refraction enables signals to propagate beyond the horizon to distant receivers unable to be reached by higher frequency (VHF and above) signals. This fact makes the HF band attractive for private and commercial interests as well as for defence forces spread across the globe.

However, the tendency of modern communication systems (very often at frequencies above 800 MHz and with line-of-site propagation) is to achieve high bandwidth communications by moving to higher and higher frequencies. This push often comes with a perception that the area of HF communications is obsolete. High-frequency communications is alive, however, and indeed undergoing resurgence despite the advances of modern communications. Spectrum management organizations monitor the HF spectrum to control and enforce licensing of HF users, while defence agencies are interested in the HF spectrum, with respect to surveillance and back-up communications. These activities may require systems capable of determining the location of a source of transmission, separating valid signals from interference and noise, and identification of signal type. Identification of signal type and HF noise are the subjects of this thesis. These areas of research are critical if the ultimate goal is the development of robust algorithms for automatic recognition of signal modulations for *real* HF signals, where *real* refers to HF signals propagating by multiple ionospheric modes, accompanied by co-channel interference and non-Gaussian noise (Giesbrecht, Clarke & Abbott 2006).

Since 2002, a prototype receiver has been under development at Ebor Computing in Adelaide, Australia. The prototype receiver is a system that far surpasses the conventional HF receiver in many important ways. Its main task is to perform direction finding, signal enhancement, and separation of HF signals. One of its other capabilities, among many, is the extraction of unique features of signals-of-interest (SOI). This feature extraction is the primary focus of the research presented here. A secondary

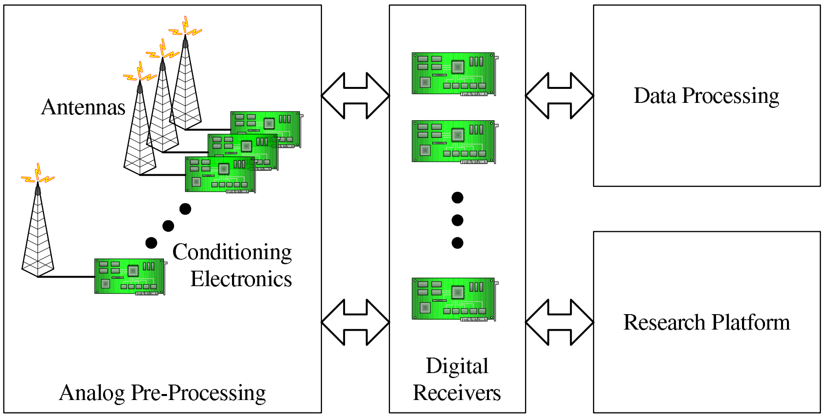

Figure 1.1. Overview of the advanced HF receiver. An overview of the advanced HF receiver. The receiver comprises four main subsystems. The analog RF subsystem contains arrays of passive antennas and other electronics to perform wideband conditioning of HF signals. The conditioned HF signals are processed in the digital domain; they are digitized by banks of wideband digital receivers and downconverted to baseband. A data processing subsystem applies various direction finding and signal enhancement algorithms to the downconverted signals. The research platform supports the work in this thesis.

focus is the description of the probability density function (PDF) of HF noise. This second area of research arises in conjunction with issues of feature extraction. Both areas of research support the work at Ebor Computing.

The prototype receiver is part of a capability-technology-demonstrator (CTD) that is designed to show that all tasks required of the receiver can be done satisfactorily in the digital domain. Except for some pre-conditioning RF electronics (*e.g.* anti-aliasing filters and RF gain control), the software and firmware performs all signal processing. Advantages of this approach include easy modifications to the receive chain (*e.g.* change of modulation technique), reduced temporal and temperature effects in components (*e.g.* oscillator drift), and a standard front-end consisting of an RF circuit for multiple communication methods.

The prototype receiver consists of multiple arrays of antennas, followed by signal conditioning electronics, multiple digital receivers, and a data processing system. Figure 1.1 shows the major sub-systems of the prototype.

The Analog RF Subsystem consists of antennas, amplifiers, attenuators, and filters. Outputs of this subsystem are fed to a rack of digital receivers that directly sample signals at frequencies up to 50 MHz and downconvert the HF channels to baseband.

The digitization of the RF signals is achieved by high-speed analog-to-digital converters (ADCs). Downconversion is accomplished with digital downconverters (DDCs). A data processing platform addresses functions such as modulation recognition, signal separation, signal enhancement, and single site location (SSL). A detailed discussion of the receiver is found in Chapter 6.

The CTD research and development program has a number of topics appropriate for a PhD program in ionospheric research, direction finding (and single site location), signal separation, and modulation recognition. Except for the SSL area, a preliminary literature survey identifies that there are few papers on modulation recognition or signal separation in the context of HF communications. For modulation recognition, most research is conducted with synthetic data and at frequencies much higher than the HF band. Research in signal separation appears to mainly concentrate on speech recognition applications. Within the SSL field, the main problem appears to be the unpredictability of the ionosphere and the inability to adequately identify propagation modes when ionosonde derived propagation data is unavailable. The advantage of research in any of these areas is that the results are directly applicable to aspects of the CTD. Moreover, the project provides a unique opportunity to conduct valuable research on a real platform to which few researchers have access. All of these areas of research could support multiple PhD programs.

1.2 Summary

The choice of topics for this thesis is guided by the realization that ionospheric research, direction finding, and signal separation are covered sufficiently well by others for the CTD project. Modulation recognition is the main area of research that is underrepresented. Literature reviews also reveal that there is a great need to apply modulation recognition methods to real HF signals. Following this line of thinking, it soon becomes clear that there is still a great misunderstanding as to what are appropriate parameters to extract from unknown signals in order to identify them. Consequently, the guiding principle for research in modulation recognition is to test existing methods on the prototype receiver with real HF signals, to propose necessary modifications to existing methods, to propose new techniques, and then to show that the new techniques and modifications improve on the performance of the existing methods. To a large extent this is achieved in this thesis, in that feature parameters are chosen and applied to real data sets. However, the application of feature parameters to real data raises the issue of: what is the PDF of real HF noise? This question spawns a separate line of research, which now forms a significant portion of the thesis at the expense of proposals for new and modified recognition techniques.

It is therefore necessary, in the next chapter, to review fundamental aspects of the ionosphere, software radio, modulation recognition, single site location (SSL), and signal separation. Reviewing these subjects provides a better understanding of the research motivation and a context for the discussions in later chapters.

Chapter 2

Background

THE study of the ionosphere, software radio, direction finding, single-station location (SSL), and signal separation is addressed by numerous researchers. A thorough treatise of each area is beyond the scope of this thesis but, a brief discussion of each area is warranted in this chapter. The topics of this thesis constitute only a small part of these fields, however, the brief reviews are nevertheless helpful in setting the scene for the discussion in the remaining chapters. The interested reader is directed to texts by Budden (1988), Davies (1990), Johnson, Desourdis Jr., Earle, Cook & Ostergaard (1997), Maslin (1987), Reed (2002), and Gething (1991) for a comprehensive examinations of these topics.

Furthermore, this chapter provides the necessary background to understand the importance of the selected research topics: the probability density function of natural HF noise, and signal features of HF signals for modulation recognition. Each of these topics are essential aspects of radiocommunications at high-frequencies (HF).

2.1 The Ionosphere

In a simplistic model, the ionosphere has three main regions: the D-, E-, and F- regions. These regions consist of partly ionized gases and free electrons or plasma. The concentration of free electrons is greatly affected by ultra-violet and x-ray radiation from the sun. Figure 2.1 illustrates the continuous nature of the density of free electrons in the earth's atmosphere.

The D-region is the most weakly ionized region and exists from about 50 km to 80 km above the earth. It allows communication at very low frequencies (VLF) because the D-region and earth form a type of waveguide but, is highly absorptive for signals with frequencies[1] between about 100 kHz to 2 MHz. As a result, effective daytime communications in this frequency range is limited to about 300 km. Attenuation by the D-region of signals above 2 MHz to 5 MHz decreases as the signal frequency increases. After sunset, the D-region disappears due to the removal of solar radiation, and consequently electrons and ions quickly recombine. The impact on communications is that, at night, signals passing through what was the D-region during the day are not absorbed but are propagated via the E and F regions[2]. The E-region covers altitudes of approximately 80 km to 150 km above the earth. Like the D-region, electrons and ions in the E-region also quickly recombine after sunset but, the E-region does not disappear entirely. The normal E-region permits limited medium-range (about 500 km to 2500 km) communications at low HF frequencies (typically less than 10 MHz). Sometimes areas of enhanced ionization in the E-region occur during the day or night. These enhanced regions are called Sporadic-E and facilitate propagation over longer ranges, sometimes via multiple hops.

The F-region exists from about 150 km to 1000 km above the earth. During the day, the F-region consists of the F1 layer (approximately 150 km to 200 km) and the F2 layer (above 250 km). Only one F layer is generally present at night above an altitude of about 270 km. Maximum ionization in the F-region occurs typically between midday and mid-afternoon but, unlike the other regions, the F-region typically remains weakly ionized throughout the night. Since the F-region is the highest of the regions,

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[1] Depending on the sunspot cycle the upper limit can be as high as 5 MHz to 8 MHz.

[2] This is why an amplitude modulation (AM) radio station can be received at locations far distant from the transmitter during the night.

NOTE: This figure is included on page 11 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2.1. Density profile of Earth's electron plasma. The density profile of electron plasma in the Earth's atmosphere is continuous. It extends from the lower atmosphere to the magnetosphere. The point of highest electron concentration is in the upper F-region. Figure courtesy University of Leicester Department of Physics.

a signal propagating by a single-hop of the F2 layer can reach from 3000 km to about 4000 km; multiple hops are required for greater distances. The maximum usable frequency (MUF) that the F-region will refract over a defined ground range depends on the degree of sunspot activity, time of day, season, and geographical location. During a sunspot maximum, the F-region can refract signals greater than 50 MHz in equatorial regions, while at a sunspot minimum the MUF might only reach 10 MHz. During 2008, the sun is at sunspot minimum.

On a side note, the Comité Consultatif International des Radiocommunications (CCIR), now called the International Radio Consultative Committee, has established a mapping procedure for monthly median M(3000)F2. The median M(3000)F2 is the ratio of the maximum usable frequency over a distance of 3000 km and the vertical critical frequency for the F2 layer. At sunspot maximum M(3000)F2 attains maximum values in low-latitude regions. For a typical day, the M(3000)F2 achieves its peak in the afternoon to early evening and is lowest prior to sunrise. The M(3000)F2 parameter and vertical critical frequency of the F2 layer is used to determine the MUF over an oblique path.

Radio-wave Propagation

High-frequency (HF) signals can propagate beyond the horizon or follow the surface of the earth. Waves that follow the surface of the earth are called groundwaves, while those refracted by the ionosphere are called skywaves. It is important to note that skywaves are refracted and not reflected as one might suppose from Figure 2.2. As discussed previously, the ionosphere is a continuum and there is no hard dividing line between ionosphere and non-ionosphere. Surface propagation can extend to ground ranges up to a few hundred kilometers with the longest ranges being over sea water and at the lowest HF frequencies. Ionospheric propagation can extend to ground ranges exceeding 10,000 km. To achieve a propagation distance such as this, the signal would typically go through multiple hops (see Figure 2.2).

Skywaves can travel via various modes or paths (*i.e.* multipath). For example, a wave refracted only once by the F-layer would be designated a 1F mode. A wave can also follow a type of waveguide created by the layers of the ionosphere. A 1F1E mode

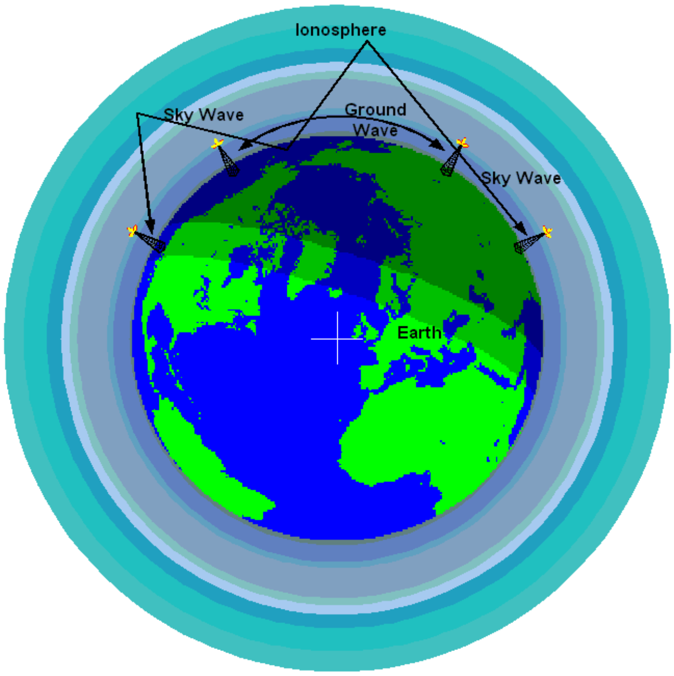

Figure 2.2. Groundwave and skywave propagation. A simple example showing groundwave and skywave propagation. The skywave ray shows multiple hops. Groundwave propagation can reach ranges up to a few hundred kilometers. Skywave propagation can extend to ground ranges exceeding 10,000 km.

indicates that the wave travels via the F-layer, then experiences a ground reflection followed by a second refraction off the E-layer. A ducted mode (or M-mode) is a wave that propagates via one hop of the F-layer, is then refracted back to the F-layer via the E-layer, before being refracted by the F-layer once more and being received at the ground.

Multiple modes of propagation (or multipath) often create difficulties for receivers. Depending on the frequency of transmission and the state of the ionosphere, multi-modal signals can be separated by delays ranging from less than 1 ms to several milli-seconds. One impact of this delay is that the multiple modes can combine constructively or destructively. When the modes combine constructively the received signal is strong. When they combine destructively fading occurs and the received signal is weak. This is only one type of fading. Fades can also occur as a result of travelling ionospheric disturbances (TID) that cause skywaves to be greatly attenuated or diffracted, solar events that enhance the D-region to the point where wave energy is absorbed, or as a result of any other event that interrupts the propagation of the signal. Another consequence of the multipath problem is that smearing (in time) of the signal can occur. The impact of smearing is inter-symbol interference (ISI) for digital modulations and in extreme cases echoes for voice signals.

HF Noise

Multipath issues are not the only problems for a receiver: electromagnetic noise also affects a receiver's ability to downconvert and demodulate a signal. Noise is composed of many components that include atmospheric noise, environmental noise, galactic noise, and electronic noise generated by the receiver itself. Atmospheric noise changes with the time of year and is largely influenced by lightning activity (both local and distant). Man-made (or environmental) noise is produced by electromagnetic radiating devices (*e.g.* electric machinery, computers). Galactic noise is produced by cosmic radiators such as the sun. It is clear that the HF noise distribution is affected by the time of day, season, electromagnetic environment, and ionosphere. Actually, it is known that HF noise is impulsive (CCIR 1986). For example, lightning activity at a distant location can, by various ionospheric modes, contribute to the local HF noise distribution. In fact in some regions, HF noise is directional and dominated by lightning activity (Coleman 2006). In other areas, such as industrial estates, the noise has a dominant component of man-made electromagnetic activity from local sources (Giesbrecht *et al* 2006). Yet, many researchers continue to assume that noise is Gaussian. That assumption is not generally valid for HF communications. Part II addresses the question: what is the probability density function of HF noise?

2.2 Software Radio

In the past, HF communication systems were analog. This meant that signals received by an antenna were downconverted to baseband using filters, oscillators, and many discrete components. Receivers were generally constructed in a superheterodyne configuration (Smith 1986) as seen in Figure 2.3. The baseband signals were then passed through demodulators to extract the information content. Often special demodulators

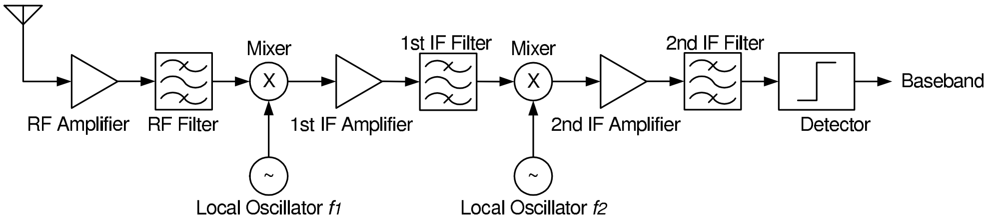

Figure 2.3. A conventional superheterodyne receiver. A conventional superheterodyne receiver consists of many components. Generally a low-noise amplifier (LNA) is followed by filters, and the first intermediate frequency (IF) oscillator. Further signal conditioning, via amplifiers and filters, occurs before the second IF oscillator is encountered. The output of the a second set of amplifiers and filters, is the baseband signal. The type of detector depends on the information content of the signal.

had to be switched in to demodulate signals with different modulation schemes. Then of course in military scenarios, there were jamming signals to contend with and the need to determine the location of the source of a transmission. Depending on the complexity of the receive system, one or perhaps two interfering signals could be rejected while a beam was formed in the direction of a signal-of-interest (SOI). This would have been done with analog computation techniques but with the advent of the digital computer many of these tasks became less cumbersome.

Software radio aims to replicate hardware functions in software running on a generic platform. In so doing many of the problems associated with receiver implementations are avoided. In addition, receiver chains can easily be changed to accommodate various modulation schemes. The idea is to digitize the incoming radio-frequency (RF) signal directly and then to perform downconversion and demodulation in digital hardware and/or software. This is now possible with current high-resolution analog-to-digital converters (ADCs) and digital downconverters (DDCs). Modulation recognition[3] algorithms may then be used to automatically choose the correct demodulator.

Today, there are many different modulation techniques. Many of these are of the family of space-time layered signals. Some techniques include direct-sequence spread spectrum (DSSS), frequency-hopped spread spectrum (FHSS), time-domain multiplexing (TDM), frequency-domain multiplexing (FDM), and parallel transmission of data

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[3] Modulation recognition is the process of automatically determining the modulation type of a signal with no foreknowledge of the signal modulation.

through multiple antennas and/or frequencies. Traditional HF monitoring, processing, and analysis cannot easily handle these signals.

Monitoring and detection of such signals using traditional methods would require numerous HF receivers. Monitoring and detection would also require some prior knowledge of the signals so as to choose the correct receiver. This is a difficult task. Furthermore, recognition of a particular SOI amongst other signals is extremely complicated with analog techniques. Early computers made these processes easier, but only recently has enough processing power been available in one package to perform all the tasks above.

Software radio is now entirely feasible, and it aims to replicate hardware functions in software running on a generic platform. In so doing many of the problems associated with hardware implementations are avoided. In addition, the receiver and transmitter chains can easily be changed to accommodate various modulation schemes. Figure 2.4 illustrates one implementation of a software radio receiver (Reed 2002). The idea is to digitize the incoming radio-frequency (RF) signal directly and then to perform downconversion and demodulation in digital hardware. High-resolution analog-to-digital converters (ADCs) and digital downconverters (DDCs) are now available for operation at sampling rates in the 100 MHz range. These sampling rates allow for direct digitization of RF signals up to around 50 MHz. A Digital-to-Analog Converter (DAC) reconstructs the baseband signal after digital demodulation and decimation.

Modulation Recognition

Another advantage offered by software radio is the ability to automatically choose the correct demodulator for a signal. This ability requires automatic modulation recognition, which is the process of determining the modulation type of a signal with no foreknowledge of the signal modulation characteristics. This field has been a topic of research since the 1980s. During those early days, modulation recognition was accomplished through multiple hardware demodulators—one for each modulation type of interest. With the advent of software radio, these multiple demodulators are being combined in software. But with either method, the purpose of modulation recognition is to determine the type of modulation so that the correct demodulator can be chosen to demodulate the signal.

Fundamental processes of modulation recognition are feature extraction and classification (see Figure 2.5). Feature extraction determines unique characteristics of the signal so that the classifier can establish the modulation type. Common features include instantaneous amplitude, variance of phase, spectral symmetry, transmission models, and higher order statistics (*e.g.* n^{th} order moments). Classifiers generally consist of threshold detection logic, artificial neural networks (ANNs), or pattern recognition algorithms.

An important question to ask is: what features are most appropriate for identifying unknown signals? This is the subject of Part III.

2.3 Single Site Location

Single Site Location (SSL), which is also called Single Station Location, is a method that estimates the bearing and range of a transmission source, based primarily on measurements at a single receiver site. A general SSL system (depicted in Figure 2.6) consists of multiple antennas, signal conditioning electronics, a receiver or receivers, a processing subsystem, an ionosonde, and a controlling system. The arrangement of the

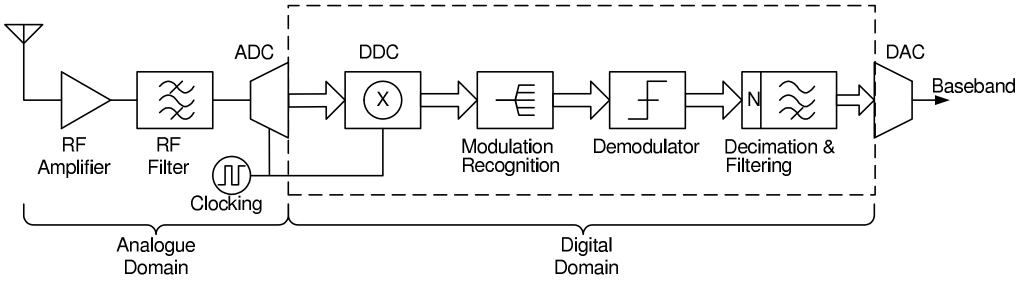

Figure 2.4. A typical software radio with digital and analog domains. A typical software radio contains the LNA and filter structure of the superheterodyne receiver prior to the first IF oscillator, but that is where the similarity ends. In place of the first IF oscillator, the software radio digitizes the RF signal and then, in the digital domain, performs direct conversion to baseband via DDCs and digital filters. The output of the DDCs and digital filters can be used for any purpose including modulation recognition and, if necessary, converted back to the analog domain with the use of a digital-to-analog converter (DAC).

antennas (*e.g.* an L-array) is such that phase differences between antennas translate to bearing and elevation-angle information. The signal conditioning electronics prepares the acquired RF signals for the receiver, while the receiver downconverts and demodulates the signals. The processing system computes direction and elevation angles, and range based on ionospheric information provided by the co-located ionosonde (or from ionosonde data recorded at remote sites). The control segment oversees the operations of the entire system. Such an SSL system structure is similar to that of the advanced HF receiver in Chapters 6 and 11 and is reminiscent of Treharne's (1981) basic SSL system.

Treharne (1981), Gething (1991), and Groller (1990) provide brief commentaries on range and bearing determination. The most common non-SSL method is to fix the position of an emitter based on estimates of bearing from two or more DF receive sites. Such *horizontal* triangulation methods, however, require sophisticated coordination between receive sites. SSL is a similar technique that performs triangulation in the vertical plane (see Figure 2.7). Given a measurement of elevation-angle β, and reflection height h, the range, R, to the transmitter is

$$R = 2d = \frac{2h}{\tan\beta}. \tag{2.1}$$

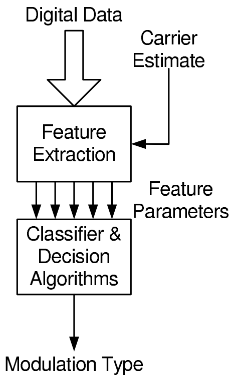

Figure 2.5. A typical modulation recognition structure. Modulation recognition generally has two stages. The first is feature extraction where, in the ideal case, an orthogonal feature set is created and passed to the second stage: classification. The orthogonal feature set allows the classifier to group observations and to associate the observations with candidate modulation types in a database of modulations. A decision on which modulation type is made by an appropriate algorithm.

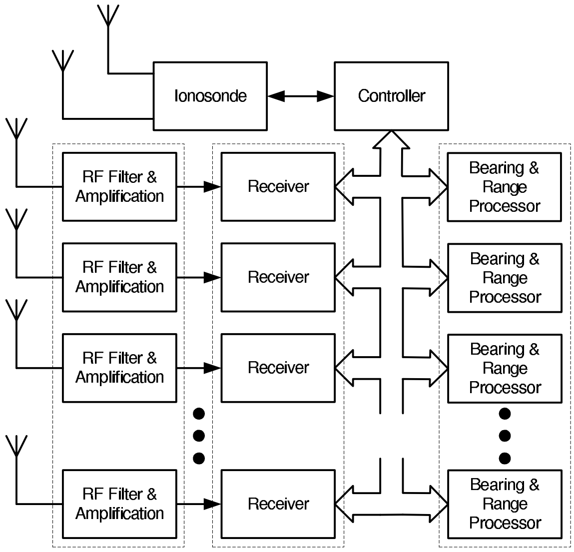

Figure 2.6. A typical SSL system. A typical SSL system requires multiple antennas, receivers, and processing modules in order to perform direction finding. For SSL direction finding includes bearing and elevation information as well as an estimate of the propagation mode and the apparent height of reflection. Consequently, ionosonde data is a necessary input to any SSL system.

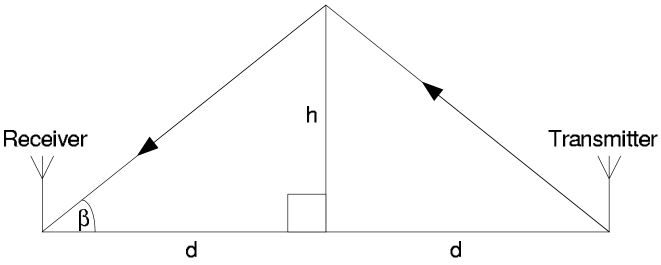

Figure 2.7. A simple model for range calculation in SSL. Range calculations for SSL is a simple matter of trigonometry. The range to the transmitter can be calculated, given the estimated height of reflection and elevation-angle of the incoming signal.

In principle, with SSL it is possible to estimate the range of the transmitter using elevation angle and bearing provided the height of reflection is known. But in general, range and bearing estimation suffers from the uncertainties of the ionosphere. These uncertainties include ionospheric tilts, travelling ionospheric disturbances (TIDs), variations in refraction regions (*e.g.* D, E, and F layers), and difficulties in identifying modes and reflection height. Consequently, accurate determinations of range and bearing require knowledge of the ionosphere along the ray path. This knowledge would ideally come from multiple ionosondes but, usually only one is present at an SSL receive site to determine ionosphere height and tilt. Predictions of the characteristics of the ionosphere along the rest of the ray path come from appropriate ionospheric models.

The SSL technique can be broken into four functional areas (Treharne 1981, Groller 1990):

- measurement of bearing and elevation,
- identification of propagation mode(s),
- estimation of ionospheric height for identified mode(s), and
- calculation of transmitter location.

Of these, the most critical to accurate location fixing are ionosphere height and identification of the propagation path. In fact, the problem is made more severe if multiple propagation modes are present. Under such conditions, two or more ionospheric reflections (and consequently ionospheric heights) are involved.

Even so, McNamara (1988) showed that range determination by *vertical* triangulation could be accurate (errors on the order of ±10%) up to approximately 3,000 km, provided an appropriate ionospheric model was chosen. He found that errors in bearing and range measurements were almost exclusively limited by ionospheric effects, and that a simple quasi-parabolic ionospheric model would suffice *in lieu* of real-time monitoring of ionospheric conditions.

The greater the distance from the transmitter the more difficult the separation of modes by the SSL system. Various researchers (Treharne 1981, Groller 1990, Gething 1991) report on the usefulness and accuracy of short-range SSL systems. In this context short-range refers to distances less than about 500 km with errors of less than ±10%. The low percentage error is due to the fact that the ionosphere is uniform for ground ranges up to approximately 300 km (Gubbay & Lynn 1988).

A simple propagation mode corresponds to one hop between earth and a layer of the ionosphere. More complicated modes consist of multiple hops between layers of the ionosphere as well as between ionospheric layers and the earth. For example, a 1F1E mode is a signal that is refracted from the F-layer back to earth and then bounced off the E-layer before arriving at the receiver. Recalling the reasons (see chapter introduction) for this discussion, an obvious track of research in SSL would have been to investigate methods of determining signal modes in an effort to reduce their effect on the accuracy of location fixing.

Bradley, Damboldt & Suessmann (2000) supported such an effort in their discussion on available modelling options for determining HF propagation modes. They listed numerous shortcomings of existing methods such as: inaccurate ionospheric models for large regions of the world, improperly addressed spatial and temporal ionospheric variations at high latitudes, poorly modelled ionospheric irregularities, too few ionospheric soundings, and uncertainties in communication equipment. They suggested that schemes must be found that 1) improve the accuracy of current methods, and 2) that are simpler than current methods.

It is well known, that an appropriate modulation scheme can combat multipath problems (Goodwin, Jeffrey & Hichens 1992, Furman 1997, Demeure & Laurent 1997, Noble, Spicer, Midwinter & Farquhar 1997). A particular modulation may therefore improve the ability of SSL systems to accurately determine range and bearing of a target transmitter. If it is known how HF signals with a particular modulation scheme behave, it may be possible to use this information to mitigate the multipath problems and thereby improve the accuracy of SSL systems or, at least, assign a quality figure to an SSL result based on modulation and ionospheric conditions. This idea provides further impetus for the modulation recognition research in this thesis.

A paper by Baker, Clarke, Massie & Taylor (1997) investigated the decomposition of modes based on phase and amplitude information extracted from the time varying transfer function of an HF sky-wave. They swept the transmit frequency of an oblique sounding link over a narrow 10 kHz bandwidth and then recorded the received baseband signals. By separating the received signals into odd and even functions and then processing them with the Fourier Transform, they were able to extract the phase component of the received signals. The phase component showed that Doppler effects degraded the phase coherence of the signals. They then represented the phase component in a Doppler frequency versus group-delay plane. They found that three or four modes existed in the received signals and that separation of the modes was difficult if the modulation bandwidth was greater than half the Doppler frequency separating the nearest signal modes. In their example the modulation bandwidth had to be less than 1 Hz to prevent the modes overlapping. They concluded that individual signal modes could be separated and intermodal interference recognized with their method but, additional signal processing techniques based on null-steering and adaptive polarization could further reduce phase distortion and thereby improve modal separation in some situations.

The identification of the number of modes and their separation is of great value because the performance of SSL systems are limited by multimode signals. If a dominant first-order mode can be identified and higher-order modes rejected, the reliability and accuracy of SSL systems would improve. One question that needs to be answered is what distinguishes a first-order mode from higher-order modes?

In fact, a combination of modulation recognition, signal separation, and mode identification techniques could be employed to improve the accuracy of SSL systems. Baker *et al* (1997) suggests that the modulation bandwidth of the signal needs to be less than 1 Hz, however, in practice modulation bandwidths exceed 500 Hz. As a result, there is little chance that the 1 Hz condition will be realized.

Smith, Angling, Cannon, Jodalen, Jacobsen & Gronnerud (2001) confirmed Baker's results on the Doppler spread of HF signal modes. In this paper, the researchers looked at HF propagation at high latitudes in Norway. They compared two tests of on oblique sounder: one where the transmit frequency was fixed, and another where the transmit frequency was hopped across a 500 kHz bandwidth. They discovered that Doppler spread was independent of SNR and that it was relatively constant across the 500 kHz band.

The performance of SSL systems is limited by the characteristics of the ionosphere. Ionospheric tilt, traveling ionospheric disturbances, uncertainty of ionosphere height, and other unknown conditions along the transmission path affect the accuracy in determining location of a distant transmitter. And, the inability of SSL systems to adequately recognize and detect arriving signal modes further complicates the calculation of transmitter position.

Common methods to address these issues rely on ionospheric models that assume stationary characteristics over a geographic region, modeling of ionospheric irregularities, and selected ionospheric soundings over portions of the earth. These techniques, though attempted in the past, are cumbersome and often inaccurate. There needs to be an efficient procedure to determine the properties of the ionosphere along a transmission path.

An initial proposal for a thesis topic, was to compare vertical and oblique ionograms along a signal transmission path and to then create a synthetic ionogram that could be related to the results of a real-time vertical ionosonde (see Figure 2.8) at an SSL receiver. For example, a vertical incidence ionosonde, oblique incidence ionosonde receiver, and SSL system could be in city $\mathbb{X}$. An oblique ionosonde transmitter and HF transceiver could be located at city $\mathbb{Y}$. The $\mathbb{Y}$-ionosonde would transmit a signal to the oblique ionosonde receiver at $\mathbb{X}$. The resulting ionogram (see Figure 2.9) would show the properties of the ionosphere along the path between the two cities. The vertical ionosonde determines the properties of the ionosphere above city $\mathbb{X}$. An HF transceiver in city $\mathbb{Y}$ could then send messages having various modulations to the SSL receiver in city $\mathbb{X}$ so that the properties of the received signal and the two ionograms could establish: 1) a relationship between oblique-incidence ionograms and local vertical-incidence ionograms; and 2) the role of modulation type, if any, in SSL bearing and range determination. The former is already under investigation by others (Gubbay & Lynn 1988), but the latter may not have the same level of attention.

Using the oblique incidence ionosonde and HF transmitter, mentioned above, a study of modulation and equalization techniques could demonstrate the most appropriate modulation and equalization techniques for a given ionospheric scenario. Such a study would consist of characterizing the ionosphere and its affect on benchmark HF transmissions. For example, for a particular ionospheric scenario it may be that the location of HF transmissions utilizing FSK are more easily discerned than similar transmissions using amplitude modulation. The question to answer is: what effect does modulation have on SSL results? Also, it may be that one equalization technique is more useful for SSL than another. The resulting question is formed in a like manner: what is the effect of equalization on SSL results?

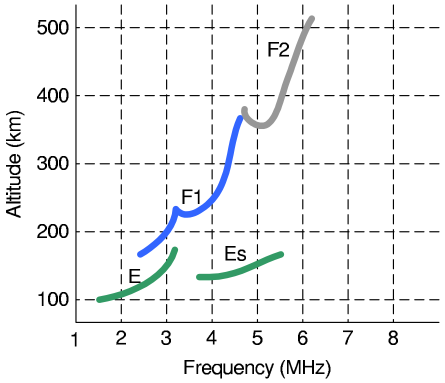

Figure 2.8. A typical vertical incidence ionogram. A typical vertical-incidence ionogram measures apparent reflection height against frequency. A vertical-incidence ionosonde transmits a frequency-swept signal in a direction orthonormal to the Earth's surface. The same ionosonde receives backscatter from the swept signal as it encounters the regions of the ionosphere. Measured observations form curves, such as those in the diagram. Each region of the ionosphere and various anomalies of the ionosphere affect the appearance of a vertical-incidence ionogram. This example has characteristics of a high-latitude ionogram with a sporadic-E layer trace.

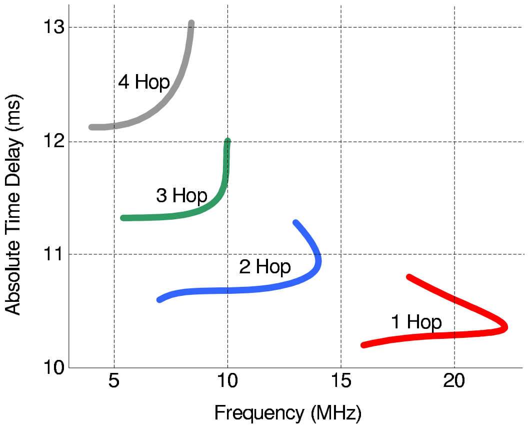

Figure 2.9. A typical oblique incidence ionogram. An oblique-incidence ionogram requires a transmitting ionosonde and a receiving ionosonde. The transmitter ionosonde sends a frequency-swept signal to the receiver and a measure of time-delay versus frequency is obtained. Each region of the ionosphere and various ionospheric anomalies affect the appearance of an oblique-incidence ionogram. This example shows that the particular transmission path has four propagation modes depending on the transmission frequency. The best frequency for transmission is near 20 MHz because only one mode exists. Between 6 MHz and 8 MHz three modes exist, which will cause multipath distortion of a signal transmitted at these frequencies.

Another possibility is that signal separation techniques may improve the ability of SSL systems to recognize and resolve signal modes. For instance, based on ionospheric predictions and models, the methods of Yen & Zhao (1996) and Erten & Salam (1999) could be adapted to estimate the expected modes. Recombining the estimated modes and correlating with the actual incoming signal would show how well the separation algorithms are able to decompose the original signal into its constituent modes. Then a comparison between bearing and range calculations on the estimated modes and the original signal and the true bearing and range of the transmitter would demonstrate the performance gain or loss of the method. If signal separation techniques do improve SSL performance, one would expect to see that the bearing and range calculation on the estimated signal modes is more accurate than the calculation on the original distorted signal.

Noise and interference cancellation techniques also exploit the spatial properties of antenna arrays. A basic technique estimates the noise and then subtracts it from the incoming signal. Another method is beamforming and null steering. Whatever the procedure, it should be possible to reduce the effects of noise and then to use algorithms such as MUSIC (MUltiple SIgnal Classification) or Capon to extract noise-reduced signal modes (Gething 1991) for better range and bearing determination.

2.4 Signal Separation

Signal separation is commonly performed in the time, frequency, and spatial domains. Temporal/spectral separation uses time/frequency characteristics of the observed signal to break it into its constituent parts. For example, an observer in a crowded room of men hears all the speakers in the room as a cacophony of low-frequency noise, but is able to easily distinguish the higher frequencies of a woman's voice when she enters the room. Each speaker forms a constituent part of the sound heard by the observer. In this case the trick is to identify the individual parts given only the resultant signal and its spectrum. Spatial separation on the other hand, attempts to separate a signal from a plethora of signals based on the physical location of the signal source relative to all other signal sources. This is commonly used in the *smart* antenna field where antenna beams are directed toward a signal-of-interest in an effort to receive that signal

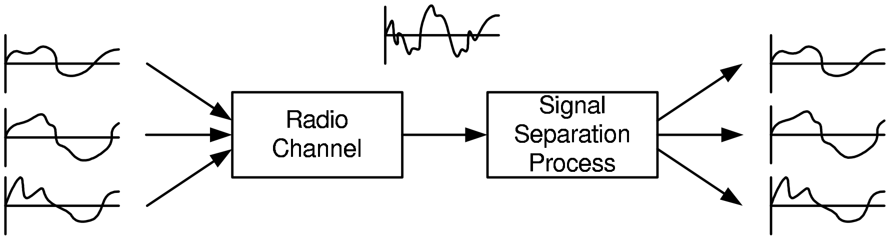

Figure 2.10. Concept of the signal separation technique. The concept of signal separation is to decompose a composite signal into its constituent parts. The decomposition process may be performed in the time, frequency, or spatial domains, or even a combination of these domains.

more clearly. In this mode, multiple sensors are necessary to target the signal source. The observer in the crowded room is able to detect the approximate location of the woman based on the time delay between the woman's voice entering one ear and then the other. Once the location is determined, the observer can turn in the direction of the woman so that both ears receive the voice signal at the same time and improve the observer's ability to hear the woman.

Figure 2.10 illustrates the concept of signal separation in the context of radiocommunications. Numerous sources transmit their signals over the radio channel, which is affected by fading, noise, Doppler shifts as well as multimode propagation and multipath effects. The job of the receiver is to decompose the received signal into its parts.

Jang & Lee (2002) demonstrated a method to separate multiple audio sources from one observed audio signal. The observed signal was modeled as a linear combination of the multiple sound sources. Each of these sound sources was similarly modeled as a linear combination of m basis functions. Separation of the audio sources from the real observed signal meant maximizing the *closeness* of the linear combination of basis functions to the real observed signal. To measure this *closeness*, the researchers used a generalized Gaussian distribution to estimate the underlying distribution of the basis function coefficients and then monitored the log-likelihood of the basis function coefficients through a number of iterations of the algorithm. Jang and Lee used the algorithm on mixtures of two sound sources from a set of four: rock music, jazz music, male speech, and female speech. They found that a mixture of jazz music and male speech was more easily separated than other combinations.

The method the authors present does not depend on assumptions like sources disjoint in the spectrogram, or the concatenation of several disjoint subspaces in time. However, their method does require a set of statistically independent basis functions. Selecting a set of basis functions for radio communications can be quite difficult because of many varied signal types. Furthermore, characteristics of the ionosphere and re-radiating structures can cause signals to appear statistically dependent and correlated. Such signals violate the criteria for statistical independence. Finally, the authors appear to investigate only the mixture of two audio sources. There is no mention of how the algorithm performs for larger mixtures.

Stanacevic, Cauwenberghs & Zweig (2002) proposed a method to simplify the separation of mixed signals arriving at a miniature microphone array for the purpose of improving sound localization for users of hearing aids. The technique, called *gradient flow*, consisted of reducing the combined signals to a set of spatial and temporal differentials. These differentials were used to estimate the direction-of-arrival of the source signals and to thereby separate them from the combined received signal. Though able to handle differentials to the m^{th} order, first-order differentials were deemed accurate enough to meet the needs of hearing aid users. With assumptions of far-field analysis (*i.e.* distance between source and array is much larger than the dimensions of the array), statistically independent sound sources, Gaussian noise, and array dimensions (*i.e.* less than the wavelength of the highest frequency in the received signal), the authors claimed that first-order differentials provided a 12 dB to 20 dB reduction in cross-talk between individual sound sources received by the array.

The algorithm presented by Stanacevic *et al* (2002) is generally applicable for HF signals with the following exceptions. Gaussian noise cannot be assumed for HF skywave propagation because noise in the HF band consists of man-made noise, atmospheric noise, and galactic noise. Secondly, multipath skywave propagation can cause components of the received signal to be highly correlated and dependent. And finally, unlike sensor arrays presented by the researchers, far-field assumptions for HF signals require distances of the order of tens of kilometers.

While Jang & Lee (2002) and Stanacevic *et al* (2002) looked at fewer than five arriving signals, Chan, Rayner & Godsill (1996) considered n independent input signal sources detected by n sensors. The n sensor outputs were a mixture of the n source signals as determined by n^2 mixing functions. The problem faced by the researchers was to find n^2 separating functions to extract the original n source signals from the n sensor outputs without knowledge of the mixing functions. They also developed a cost function and minimized it with respect to the separating functions based on assumptions of constant power and that at each sensor one of n source signals was clearly received unmixed with the other sources. Their results showed, with limited success, that the algorithm was able to separate estimates of up to three source signals. However, their method requires independent source signals. In the HF environment, the ionosphere can introduce multiple propagation paths for a signal. Each of these propagation paths can be treated as separate but dependent signals from the viewpoint of the separation algorithm. In such a situation their method of separation fails.

Ham & Faour (1999) conducted analyses of infrasound (below audible frequencies) signals less than 2 Hz from volcanic, gravitational, and mountain events[4]. They used independent component analysis (ICA) to separate unknown source signals from the linear mixtures received by multiple sensors. With the assumption of zero-mean wide-sense stationary source signals, they showed that neural networks could be used to whiten the received signals, separate them, and then estimate their ICA basis vectors. The whitening process normalized the variances of the observed signals to unity. They then used the kurtosis (fourth-order cumulant) of the data in an adaptive separation algorithm. Finally the neural network was trained with a steepest descent approach in order to estimate the ICA basis vectors. Test results showed that signals recorded during volcanic eruptions, gravitational waves, and mountain associated waves (MAW) could be separated, with high correlation coefficients (greater than 0.94), from a random but linear combination of the signals as received by four sensors.

Ham & Faour (1999) use a technique that appears adaptable to the HF band except that they assume zero-mean wide-sense stationary signals, which is not always valid for radio-communications. In addition, their work at frequencies less than 2 Hz allows the neural network to be trained very quickly (*e.g.* within 250 epochs). Operation in the HF band may dictate much longer training periods for the neural network.

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[4] The impetus for the work was the development of systems to enforce the Comprehensive Nuclear Test-Ban Treaty (CTBT).

Other researchers, such as Yen & Zhao (1996), Park, Jung, Lee & Lee (1999), and Erten & Salam (1999) have focused on signal separation for speech recognition. Though their techniques are targeted at speech recognition applications, they nevertheless could find use in HF applications.

For example, Yen & Zhao (1996) proposed a method for adaptive de-correlation filtering (ADF). The ADF method attempted to de-correlate input speech signals by comparing the variances and covariances of estimates of the source signals with defined thresholds in the time domain and frequency domain. They showed that a correlation coefficient could be used to detect when one signal was active compared to an inactive one.

Their method does show an ability to separate voice signals, but more striking is the fact that their correlation coefficient can accurately detect when one of multiple voice signals falls silent. This could be exploited in surveillance systems to detect a valid signal from an interfering one.

Erten & Salam (1999) also considered extraction of voice signals. In their method they proposed state space methods for blind signal separation of voice. Instead of the common static mixing matrix in blind signal separation techniques, they opted for a dynamic mixing matrix. This had the advantage of addressing unknown and possibly variable signal propagation delays, nonlinear mixing functions, and unknown numbers of source signals which the static mixing matrices could not handle. They defined a dynamic mixing equation

$$\tau \dot{U}(t) = -U(t) - DU(t) + M(t) \tag{2.2}$$

where τ was a small time constant, $U(t)$ was the estimate of the original signal sources, D was the iteratively determined mixing matrix, and $M(t)$ was the mixed signal vector. Their results showed that the method worked very well for the separation of voices and background noise.

Their paper is, perhaps, a defining article on signal separation. The researchers target the separation of voices from a mixed signal, but the method they use seems directly applicable to HF signals experiencing nonlinear processes. With such a technique, it may be possible to more accurately model the effects of the HF transmission channel on signals of interest.

Many researchers attack the signal separation issue with independent component analysis (ICA) techniques. Note that ICA is a statistical method for analyzing hidden facets of random variables, measurements, or signals. In ICA, data variables are estimated based on a large sample space of observations, and linear or nonlinear combinations of those observations. The mixing function that combines the observations is also unknown. With the assumption that the data variables are Gaussian and mutually independent, ICA can extract independent components of the input signals and thereby separate signals.

Another common thread to signal separation is the assumption of independent inputs. For the most part, different signal sources in the HF band are independent. However, if propagation of a signal occurs by multiple layers of the ionosphere, the multipath signals at the reception point will be correlated to an extent that is dependent on the relative properties of the various propagating modes. The idea then, is to see what amount of correlation and independence of HF signals will cause the algorithms to fail or succeed. It appears that few researchers have considered this aspect of their algorithms.

An investigation of this issue would require a receiver, a nearby HF transmitter, and a distant HF broadcasting station. The nearby transmitter would transmit a direct HF ground-wave to the receiver. It would also need to have a direct connection (*e.g.* by terrestrial link) to the distant station and be capable of cleanly re-transmitting the broadcast of the distant transmitter or mixing the clean re-transmission with an interfering signal through a mixing function. The re-transmission would serve as a reference signal because it is a ground-wave that is undistorted and merely attenuated and delayed (Maslin 1987). The distant transmitter would transmit an HF sky-wave to the receiver. This sky-wave is likely to arrive at the receiver via multiple modes (multipath), variable attenuation and delays, fading, frequency shifts, spreading, time dispersion, and delay distortion created by the ionosphere (Maslin 1987).

A correlation coefficient could then measure the similarity of each mode of the sky-wave with respect to the reference signal. The nearby transmitter could adjust its transmission (perhaps by varying time-delay or introducing uniform random noise) in such a way as to vary the correlation coefficient. Then the success rate of a number of the signal separation algorithms could be plotted against the correlation coefficient.

An *independence* coefficient may also be of use. Inherent in a measure of statistical independence are the distributions of the signals. Observations of the reference, interferer, sky-wave, and mixed signal would give their distributions. The next step would be to compare the sky-wave and its distribution with the reference to determine the effect that the ionosphere has on the independence. Then, by adjusting the weighting of each input of the mixing function the level of independence between the sky-wave and mixed signal would change and yield a graph of success rate of separation algorithms versus independence coefficient.

A slightly different view involves measuring the efficiency of the separation algorithms. The nearby transmitter could transmit an interferer while the CTD prototype receives the sky-wave broadcast. The success rate of the separation algorithms could be plotted against signal-to-interference ratio (SIR).

Finally, the method by Yen & Zhao (1996) is able to detect when a source or interferer falls silent. This detection ability could trigger other algorithms to *hone-in* on the signal-of-interest (SOI). One of the *hone-in* algorithms could be the one by Erten & Salam (1999). This hybrid of algorithms could then be compared against each of the individual algorithms to see which performs better under which circumstances.

2.5 Summary

This chapter presents a brief review of the ionosphere as well as a discussion of current research in the fields of software radio, single site location, and signal separation. The discussion raises issues with potential for numerous PhD research topics. The selection of two topics of study for this thesis, namely the HF noise PDF and signal features for modulation recognition, is justified for the following reasons.

Most research ideas presented in this chapter have a scope of work that is beyond that required by Ebor Computing in the development of its advanced HF receiver. Secondly, the three areas of research (*i.e.* software radio, SSL, and signal separation) have a common issue that appears to garner little attention in the literature, namely, modulation recognition for HF signals. It is true, modulation recognition is an area of active study by researchers around the globe. Yet, there are few addressing modulation recognition issues for communications in the HF band. Thirdly, many researchers concentrate on the feature extraction and classification parts of modulation recognition without dutifully considering the most useful feature parameters. In fact, across the literature a *trial-and-error* type approach to the selection of feature parameters is common. Also, as the reader will see in later chapters, the assumption of Gaussian noise is a common practice among modulation recognition researchers. Often this assumption is made without justification. It is therefore evident that measuring the PDF of HF noise is necessary. Lastly, the advanced HF receiver provides an opportunity to test feature parameters for modulation recognition algorithms against *real* HF signals, and also to directly measure the PDF of HF noise. Few researchers have this opportunity available to them.

The scene is now set for a lengthy discussion of HF noise and signal features in Chapter 4. However, before venturing into the details it is worthwhile highlighting the contributions of this thesis and commenting on the thesis organization. The next chapter fulfils this role.

Chapter 3

Thesis Statement

THE thesis statement identifies the document structure and topics of research. It identifies the goals of the thesis, which are to measure the probability distribution of HF noise, model the probability distribution, evaluate useful signal features for modulation recognition, and to apply the selected features to real HF signals. Importantly, the thesis summary also highlights original contributions of this research.

3.1 Organization and Content

This thesis is organized in three parts. The first part deals with background information and sets the context for the research topics of the second and third parts. Each part is divided into chapters, and each chapter into sections. The general flow of each part consists of an introduction, background material, methods of investigation, experimental setups, results and discussion, issues to be addressed, and conclusions.

The discussion in this thesis highlights two areas of research for HF communications: Modulation Recognition, and HF Noise. It particularly addresses two questions: 1) What is the PDF of natural HF noise? And, 2) which signal features are appropriate for identifying the modulation type of HF signals? Part II attempts to answer the first question, while Part III applies various feature extraction algorithms to real HF signals and identifies which features are useful for automatic modulation recognition of specific HF signals.

The noise in the HF spectrum is known to be impulsive, consisting of environmental noise, atmospheric noise, and galactic noise (CCIR 1986). Man-made noise is primarily due to electromagnetic radiating devices. Atmospheric noise is largely influenced by lightning activity and can be shown to be directional (Coleman 2006). Galactic noise is composed of electromagnetic radiations from cosmic radiators such as the sun. Many researchers assume Gaussian noise for their analyses. The work in this thesis shows that such an assumption is not generally valid for HF communications.

Modulation recognition is the process of identifying a modulation scheme through feature extraction and classification. Numerous methods exist for such identification, but many of the methods lack sufficient testing with *real-world* data, especially for applications in the HF band. Few researchers analyze these algorithms with anything but synthetic signals and therefore state performance results without verification on real data. The work in this thesis applies various algorithms to real HF signals and evaluates the results.

3.2 Thesis Objectives

The goals of this work are summarized as follows:

1. measure the probability density function of HF noise,
2. choose a possible model for the probability density function,
3. apply various feature parameters to real HF signals, and
4. evaluate and select useful feature parameters,

to support the ultimate goal of developing robust modulation recognition algorithms for real HF signals corrupted by co-channel interference, multiple propagation modes, and noise.

3.3 Original Contributions

Four original contributions are related to the statistics of HF noise, five to signal features for automatic modulation recognition, and one relates to both fields. These attestments are as follows.

Contributions to the Study of HF Noise

1. Two new thresholding methods—the *swept-narrowband method* and the *broadband method*—for measuring the probability density function of HF noise, the results of which are supported by predictions of HF noise levels by the International Telecommunications Union (ITU), and independent measurements of HF noise by Ebor Computing.

2. Observations of the probability distribution of HF noise in an urban environment, which shows the effect of man-made noise on the HF noise PDF; and observations of the probability distribution of HF noise in a remote environment, which shows little contribution from man-made noise sources. Both sets of observations illustrate that the probability distribution of HF noise has a man-made

component (which is Gaussian in nature) and an impulsive component (which is non-Gaussian); a strong Gaussian component dominates in the urban environment, and a strong impulsive component dominates in the remote environment.

3. A useful and relatively accurate model for HF noise is derived from the single parameter Bi-Kappa distribution. A single parameter controls the impulsive and Gaussian components of the HF noise model.

4. A method for assessing whether or not a HF receiver is externally noise limited. This assessment is based on the shape of the PDF calculated, with the new thresholding techniques, from data collected by the receiver under test.

Contributions to the Study of Automatic Modulation Recognition

1. Development of substantial **MATLAB**® code for the analysis of automatic modulation recognition algorithms with real and/or synthetic data.

2. Evaluation of three signal features using real and synthetic data: the coherence function, Benedetto, Caglioti & Loreto's (2002) entropy function, and a modification of Aisbett's (1986) *hash* function. The evaluations confirm that the coherence function is not suitable as a unique signal feature for automatically recognizing a modulation type. The evaluations further confirm that the SNR function, derived from Aisbett's *hash* function, can be used to accurately estimate the SNR of a signal over a short range of SNR.

3. Application of Benedetto's entropy function to real HF signals with results that show the entropy function can be used to separate some HF signals.

4. Development of a new parameter, called the Coherence-Median-Difference, useful in the spectral analysis of *m*-ary FSK signals. This measure provides an indication of whether or not the coherence at the symbol frequencies dominates the coherence at all other frequencies in the analysis bandwidth.

5. Development of a new parameter, called the Mean-Separation-Distance, useful in the analysis of signal separability via Benedetto *et al*'s (2002) entropy function.

This parameters provides a measure of the separability of signals based on their entropy functions.

Contribution to the Development of HF Receivers

1. Development of a proprietary (through Ebor Computing) broadband HF receiving system, whereby the entire HF spectrum is analyzed, processed, and downconverted to baseband for the purposes of signal enhancement, signal separation, direction and range finding, as well as signal characterization and databasing.

3.4 Summary

The thesis statement in this chapter outlines the organization of the thesis, the objectives, and original contributions. The thesis has three parts that focus on the contextual basis for the thesis, HF noise, and signal features for modulation recognition. The latter two parts address the four thesis objectives and, moreover, provide valuable contributions to the study of HF noise and automatic modulation recognition. An additional contribution is to the development of HF receivers.

Having completed the thesis statement, it is now time to delve into the detail foreshadowed in Chapter 2. Chapter 4 begins the discussion on HF noise.