A NEW APPROACH FOR THE ASSESSMENT OF HF CHANNEL AVAILABILITY UNDER IONOSPHERIC DISTURBANCES

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ABSTRACT

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High Frequency (3-30 MHz) (HF) Ionospheric Channel is used for military, civilian and amateur communications. By using Ionosphere, communication for distances beyond the line of sight is achieved. The main advantage of this type of communication is that it does not to require a satellite to communicate with a point beyond the line of sight. Actually the Ionosphere is used instead of a satellite. To use Ionosphere but not a satellite means independent communication for a country.

The disadvantage of HF Ionospheric Communication is that the characteristics of the reflecting media (i.e. channel's transfer function) depends on many variables, e.g. sun spot number, hour of the day, season, solar cycles etc., so that mathematically modeling the channel is very difficult.

Since military standards like STANAG 4538 [2], STANAG 4285 [3], STANAG 4415[4], MIL-STD-188-110A [5] and MIL-STD-188-141A [6], define the required performance of an HF modem in terms of Signal to Noise Ratio (SNR), Doppler Spread and Delay Spread according to desired conditions, a new approach to characterize the channel in terms of these three parameters is presented.

In this thesis, HF Channel is considered as a system which involves various physical and chemical processes. A new method to characterize the HF channel to be used for modem performance evaluation is presented.

In this study, it is aimed to relate modem/channel availability with the magnetic indices, which may be considered as the disturbances to the system. For this purpose the data taken from an HF communication experiment is used to model the channel to be used for modem availability calculations.

The aim of the study is to asses the HF Channel Availability under Ionospheric Disturbances.

This new technique will be a useful tool for HF Modem operators to select the optimum data rate or modulation method during HF Communication.

Keywords: High Frequency Communication, HF Modem, Magnetic Indices, Modem Availability, Ionospheric Disturbances, Performance Surfaces, HF Channel

ÖZ

YÜKSEK FREKANS KANALININ KULLANILIRLIĞINA İYONKÜRESEL DÜZENSİZLİKLER ALTINDA DEĞER BİÇİLMESİ İÇİN YENİ BİR YAKLAŞIM

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Yüksek Frekanslı (3-30 MHz) (YF) İyonküresel Kanal askeri, sivil ve amatör iletişimde kullanılmaktadır. İyonküre kullanımıyla görüş çizgisinin ötesindeki noktalarla iletişim sağlanmaktadır. Bu tür iletişimin başlıca getirisi görüş çizgisi ötesindeki bir noktayla iletişim sağlanırken uydulara gereksinim duyulmamasıdır. İletişimde uydular yerine İyonküre kullanımı ülke haberleşmesinin bağımsızlığı anlamına gelmektedir.

YF İyonküresel İletişimin götürüsü yansıtıcı ortamın (İyonküre'nin) özelliklerinin günün saati, mevsim gibi pek çok değişkene dayanıyor olması ve bu nedenle de matematiksel olarak modellemesinin hayli güç olmasıdır.

STANAG 4538 [2], STANAG 4285 [3], STANAG 4415[4], MIL-STD-188-110A [5] ve MIL-STD-188-141A gibi askeri standartlar, YF Modemlerin başarımını, istenen şartlar altında, İşaret Gürültü Oranı (İGO), Doppler Dağılımı ve Gecikme Dağılımı değişkenleri türünden tanımladığından, kanalın tanımlanmasında bu üç değiştirgenin kullanıldığı yeni bir yaklaşım uygulanmıştır.

Bu çalışmada, YF Kanalı çeşitli fiziksel ve kimyasal süreçleri içeren bir dizge olarak değerlendirilmiştir. YF Kanalının modem başarımının değerlendirilmesinde kullanılmasına yönelik olarak tanımlanmasını sağlayan yeni bir yöntem önerilmiştir.

Çalışmada, modem/kanal kullanılırlığının sistem için düzensizlikler olarak değerlendirilebilen manyetik göstergelerle ilişkilendirilmeleri amaçlanmıştır. Bu amaçla, bir YF iletişim deneyinden elde edilmiş veriler kullanılmıştır.

Çalışmanın amacı, YF Kanal kullanılırlığına İyonküresel düzensizlikler altında değer biçilmesidir.

Bu yeni yöntem, YF Modem kullanıcılarının en iyi veri oranı ya da kipleme ("modulation") yöntemi seçiminde kullanılabilecek yararlı bir araç olacaktır.

Anahtar Kelimeler : Yüksek Frekanslı İletişim, YF Modem, Manyetik Dizinler, Modem kullanılırlığı, İyonküresel Düzensizlikler, Başarım Yüzeyleri, YF Kanal

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CHAPTER 1

INTRODUCTION

1.1 Problem Definition

High Frequency (3-30 MHz) (HF) Ionospheric Channel is used mostly for military, civilian and amateur communications. With this type of communication transmitted signals are reflected from the Ionosphere to long distances. This is similar to satellite communication. Ionosphere is used instead of satellites in the HF communication. However, characteristics of the reflecting media (i.e. channel's transfer function) depends on many variables, e.g. sun spot number, hour of the day, season, solar cycles etc., so that mathematically modeling the channel is very difficult.

Most of the studies aim to provide usable frequency values for the channel. For example Real Time Channel Evaluation (RTCE) aims to provide frequency selection data which will give the communicator a 90 % probability of satisfactory communication at any time [1]. There are several computer programs that evaluate Maximum Usable Frequency (MUF) values. ASAPS and Proplab-Pro are two well known ones of these programs. (MUF is defined in Section 2.2.1.)

Since HF Channel is used for military communication, there are many military standards for the military HF modems like STANAG 4538 [2], STANAG 4285 [3], STANAG 4415 [4], MIL-STD-188-110A [5] and MIL-STD-188-141A [6]. These military standards define the required performance of an HF modem in terms of Signal to Noise Ratio (SNR), Doppler Spread and Delay Spread for a required data rate, Bit Error Rate (BER) and other conditions like the modulation type. HF Modems define performance surfaces on the SNR, Doppler Spread and Delay Spread space according to desired conditions. These surfaces are obtained by a technique defined in [7]. It is important that the performance of a modem over a channel is determined by using of these surfaces meaning these three parameters; SNR, Doppler Spread and Delay Spread. So the channel is characterized-defined by these three parameters.

1.1.1. Existing Approaches on Modem Availabilty:

Different studies have been conducted to evaluate the performance of different HF modems. Some studies used the data supplied by The Doppler and Multipath Sounding Network (DAMSON) [8]. DAMSON is a channel sounder which is used to characterize narrow band channels by measuring their SNR, Doppler Spread and Delay Spread parameters.

Data from the high latitude DAMSON network were analyzed to determine the diurnal distribution of Doppler spread, multipath spread and SNR on each high latitude path. An important result of DAMSON work was the specification of the operating envelope for the low data rate NATO HF modem, STANAG 4415 [8]. In [9] the seasonal variations in the channel characteristics were also considered.

DAMSON data were also used for modem availability calculations. The availability of a modem is estimated by placing each DAMSON composite channel measurement on the modem characterization to determine the difference between the measured SNR and the SNR of the surface [8]. This is achieved by applying real path measurements usually taken over 24 hours using DAMSON to three-dimensional performance surfaces [10].

However no study is carried to relate the modem performance to Ionospheric disturbances as far as we know.

In this thesis a new method to characterize the HF channel by relating modem availability to Ionospheric disturbances is presented.

1.2 Scope of the Thesis

In this thesis, HF Channel is considered as a system which involves various physical and chemical processes. A new method to characterize the HF channel to be used for modem performance evaluation is presented.

The aim of this study is to relate modem availability to magnetic indices, which may be considered as the disturbances to the system. For this purpose the data taken from an HF communication experiment is used to model the channel to be used for modem availability calculations.

Figure 1.1 shows HF Communication Channel model used in this study. In this figure;

s(t) : transmitted signal

d(t) : ionospheric disturbances

r(t) : the signal output of the HF channel

p(t) :the signal output of the HF modem

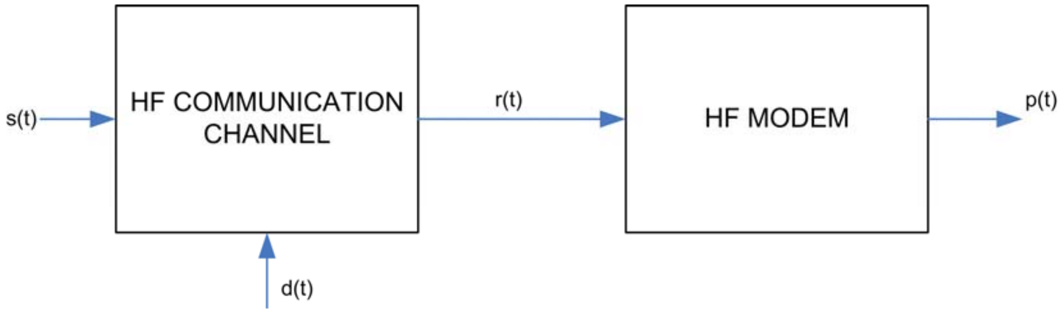


Figure 1.1: HF communication channel model

It should be noted that the communication method defines the modem requirements:

data rate: bit-per-second (bps); 75 bps, 150 bps, 300 bps, etc.

Modulation Type: Binary Phase Shift Keying (BPSK), Frequency Shift Keying (FSK), etc.

Another parameter which defines the modem requirements is Bit Error Rate (BER) which is the probability of bit error measured at receiver output [11]. It is expressed in terms of 10^{-n} where n is an integer. (For example; 10^{-4}, 10^{-9} etc.)

Modem availability is the rate that the modem works satisfactorily meaning generating desired p(t).

In this study it is aimed to assess the modem availability from d(t).

1.3 Outline of the Thesis

In Chapter 2, general information about HF Channel, Ionospheric Communications, propagation mechanisms, modem availability and Ionospheric parameters are presented. In this chapter, modem performance surfaces are also presented.

In Chapter 3, the main contribution of this thesis study is presented. In this chapter,

1. The relation of Disturbance Storm Time (DST) index to SNR, Doppler Spread and Modified Power Delay Spread are observed.

2. These relations are examined in terms of correlations, spectrograms and histograms. Only histograms give meaningful results.

3. Using histograms, conditional probability density functions (pdf) and marginal pdf's are obtained.

4. By using Bayes' Theorem, the dependences between DST and SNR, between DST and Doppler Spread and between DST and Modified Power Delay Spread are shown.

5. A four dimensional joint pdf is obtained by using the method defined in Section 2.4.

6. Conditional density function for desired DST index is obtained and the probability of modem availability is evaluated.

CHAPTER 2

IONOSPHERIC COMMUNICATIONS

2.1 Short Information Concerning Ionosphere

Incoming ultra-violet radiation and X-rays from the Sun ionize the Earth's atmosphere. At great heights of the order of 1,000 km or more the atmosphere is almost fully ionized, but it is so rare that the ion and electron concentrations are very small. At lower levels in the atmosphere there is more gas to be ionized so that the radiation is more strongly absorbed and the ion concentrations are greater. At still lower levels the radiation has been almost entirely used up so that the degree of ionization is again small [12]. At this level (near the ground), the atmosphere is said to be neutral. That is, it is not ionized and it is comparably almost non-conductive [14]. The region where the ion and electron concentrations are greatest is known as the ionosphere [12].

When any part of the Earth's atmosphere is in equilibrium, its structure and state may be considered to be controlled by the Earth's gravitational field so that it is a horizontally stratified system [12].

The height where ionization reaches a maximum depends on the absorption coefficient of the air for the ionizing constituent of the Sun's radiation, and the mechanism by which ions and electrons are removed. Different radiations from the Sun ionize the ionosphere differently and result in maxima at different heights [12]. Thus there are several different ionospheric layers of ionization. The main layers are known as E and F [12], [13], [14]. The names for these layers were originally introduced by Sir Edward Appleton who used the letters E and F for Electric and Field [e1]. In the F layer, the ion and electron concentrations are only about a hundred-thousandth (10^{-5}) of the concentration of neutral particles, and in the E-layer this number is about 10^{-11} [12], [14].

The E layer peaks at 105-110 km [13], [15]. It mostly disappears but does not vanish at night; a weakly ionized layer remains [15]. The sporadic E region (symbolized as Es or E_s) is a traveling ionospheric cloud of intense ionization [14]. Sporadic-E is significant in radio propagation because it may reflect signals that would otherwise penetrate to the region F, though in some cases it is partly transparent [15]. It is not strongly associated with solar ionizing radiation and can occur at almost any time of the day [14],[15].

The diurnal and seasonal variations of F layer are more complex than the E layer [13]. During daylight the curve of electron number density versus height, for the F-layer, often shows an auxiliary peak below the maximum of electron density [13]. This is known as the F1 layer and it may occasionally attain an actual maximum [13]. The main maximum above the F1 layer is the F2 layer [13].

The F1 layer does not always appear [15]. It peaks at 160-180 km [15]. In fact, it seldom exists as a distinct peak and for this reason it is sometimes called as F1 layer [15]. It does not have a major effect on HF communications [16].

The F2 layer has the greatest concentrations of electrons of any layer, and therefore it is the most important region for HF waves [15]. Unfortunately, it is the region which is most variable and the most difficult to predict [15]. It peaks at 200-400 km [15] and persists at night [16]. It is the uppermost layer, it also the most highly ionized [8, 13].

In daytime there occurs another layer down E region [13]. This has been called as D layer [13]. It is the part below about 95 km which is not accounted for by the process of the E region [15]. It is also the most complex part of the ionosphere from the chemical point of view [15]. The degree of ionization depends on attitude of the sun above the horizon, and thus it disappears at night [15]. D layer absorbs Medium

Frequency (MF) and High Frequency (HF) waves and reflects some Very Low Frequency (VLF) and Low Frequency (LF) waves [17].

2.2 HF Communications

The HF band is defined as the electromagnetic spectrum between 3 MHz and 30 MHz, corresponding to wavelengths between 10m and 100m. Radio communications using this frequency band is referred to as HF communications. The lower limit is sometimes stretched below the formal definition, down to about 1.5 MHz, when using the term HF communications.

2.2.1. Propagation Mechanisms

Two major propagation mechanisms exist for radio waves in the HF band: Groundwave, where the waves propagate along the surface of the Earth, and skywave, where the waves are reflected back to Earth from the ionosphere.

Figure 2.1 shows different propagation paths for HF radio waves.

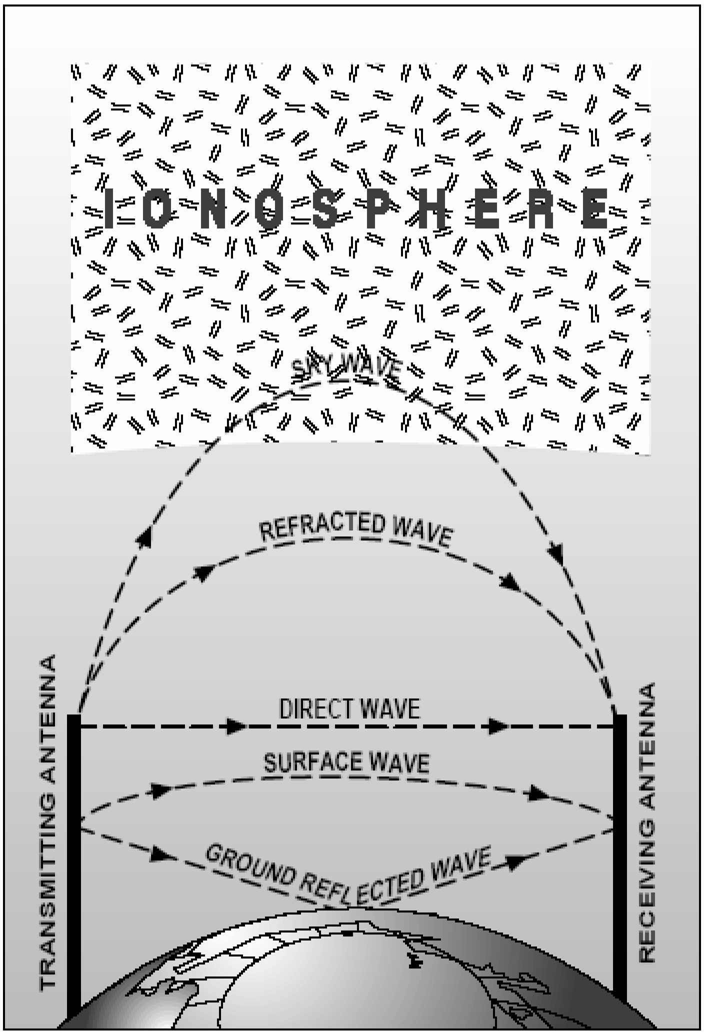


Figure 2.1: Propagation Paths [16]

The terminology that has grown up around the ionosphere and skywave propagation includes several names and expressions whose meanings are not obvious. Some of the terms more relevant to the subject of this thesis will be clarified more:

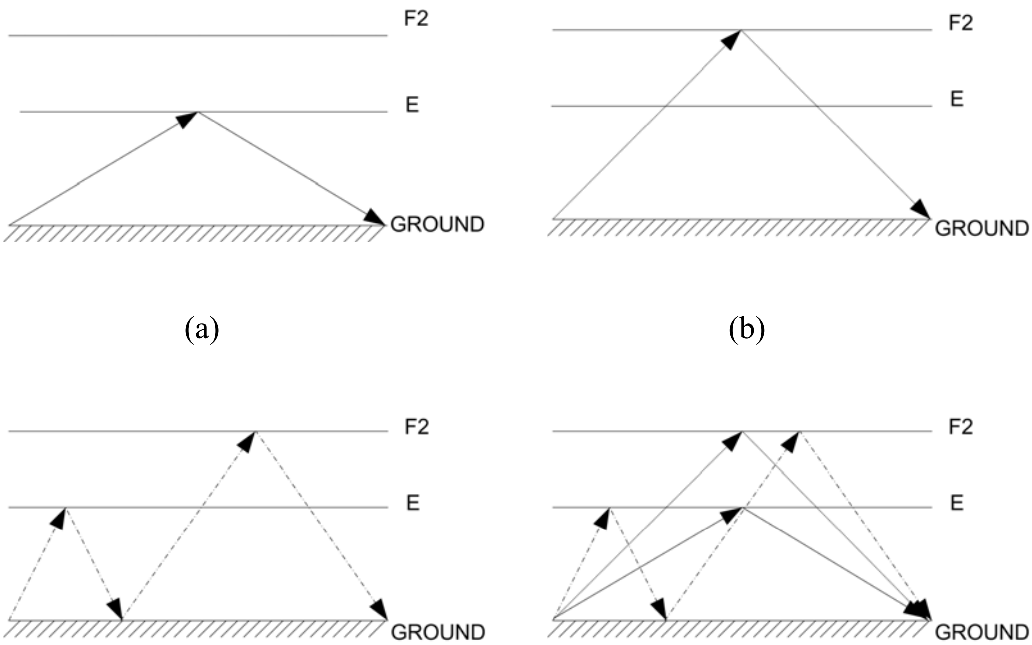
The *critical frequency* (f_c) for a given layer is the highest frequency that will be returned down to earth by that layer after having been beamed straight up at it. It should be noticed that it is the highest vertically propagated frequency [19].

As seen from the definition there are multiple critical frequencies for the various layers. A critical frequency is symbolically denoted by "f_O". The layer to which the critical frequency applies is then appended to this. For example, f_OF_2 (or foF2 as common) refers to the critical frequency of the F2 layer of the Earth's ionosphere.

Any signal that has a frequency higher than the critical frequency of the E layer (foE) will penetrate the E layer and travel on toward the F1 layer. If the frequency of the signal is higher than foF1, then the signal will penetrate that layer and pass on toward the F2 layer. If the frequency of the signal is higher than the F2 layer, it will penetrate the ionosphere altogether and be lost to space since the electron density in the ionosphere is greatest at the peak of the F2 layer. The foF2 value therefore also represents the penetration frequency for the ionosphere as a whole, for vertically propagated signals [14].

The *maximum usable frequency* (MUF) is also an important parameter affecting the HF communication. There are two forms of MUF; the Basic MUF and the Operational MUF [14]. The Basic MUF (Junction Frequency) is the highest frequency that can be supported and returned by the ionosphere for a given angle of incidence. It is dependent upon ionospheric refraction alone. The Operational MUF is the highest frequency that provides acceptable propagation between two points on the Earth. Similar to fc, there are multiple MUFs for E and F layers. For all MUF calculations path length is an important parameter. According to path length control point locations are used to determine the Basic MUF calculations; the critical frequency of the layer is calculated for the control point location. The Basic MUF is related to fc by means of angle of incidence. The Operational MUF is related to Basic MUF by some statistical calculations depending on the seasonal, daily variations of the ionosphere [12,14]. There are several computer software that evaluate MUF values. ASAPS and Proplab-Pro are two well known ones of these softwares.

The *multipath propagation* arises because replicas of the transmitted signal arrive at the receiver after reflection from more than one ionospheric layer, and/or after multiple reflections between the ionosphere and the ground [20]. Each signal (or propagation mode) generally arrives with a different time delay, causing either constructive or destructive interference, which, when viewed in the frequency domain, dictates the coherence bandwidth of the channel [20]. Figure 2.2.a shows a skywave with single-hop, reflected from E layer, Figure 2.2.b shows a skywave with single-hop, reflected from F2 layer, Figure 2.2.c shows a 2-hop skywave, Figure 2.2.d shows a multipath propagation with the skywaves presented in Figure 2.2.a, Figure 2.2.b and Figure 2.2.c.



(a) (b) (c) (d)

Figure 2.2: Skywave propagation examples: (a) and (b) single-hop, (c) 2-hop and (d) multipath.

Frequency (Doppler) shifts can be imposed on the transmitted signal by the temporal variability of the ionosphere [20] .

Fading is the fluctuating in signal strength at the receiver and it's the result of time-variant multipath characteristics of the channel [21],[18]. Fading can be slow or fast, frequency-selective or frequency non-selective.

If the channel response changes within a symbol interval, then channel is regarded as fast fading. Otherwise the channel is regarded as slow fading [22]. Let $(\Delta t)_c$ be the channel's coherence time,

$$(\Delta t)_c \approx \frac{1}{B_d} \tag{2-1}$$

where B_d (Hz) is the *Doppler spread.*

When $(\Delta t)_c < T_s$ where T_s is a symbol interval, the channel fading is time-selective, if $(\Delta t)_c > T_s$ than the channel fading is said to be time non-selective [22].

If the signal bandwidth is smaller than the channel coherence bandwidth (B_s) than the channel is said to be frequency non-selective, otherwise the channel said to be frequency-selective [22] . Let $(\Delta f)_c$ be the channel's coherence bandwidth,

$$(\Delta f_c) \approx \frac{1}{T_m} \tag{2-2}$$

where T_m (ms) is the *multipath spread* of the channel.

When $B_s < (\Delta f)_c$, then the signal is faded in a similar manner for all the frequency, and the fading is said to be frequency non-selective, and is also called frequency flat [22].

When $Bs > (\Delta f)_c$, the fading is said to be frequency-selective, and the multiple resolvable paths may appear [22] .

The *composite multipath spread* is a measure of the overall temporal spread of the incoming signal; however, no account is taken of the relative powers contained within the various detected modes. Consequently, measurements have also included a parameter, known as the *effective multipath spread*, which takes the relative modal powers into account and was found to provide better results than the composite multipath spread when employed in modem tests using an HF channel simulator. The definitions of the three spread parameters is as follows (as defined in [23]):

1. *Composite multipath* spread is taken as the temporal separation between the rising edge of the first detected mode and the falling edge of the last detected mode, with a correction applied for the width of the transmitted pulse.

2. *Effective multipath spread* is a measure of multipath spread which gives a good agreement between the expected modem characteristics and the modem performance under the complex propagation conditions encountered at high latitudes. The equivalent multipath spread is calculated for a pair of modes by determining the multipath separation between the rising edge of the central 80% power region of the first (in delay time) mode and the trailing edge of the central 80% power region of the last mode (corrected for the transmitted pulse width) and weighting the separation with the ratio of the two modes' total powers. This ratio is always arranged so as to be equal or less than unity. This procedure is applied to each pair of modes in turn and the equivalent multipath spread taken as the maximum value found. If only a single mode is present, then the effective multipath spread is taken to be the mode's 80% power spread, again corrected for the width of the transmitted pulse.

3. *Composite Doppler spread* is defined as the narrowest spectral width containing 80% of the received signal power. In all cases, a correction is applied for the base noise level.

2.3 Joint and Conditional Probability Density Functions

Joint, conditional and marginal probability density functions are used for modem availability calculations in Chapter 3. Here a small review obtained from [24] and an illustrative example from [25] is presented.

2.3.1. Joint Density Function:

Let X_1, X_2, ..., X_n be n random variables all defined on the same probability space. The **joint discrete density function** of X_1, X_2, ..., X_n, denoted by

$$f_{X_1, X_2, \dots, X_n}(x_1, x_2, \dots, x_n) \tag{2-24}$$

is the following function:

$$f_{X_1, X_2, \dots, X_n} : R^n \to R$$

$$f_{X_1, X_2, \dots, X_n}(x_1, x_2, \dots, x_n) = P[X_1 = x_1, X_2 = x_2, \dots, X_n = x_n] \tag{2-25}$$

For n=2

$$f_{X_1, X_2}(x_1, x_2) = P[X_1 = x_1, X_2 = x_2] \tag{2-26}$$

2.3.2. Marginal Density Function:

Continuous:

$$f_{X_1}(x_1) = \int_{-\infty}^{\infty} f_{X_1, X_2}(x_1, x_2) dx_2 \tag{2-27}$$

Discrete:

$$f_{X_1}[x_1] = \sum_{x_2} f_{X_1,X_2}[x_1, x_2] \tag{2-28}$$

2.3.3. Conditional Density Function:

$$f_{X_1|\,X_2}(x_1|\ x_2) = P[X_1 = x_1|\ X_2 = x_2] \tag{2-29}$$

Continuous:

$$f_{X_1|\,X_2}(x_1|\ x_2 = k) = \frac{f_{X_1,X_2}(x_1, x_2 = k)}{f_{X_2}(x_2)} \tag{2-30}$$

Discrete:

$$f_{X_1|X_2}[x_1|x_2 = k] = \frac{f_{X_1,X_2}[x_1, x_2 = k]}{\sum_{X_1} f_{X_1,X_2}[x_1, x_2 = k]} \tag{2-31}$$

The principles of joint pdfs are more easily demonstrated for a discrete example, as below (example from [25]). We have two joint pdfs, one exhibiting independence.

Table 2.1: Joint pdf of dependent variables

	Dependent			
$x \setminus y$	1	2	3	$f_X(x)$
2	0.2	0	0.2	0.4
4	0	0.2	0	0.2
6	0.2	0	0.2	0.4
$f_Y(y)$	0.4	0.2	0.4	
$f_{Y\|X}(y\|x=2)$	0.5	0	0.5	

Table 2.2: Joint pdf of independent variables

	Independent			
$x \setminus y$	1	2	3	$f_X(x)$
2	0.2	0.12	0.08	0.4
4	0.2	0.12	0.08	0.4
6	0.1	0.06	0.04	0.2
$f_Y(y)$	0.5	0.3	0.2	
$f_{Y\|X}(y\|x=2)$	0.5	0.3	0.2	

The probabilities *within* the table summarize the **joint density** of x and y, which we can denote $f_{X,Y}(x,y)$. Hence $f_{X,Y}$ (4,3) = 0.08 (Table 2.2), which is the probability that x=4 *and* y=3.

The row/columns labeled $f_Y(y)$ and $f_X(x)$ give the **marginal** densities of y and x respectively. They tell us the probabilities of x or y taking on a particular value, irrespective of the value of the other variable. Thus for both tables, f_Y (y=1) = 0.5, there is overall a 50% chance of getting y=1. The f_Y (y) values are obtained by summing (over x) the joint densities. $f_X(x)$ is obtained by summing over y.

The individual rows (and columns) give the **conditional densities**, $f_{Y|X}$ ($y|x$) and $f_{X|Y}$ f($x|y$). These are the densities of y (x) *given* a particular value of x (y). Note that we have to scale up the numbers in order to get a valid density function (i.e. sums to one). Thus for $f_{Y|X}$ ($y|x$=2) (Table 2.2) the numbers 0.2, 0.12, 0.08 sum to 0.4, not 1. We therefore scale up by dividing by 0.4, to give 0.2/0.4 = 0.5, 0.12/0.4 = 0.3 and 0.08/0.4 = 0.2. The conditional density $f_{Y|X}$ ($y|x$=2) thus consists of the probabilities 0.5, 0.3, 0.2.

2.4 Modem Availability

Modem availability is quantified as a fraction or percentage of time that the modem will function satisfactorily [20]. In order to determine this, a long data set of on-air measurements is indispensable. The Doppler and Multipath Sounding Network (DAMSON) system is the most widely used system which supplies this data. A more detailed description of DAMSON can be found in [8].

Performance surfaces method is a convenient way to present the performance of HF modems. A performance surface defines the required Signal to Noise Ratio (SNR) to reach the desired Bit Error Rate (BER), for each combination of delay and Doppler spread [26]. The delay spread mentioned is the Effective Multipath Spread and the Doppler Spread is the Composite Doppler Spread. Both of these variables are defined in Section 2.2. . Modem performance surfaces are first defined by P. C. Arthur and M. J. Maundrell in [27].

The availability of a modem can be estimated by placing each composite-channel measurement on the modem characterization to determine the difference between the measured SNR and the SNR of the surface (the SNR difference). A positive SNR difference indicates that the channel would support the specified BER [20]. In [20] it is claimed that this technique is in good agreement with on-air modem tests.

Performance surfaces typically show one region where the SNR requirement is roughly constant, one region where reliable communication cannot be achieved for any SNR, and a transition between these two regions. The transition is normally abrupt in the multipath direction, and soft in the Doppler direction [26]. Figure 2.3 shows a performance surface for a serial modem, operating at 1200 bps, with short interleaver, to satisfy MIL-STD-188-110A [20].

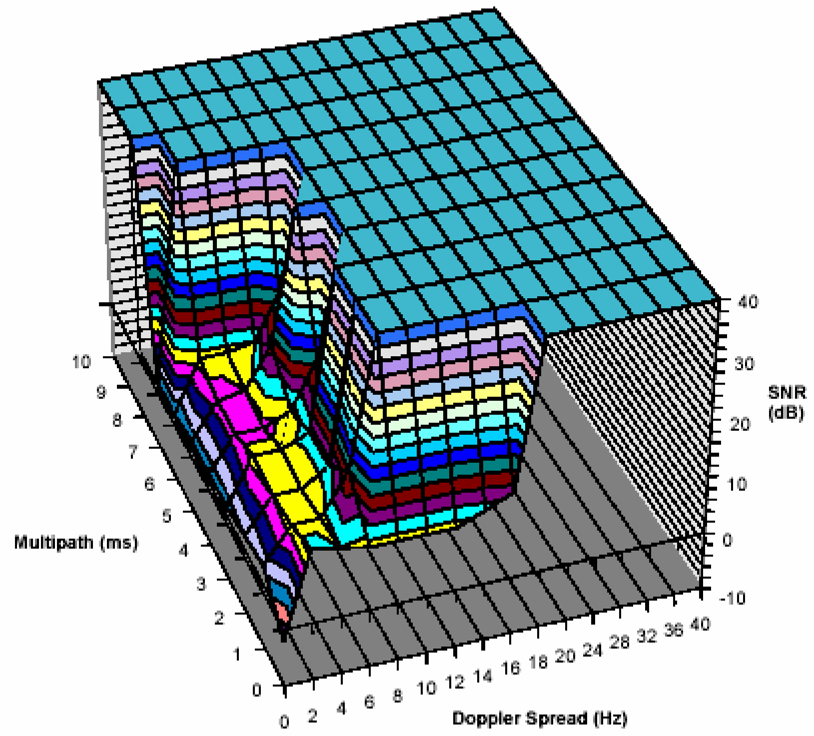
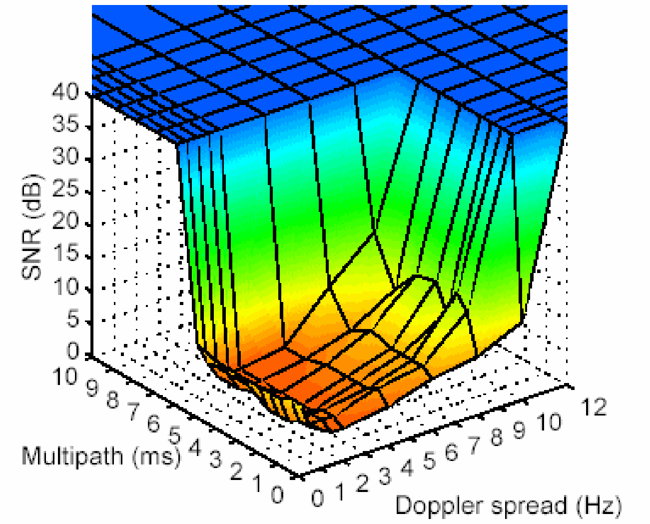
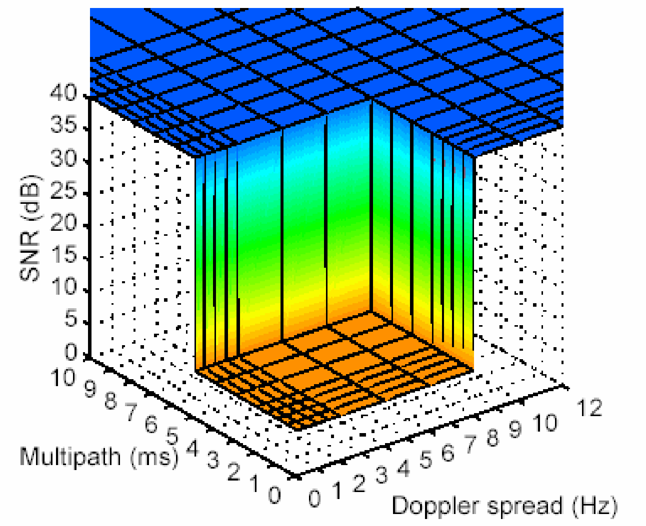


Figure 2.3: A typical modem characterization for a MIL-STD-188-110A serial, short interleaver, operating at 1200 bps [20] and originally [27].

Approximated performance surfaces are used in some studies in order to simplify the analysis. Figure 2.4 shows a real and an approximated performance surfaces taken from [26].Table 2.3 shows the approximate requirements to SNR, Doppler spread and delay spread for different data rates, deduced from performance surfaces in (ITU, 2000) and STANAG 4539 [26].



a. Real Performance Surface



b. Approximated Performance Surface

Figure 2.4: Typical performance surface for 1200 bps 8-PSK serial tone modem (ITU, 2000), and approximated performance surface [26].

Table 2.3: Approximate required SNR, Doppler spread and multipath spread when using STANAG 4539 waveforms/modems [26].

Data Rate (bps)	SNR (dB)	Doppler Spread (Hz)	Delay Spread (ms)
2400	> 14	< 4	< 5
1200	> 7	< 8	< 5
600	> 3	< 12	< 5
300	> 0	< 16	< 5
150	> -3	< 10	< 5
75	> -7	< 40	< 16

2.4.1. Availability Calculations:

If the modem works satisfactorily for the delay spread, Doppler spread and SNR values determined by a point, then this point is defined as available point.

According to definition in Section 2.4, modem availability is calculated as follows

$$\text{modem } availability = 100 \times \frac{(\text{number of available points})}{(\text{total number of points})} \tag{2-24}$$

2.5 Space Weather

Space Weather is defined as: “conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems.” (definition used by the US National Space Weather Plan (NSWP)) [28]. Another definition of the Space Weather is: “a consequence of the behavior of the sun, the nature of the Earth’s magnetic field and atmosphere and our location in the solar system.” (definition used by The National Oceanic and Atmospheric Administration/Space Environment Center (NOAA/SEC)) [28]. Effects of Space Weather on ground-based systems are briefly summarized in [29].

Geomagnetic indices constitute data series aiming at describing a planetary scale of the magnetic activity or some of its components. The data series of long time periods (approximately 50 years for DST index [34]) for different magnetic indices are available. Because they provide a continuous monitoring of the magnetic effects of processes taking place in the ionosphere and magnetosphere, geomagnetic indices are basic data in the development of Space Weather research.

There are many ionospheric parameters affecting the ionospheric HF communications. In the following section only the DST index will be described shortly. For the descriptions of other magnetic indices, please refer to [30].

2.5.1. Disturbance Storm Time (DST) Index

Worldwide magnetic disturbances lasting one or more days are called magnetic storms [30]. Magnetic storms usually begin with a sudden worldwide increase in the magnetic field [30].

DST index represents variations of the H (northward) component of the magnetic perturbations due to changes of ring current and is computed at hourly intervals [30].

The unit of DST index is nT.

A temporal profile of DST that would typically be recognized as a storm is shown in Figure 2.5.

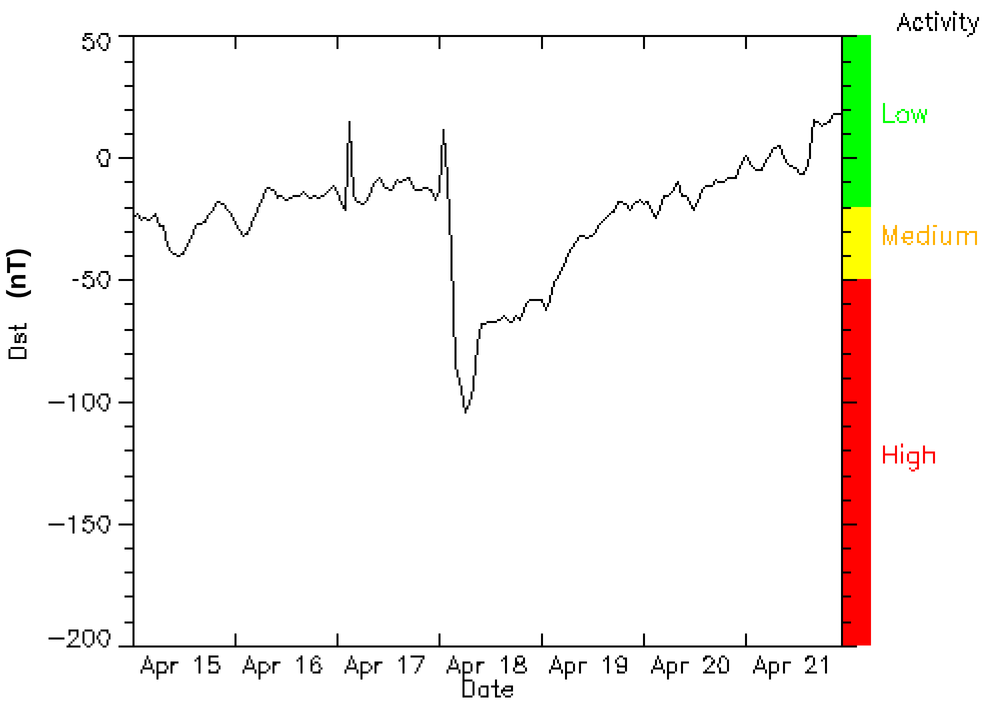


Figure 2.5: A typical storm in DST [31].

It is seen in the Figure 2.5 that prior to the storm, DST varies about some level around 0 nT. The start of the storm is identified by a rapid drop in DST over several hours. It reaches a minimum and then recovers more slowly to pre-storm levels.

A common classification of the DST is seen in Table 2.4.

Table 2.4: The relation between magnetic storms and the DST index [31].

Weak storm	Minimum Dst below -30 nT
Moderate storm	Minimum Dst below -50 nT
Strong storm	Minimum Dst below -100 nT
Severe storm	Minimum Dst below -200 nT
Great storm	Minimum Dst below -350 nT

2.5.1.1 DST Estimation

There exist some organizations estimating DST values. These organizations supply the estimated values through internet. [35] is an example of these internet web pages.

CHAPTER 3

A NEW APPROACH TO MODEM AVAILABILITY

3.1 Introduction:

Throughout the study the data from two different sources are used. One of data sources is the experiment made between Leicester, UK (52.63_ N, 1.08_ W) and Uppsala, Sweden (59.92_ N, 17.63_ E). The experiment was held in the year 2001. The path was about 1400 km. Figure 3.1 shows the path.

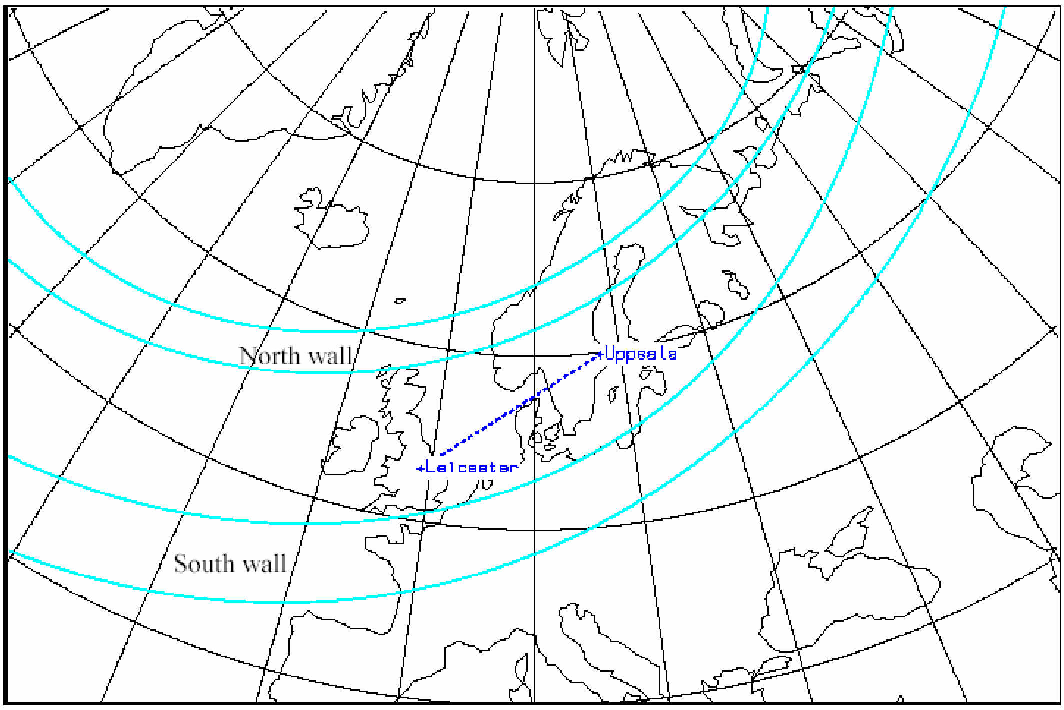


Figure 3.1: A map showing propagation between Uppsala and Leicester [32]

Six frequencies were used during the experiment, namely 4.6, 7.0, 10.4, 11.1, 14.4, and 18.4 MHz. Transmissions on each frequency were made over a period of thirty seconds with an overall cycle time of 3 minutes. Each transmission period contained two 13-bit Barker-coded Binary Phase Shift Keying (BPSK) transmissions each of 2 s duration with a chip rate of 1667 baud.

The aim of the experiment was to examine the effect of trough on a variety of variables like time of flight, direction of arrival. In our study since we do not use these parameters the definitions of them is not presented. However to clarify the aim of the experiment a short information about trough is presented.

The *electron density trough* is the ionospheric projection of the magnetospheric plasmapause [36]. A typical density trough is characterized by abrupt change in ambient electron density over a very small special distance. The ionospheric electron density trough is prominent at night time and during winter season. The trough moves towards the lower latitudes and becomes deeper in depth during magnetic storms following the solar disturbances [33].

Second data source is the National Geophysical Data Center. DST index data obtained from the database of this center is used throughout the study.

3.1.1. General Information on Data Obtained from the Uppsala-Leicester Experiment:

There are 6 MATLAB data files (.mat). Each of them contains data for a specific frequency, 4.6, 7.0, 10.4, 11.1, 14.4, and 18.4 MHz. Table 3.1 shows the names and meaning of the variables.

Table 3.1: Parameters in a data file

Parameter	**Information:**
timeday	Time of day (in decimal days, i.e. 5.5 is midday on 5th January)
tofmode	time of flight (ms) of up to 4 modes
tofazim	azimuth of modes in tofmode
tofelev	elevation of modes in tofmode

delspread	Delay (ms)
mpspread	modified delay (ms, taking account of relative power of modes)
dopspread	Doppler spread
doppler	Doppler frequency (Hz)
snr	SNR in 3 kHz bandwidth
antindf	A 1 in a column indicates whether the signal from that antenna (there were 6 antennas) was of sufficient strength to be used in the direction finding algorithm. 5 or 6 should give a reliable azimuth and elevation, 4 may be Ok, 3 is probably not reliable (unless the snr is otherwise very high), 1 or 2 and the direction information will be unusable.

3.1.2. Information on the parameters directly used in our study

As discussed in Section 2.4. a modem performance is defined in terms of three parameters; Effective Multipath Spread, Composite Doppler Spread and SNR. For Four of the parameters in the database are used throughout our study; *timeday*, *mpspread*, *dopsread* and *snr*.

3.1.2.1. *timeday:*

This parameter is in decimal days, i.e. 5.5 is midday on 5th January. Figure 3.2 shows a sample part of *timeday* data.

Since the *timeday* parameter is actually a recording of the Global Positioning System (GPS) clock at the instants of measurement, this data is used to synchronize the *mpspread*, *dopspread* and *snr* variables to DST data.

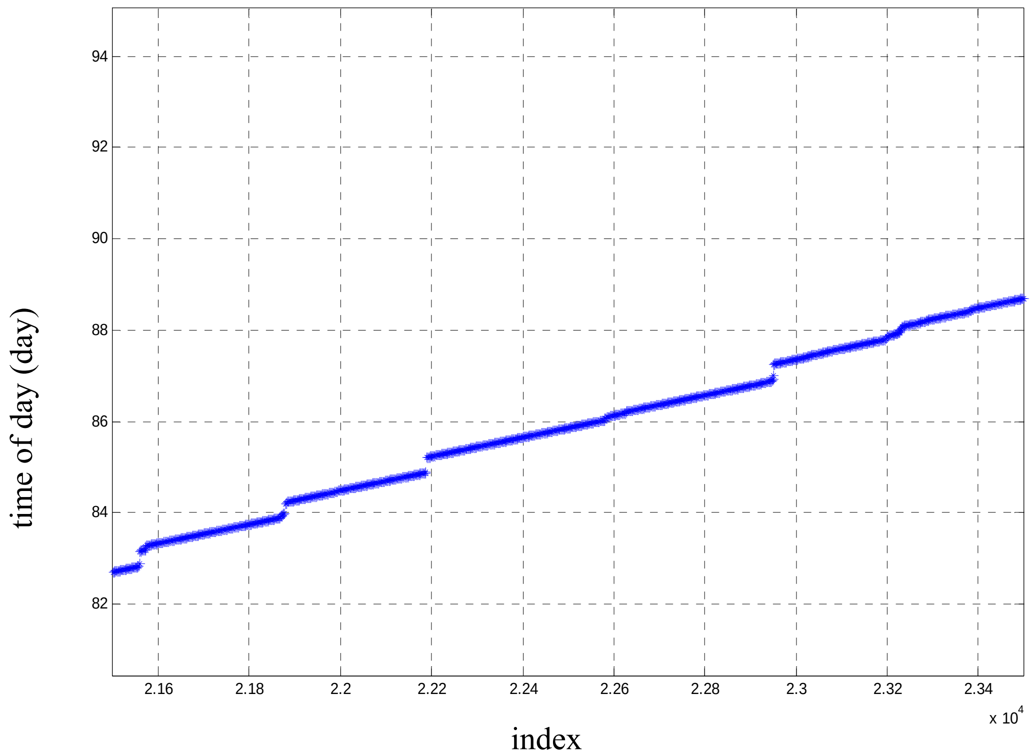


Figure 3.2: A sample part of the “time of day” data

3.1.2.2. *mpspread*:

This parameter is nothing but the Effective Multipath Spread defined in Section 2.2.1. It will be called as Modified Power Delay Spread for the rest of this document. It should be noted that this is a derived variable. This derivation is not performed by us. It was already derived when we obtained the database. Figure 3.3 shows a sample part of Modified Power Delay Spread.

Figure 3.3: A sample part of the “Effective Multipath Spread” data

3.1.2.3. *dopsread*:

This parameter is the Composite Doppler Spread (Hz) defined in Section 2.2.1. It will be called as Doppler Spread for the rest of this document. It should be noted that this is a derived variable. This derivation is not performed by us. It was already derived when we obtained the database. Figure 3.4 shows a sample part of Composite Doppler Spread.

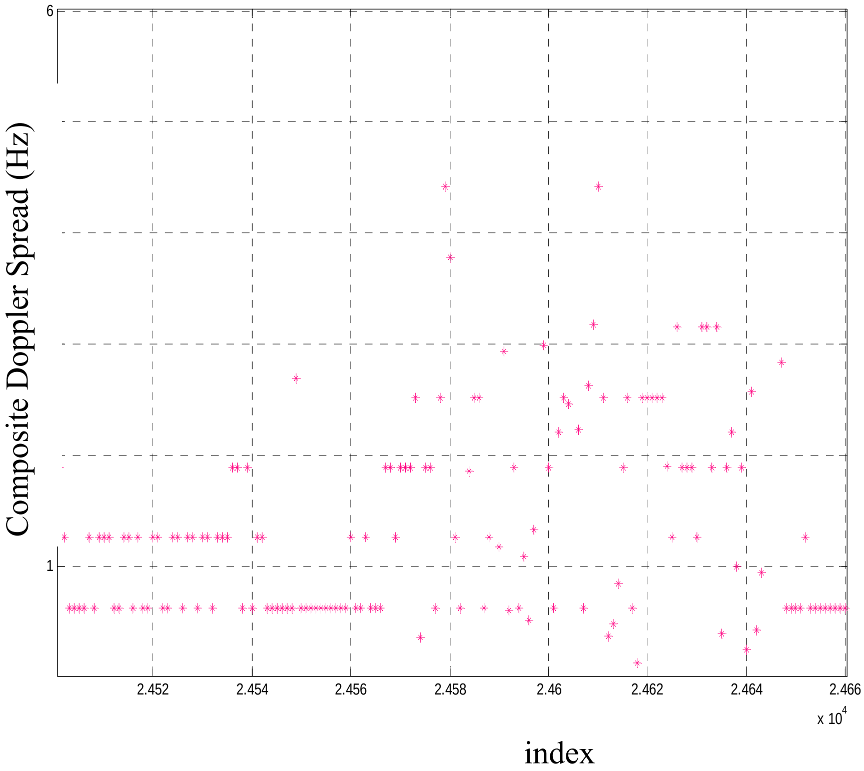


Figure 3.4: A sample part of the "Composite Doppler spread" data

3.1.2.4. *snr:*

This data is the signal-to-noise ratio in 3kHz bandwidth. Figure 3.5 shows a sample part of SNR.

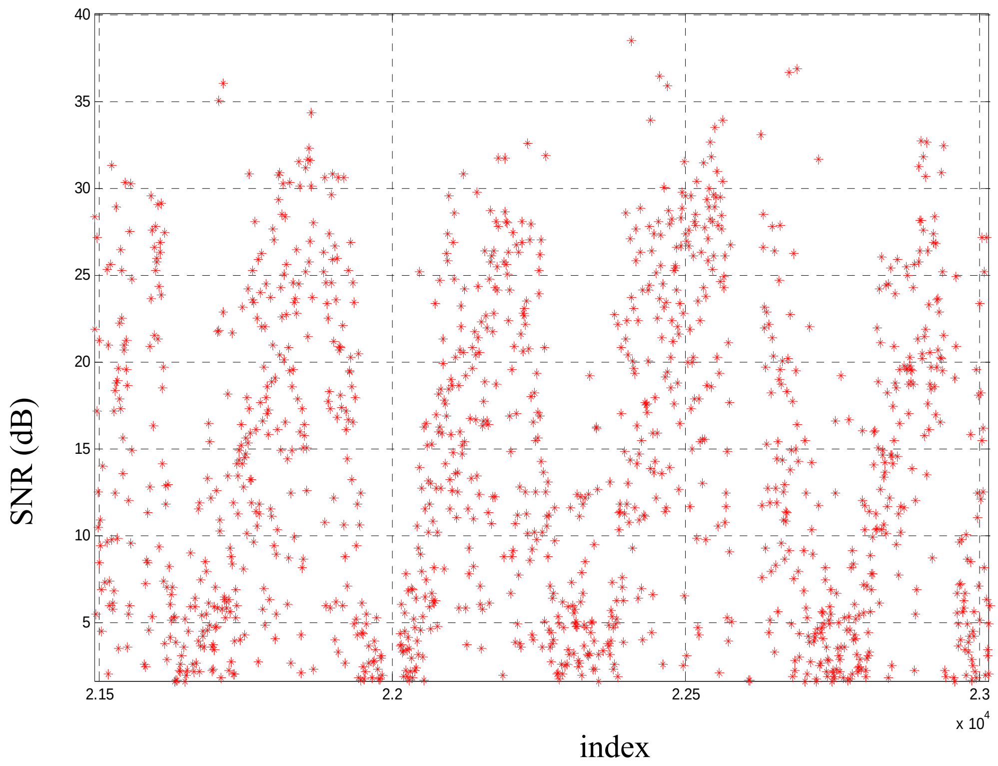


Figure 3.5: A sample part of the “SNR” data

3.1.2.5. DST Data:

DST index of 2001 is obtained from National Geophysical Data Center’s database [34].

Since DST is an hourly index hourly mean values of the *mpspread*, *dopspread* and *snr* parameters are evaluated and used throughout the study.

It should be noted that *timeday* variable is used to synchronize *mpspread*, *dopspread* and *snr* parameters to DST data.

3.2 SNR, Doppler Spread and Modified Power Delay Spread correlations with Magnetic Indices:

During the investigations concerning about SNR, Doppler Spread, Modified Power Delay Spread and some well known Ionospheric indices, it was observed that these quantities are related.

Figures 3.6-3.8 show the dependence of data on DST index. Please note that DST index is an hourly index, meaning that it changes every hour. Therefore, the hourly mean values of the data are evaluated and used in the plots to demonstrate the relationships.

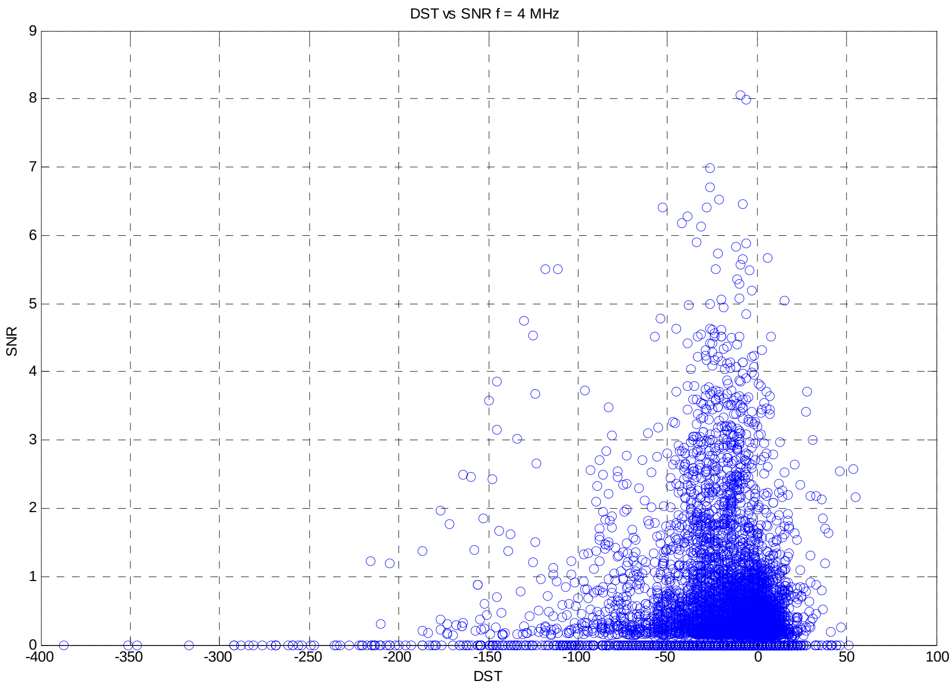


Figure 3.6: DST vs. SNR, f = 4 MHz

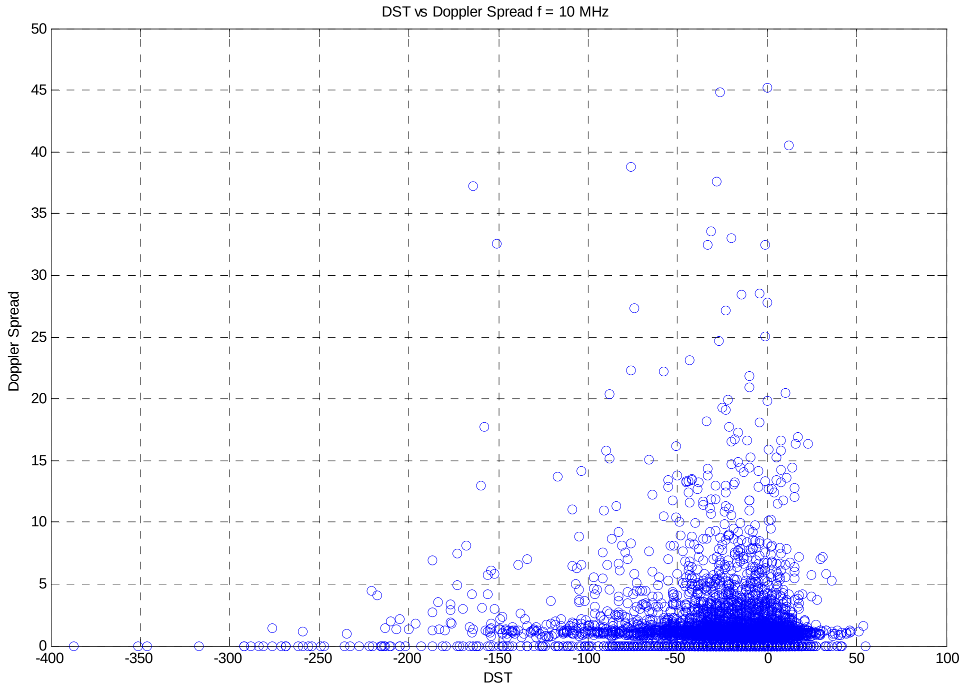


Figure 3.7: DST vs. Doppler Spread, f = 10 MHz

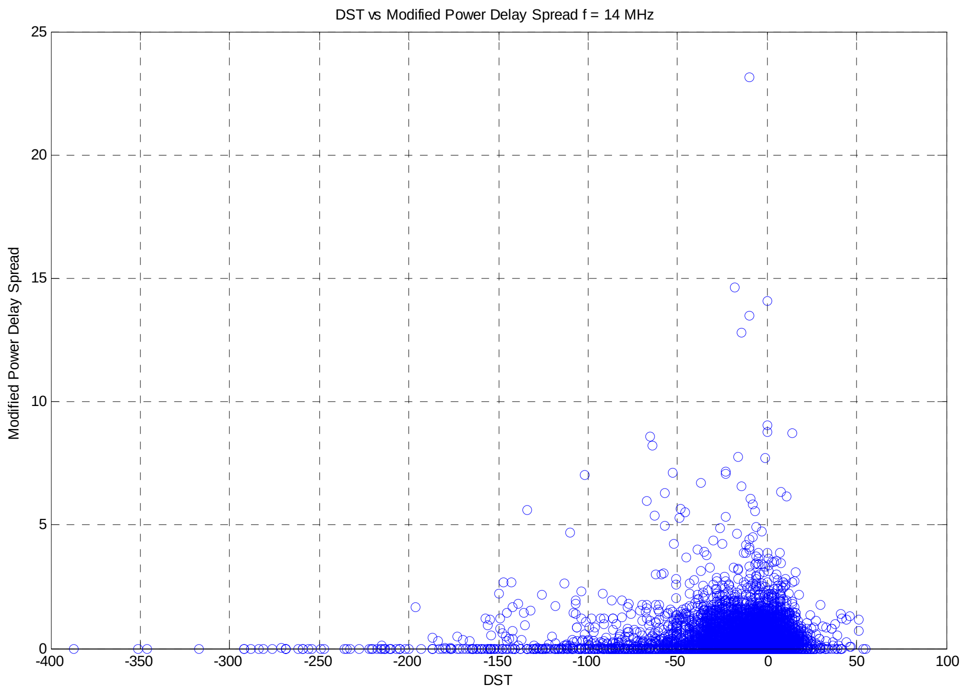


Figure 3.8: DST vs. Modified Power Delay Spread, f = 14 MHz

3.3 Mathematical Formulations:

3.3.1. Correlations:

After observing Figures 3.6-3.8, attempts have been made to express these relationships mathematically. During this study, it is checked whether the data and the magnetic indices are correlated. However as seen from Figures 3.6-3.8 since there is no linear relation between them their correlation coefficients were low.

3.3.2. Spectrograms:

The second study was to construct the spectrograms of the SNR, Doppler Spread and Modified Power Delay Spread data. As seen from the Figures 3.9, 3.10 and 3.11 the spectrogram data do not contain frequency patterns to relate these data to magnetic indices.

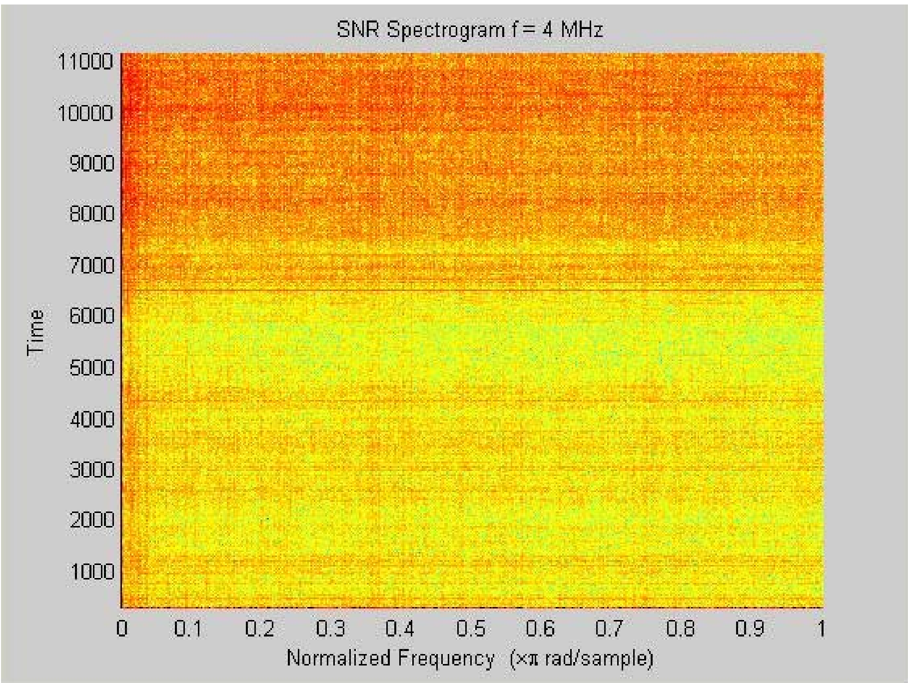


Figure 3.9: Spectrogram for SNR, f =4 MHz

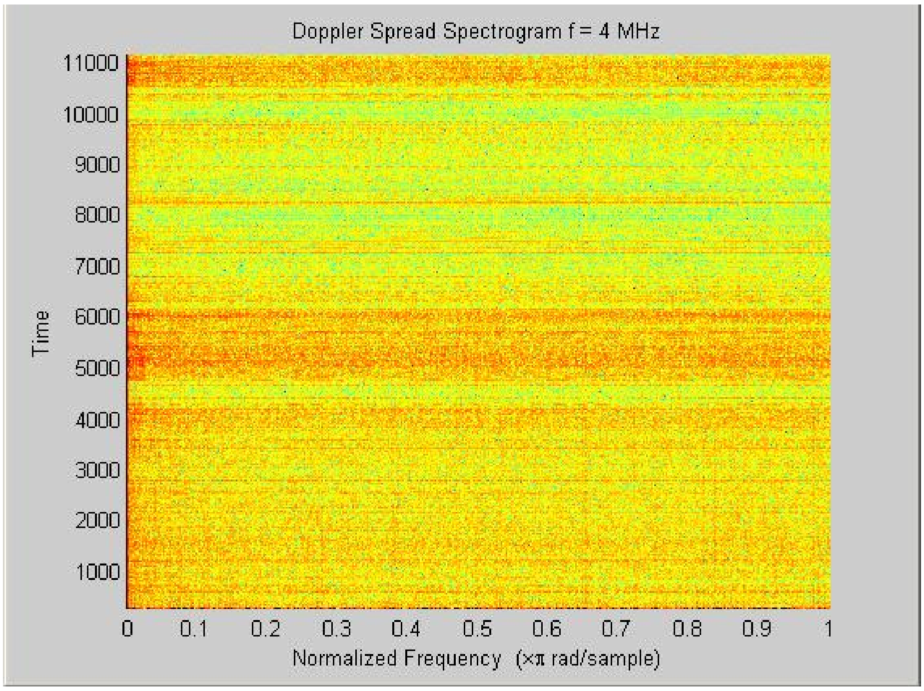


Figure 3.10: Spectrogram for Doppler Spread, f = 4 MHz

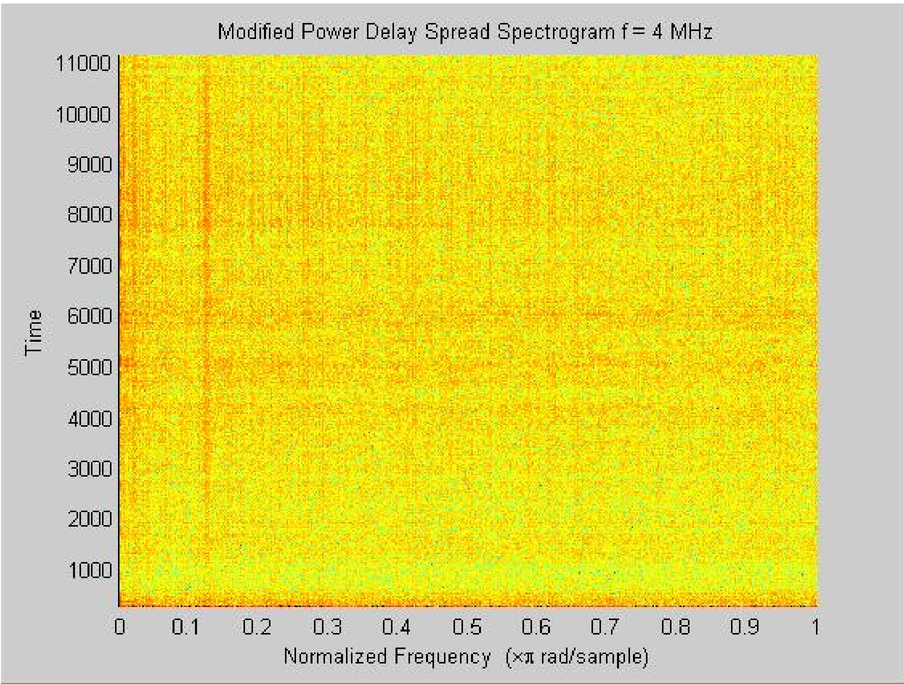


Figure 3.11: Spectrogram for Modified Power Delay Spread, f =4 MHz

3.3.3. Histograms:

First of all it should be noted that Figures 3.6-3.8 present distributions. If the histogram of the SNR data for 4 MHz and (-DST) index is plotted than the distribution can be more obviously seen as indicated in Figure 3.12.

One should note that the joint probability density function of SNR and DST (or negative of DST) can be computed in a similar manner.

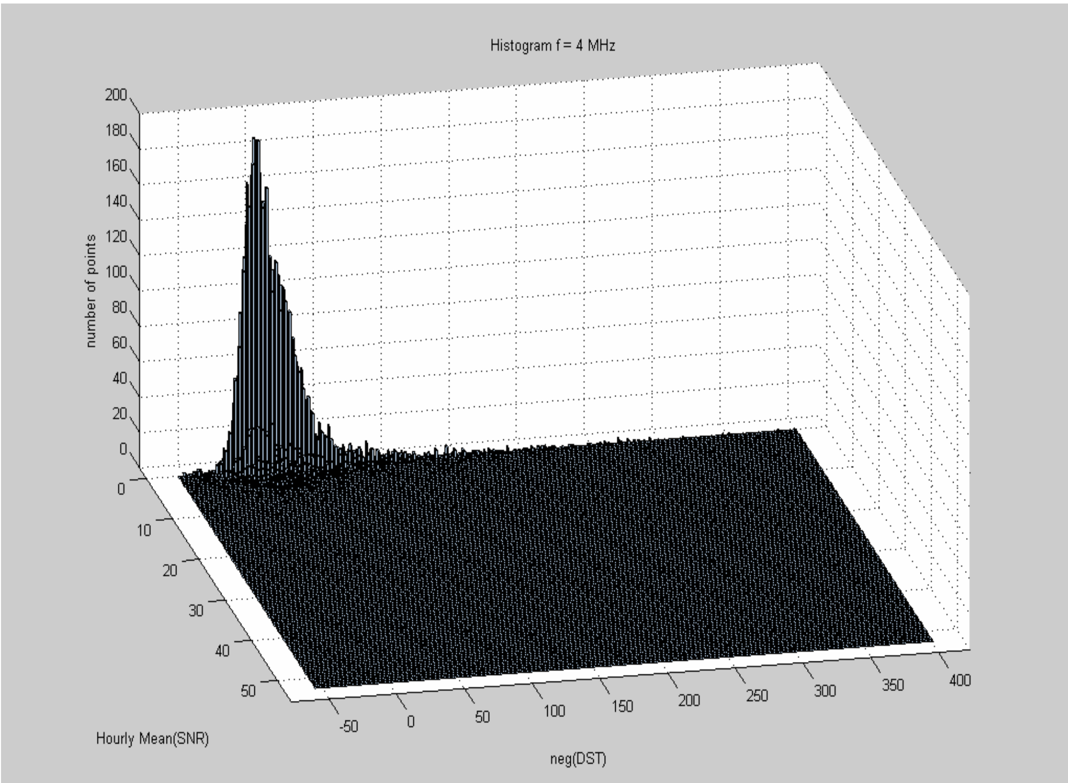


Figure 3.12: Histogram for negative of DST and Hourly Mean of SNR, f =4 MHz

3.3.4. Computing Joint Probability Density Functions:

Joint pdf (probability density function) is evaluated as following:

1. The x-y (e.g. SNR-DST plane) is separated into unit cells

2. The number of points in any unit cell is counted

3. The density related to any unit cell is the number of points in that cell divided by total number of points.

As seen from Figure 3.13 the number of points in cell B is higher than the number of points in cell A.

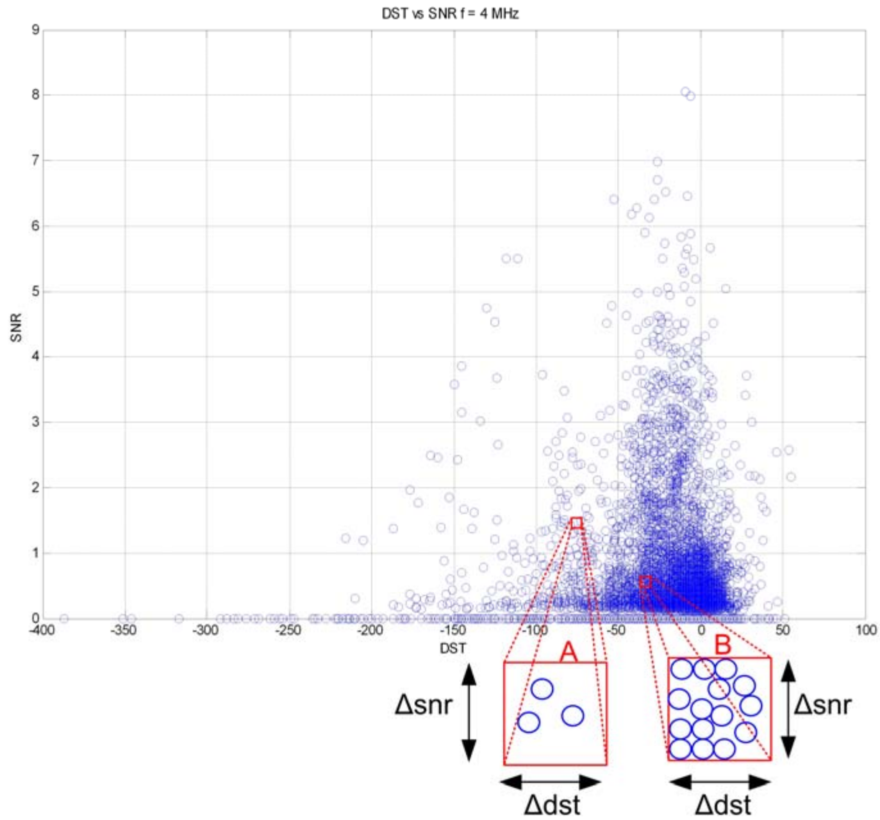


Figure 3.13: Calculation of joint pdf

Figure 3.13 shows the scatter plot of hourly mean SNR and negative DST. Joint pdf is actually an mxn matrix where;

$$m_{\min} = ceiling\left(\frac{\max(SNR)}{\Delta snr}\right) \tag{3-1}$$

$$n_{\min} = ceiling\left(\frac{|\max(DST) - \min(DST)|}{\Delta dst}\right) \tag{3-2}$$

Please note that since minimum value of SNR is zero and the minimum of DST is a negative number (e.g.-387 for year 2001), actually there is no difference between the formulae of minimum m and minimum n. m and n take larger values than these ones. This will result in adding zero rows or columns to joint pdf matrix accordingly.

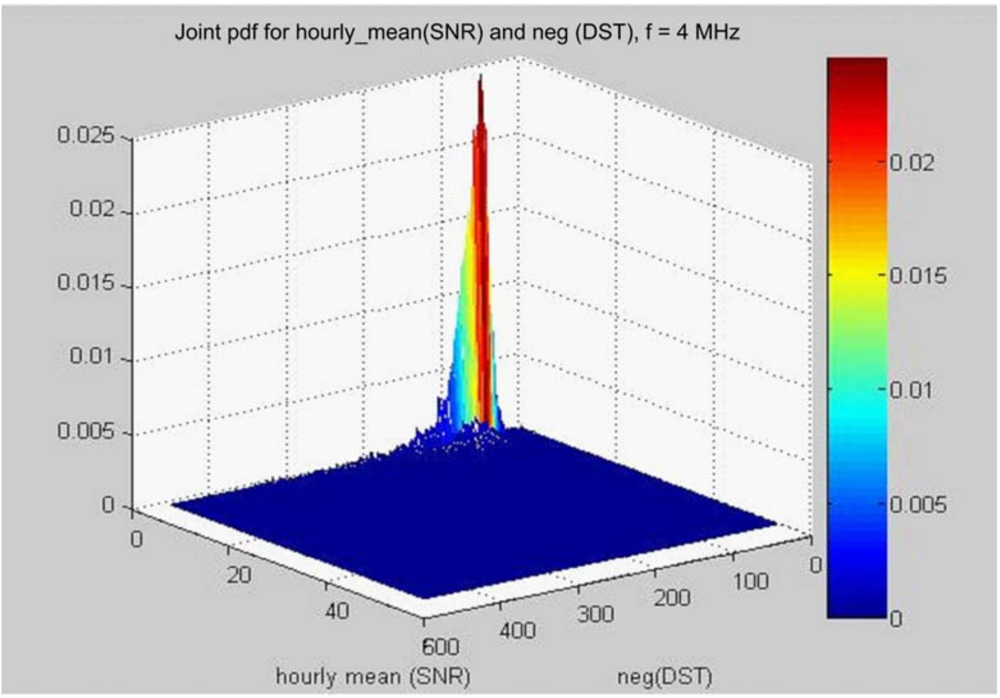


Figure 3.14: Joint pdf for hourly mean of SNR and negative of DST, f= 4 MHz

It is obvious that choosing smaller "Δ" values (increasing resolution) will give better results. However due to computational difficulties, during joint pdf and conditional pdf calculations Δdst=1, Δsnr=0.5, Δmpspread=0.5 and Δdopspread=0.1 are selected. By doing so a joint pdf matrix of approximately 400x100x100x100 points is evaluated.

3.3.5. Computing Conditional Density Functions:

After obtaining joint density functions by using the method described in Section 2.4.3, conditional pdfs are evaluated.

As an example of calculation method, the conditional density function of SNR, related to DST will be investigated in this section.

As mentioned in Section 2.6, DST parameter mostly takes negative values. To be able to compare the results of this parameter with ones of the other magnetic indices, the negative of DST value that is

$$nDST = -1 * DST \tag{3-3}$$

will be used in the following sections.

As described in previous section joint density function is an mxn matrix.

$$f_{SNR,nDST}(snr,ndst)=\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & c_{1,n} \\ . & . & & & & & & & & . \\ . & & . & & & & & & & . \\ . & & & . & & & & & & . \\ . & & & & c_{i,j} & & & & & . \\ . & & & & & . & & & & . \\ . & & & & & & . & & & . \\ . & & & & & & & . & & . \\ . & & & & & & & & . & . \\ c_{m,1} & c_{m,2} & c_{m,3} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & c_{m,n} \end{bmatrix}_{mxn} \tag{3-4}$$

where

$$\sum_i \sum_j c_{i,j} = 1 \tag{3-5}$$

Let's define a conditional density function of SNR as $f_{SNR|nDST}$ ($snr|ndst=ndst_0$) where $ndst_0$ is a known nDST value. This function is nothing but the normalized version of a column vector of $f_{SNR,nDST}(snr,ndst)$. Let us define this column vector as k^{th} column vector. Than the conditional density function will be

$$f_{SNR|nDST}(snr \mid ndst = ndst_0) = \frac{1}{\sum_{i=1}^{m} c_{i,k}} * \begin{bmatrix} c_{1,k} \\ c_{2,k} \\ . \\ . \\ . \\ c_{i,k} \\ . \\ . \\ . \\ c_{m,k} \end{bmatrix}_{mx1} \tag{3-6}$$

where

$$k = \frac{-1 * \min(nDST) + ndst_0}{\Delta dst} = \frac{\max(DST) - dst_0}{\Delta dst} \tag{3-7}$$

Please note that

$$dst_0 = -1 * ndst_0 \tag{3-8}$$

Figures 3.15, 3.16 and 3.17 show the conditional pdfs of SNR data (transmission frequency= 4 MHz) with DST= 0, DST= -50, DST=- 100.

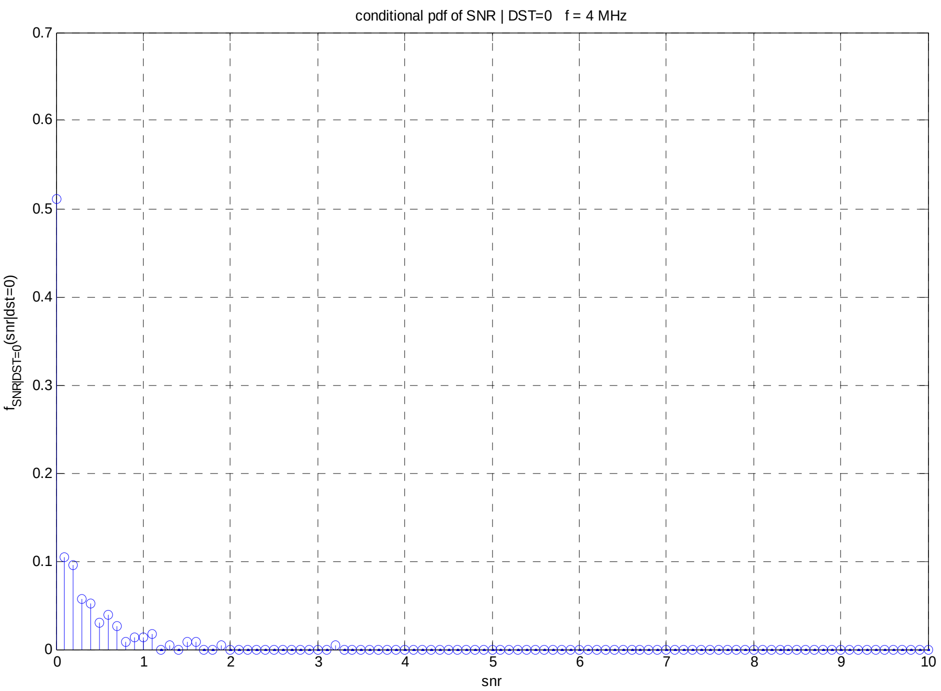


Figure 3.15: Conditional pdf of hourly mean of SNR, DST= 0, f=4 MHz

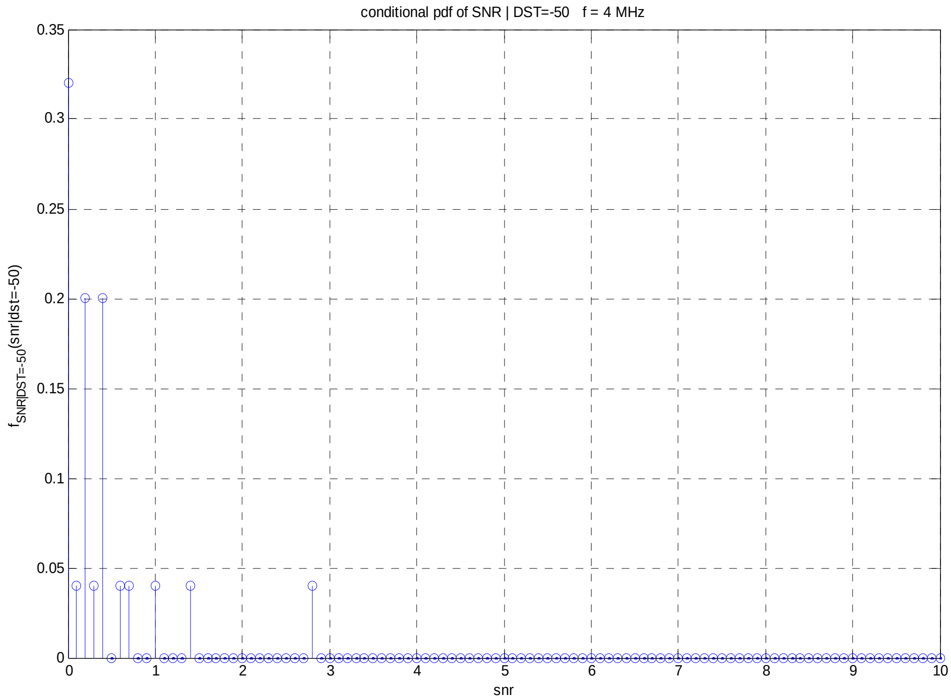


Figure 3.16: Conditional pdf of hourly mean of SNR, DST= -50, f=4 MHz

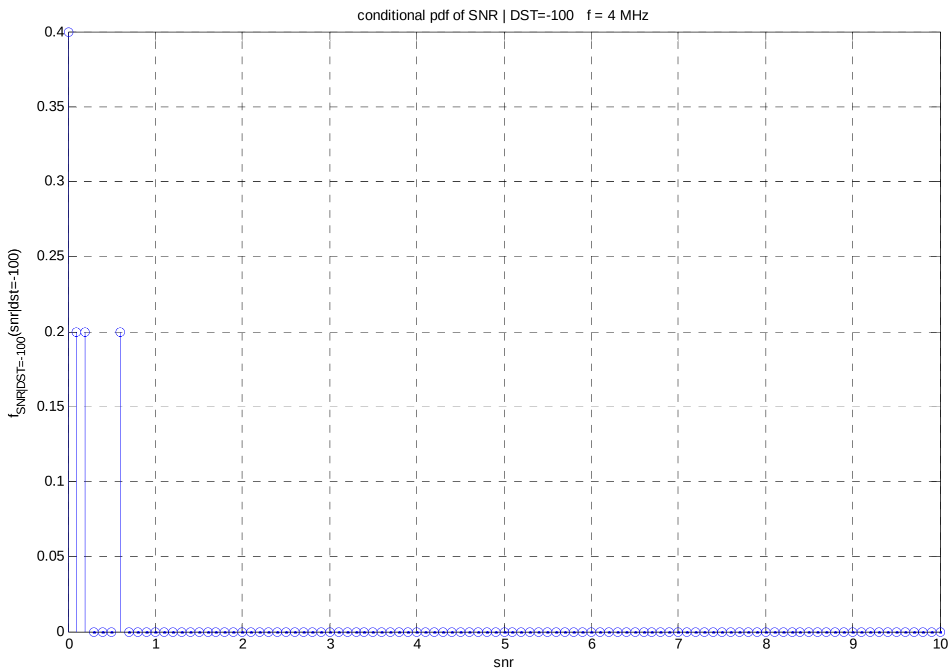


Figure 3.17: Conditional pdf of hourly mean of SNR, DST= -100, f=4 MHz

3.3.6. Computing Marginal Density Functions:

Let's define the marginal density function of SNR as $f_{SNR}(snr)$.

$$f_{SNR}(snr) = \begin{bmatrix} \sum_{t=1}^{n} c_{1,t} \\ \sum_{t=1}^{n} c_{2,t} \\ . \\ . \\ . \\ \sum_{t=1}^{n} c_{i,t} \\ . \\ . \\ . \\ \sum_{t=1}^{n} c_{m,t} \end{bmatrix}_{mx1} \qquad (3\text{-}9)$$

Figure-3.18 shows the marginal pdf of SNR data (transmission frequency= 4 Mhz) calculated from joint density function $f_{SNR,nDST}(snr,ndst)$.

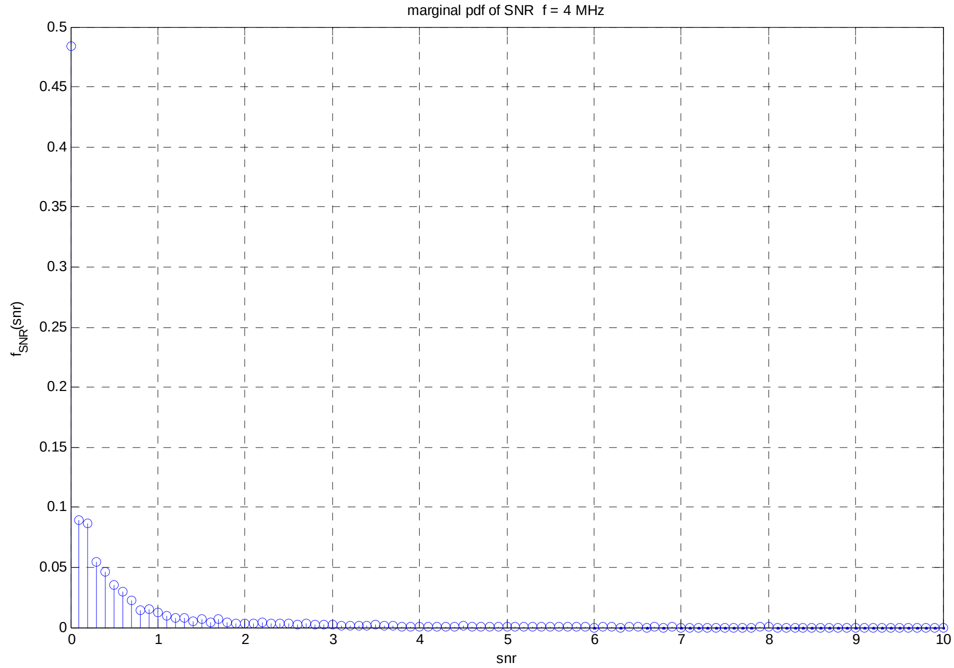


Figure 3.18: Marginal pdf of hourly mean of SNR, f=4 MHz

3.3.7. Independence:

According to Bayes' Theorem, if SNR and DST are independent then

$$f_{SNR,nDST}(snr,ndst) = f_{SNR}(snr) * f_{nDST}(ndst) \tag{3-10}$$

$$f_{SNR,DST}(snr,dst) = f_{SNR}(snr) * f_{DST}(dst) \tag{3-11}$$

Independence check is performed for different combinations of transmission frequency and DST. After this study, dependence of SNR and DST is observed as expected.

The method followed to check the independence of the parameters is explained below. For simplicity the SNR and DST parameters are used in the explanation.

1. Joint pdf, $f_{SNR,nDST}(snr,ndst)$ is evaluated as mentioned in Section 3.3.5. Please note that $f_{SNR,nDST}(snr,ndst)$ is an mxn matrix.

2. Marginal pdfs f_{SNR} (snr) and $f_{nDST}(ndst)$ are evaluated as mentioned in Section 3.3.6.Please note that f_{SNR} (snr) is an array of length m and $f_{nDST}(ndst)$ is an array of length n.

3. A dummy matrix with no physical meaning $F=f_{SNR}$ $(snr)*f_{nDST}(ndst)$ is evaluated. Please note that F is an mxn matrix.

4. The difference matrix $D= f_{SNR,nDST}(snr,ndst)-F$ is evaluated.

5. The largest singular value of the D matrix is found.

6. If the value found in 5. is different than 0, than DST and SNR are dependent.

3.3.8. Calculating the Modem Availability:

Modem availability is defined in Section 2.5. For a given magnetic condition modem availability is calculated according to following procedure:

1. Conditional probability density functions of SNR, Doppler Spread and Modified Power Delay Spread are obtained.

2. The probabilities of the points that are on the upper side of the modem surface (available points) are evaluated by using the conditional probability functions.

Figure 3.19 shows an approximated modem availability surface plotted according to Table 2.1, 1200 bps. As seen in Figure 3.19 if a point is on the upper side of the blue surface than it is an available point (a green one), otherwise it is an unavailable one (a red point in the figure).

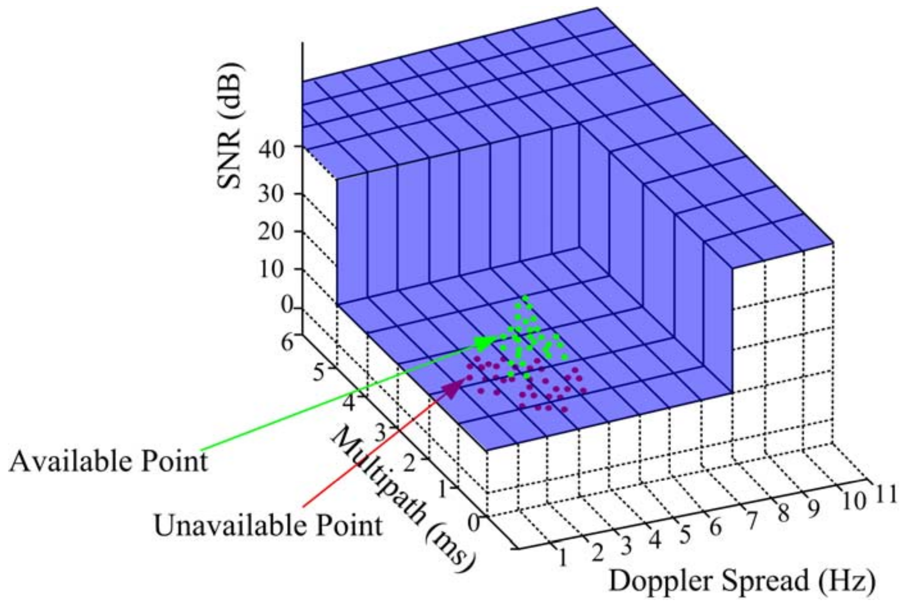


Figure 3.19: Approximated availability surface according to STANAG 4539.

3.3.8.1 Conditional Density Function of SNR, Doppler Spread and Modified Power Delay Spread according to DST conditions:

Let us define the conditional density function as $f_{DOPSPREAD,MPSPREAD,SNR|nDST}(dopspread,mpspread,SNR|ndst=ndst_0)$ where "dopspread" designates Doppler Spread and "mpspread" designates Modified Power Delay Spread.

Actually $f_{DOPSPREAD,MPSPREAD,SNR|nDST}(dopspread,mpspread,SNR|ndst=ndst_0)$ is a function similar to $f_{SNR|nDST}(snr|ndst=ndst_0)$ with a difference of being a function of 4 variables.

As $fSNR_{|nDST}$ $(snr|ndst=ndst_0)$ is a two dimensional matrix with (mxn) as described in (3-4), $f_{DOPSPREAD,MPSPREAD,SNR,|nDST}(dopspread,mpspread,SNR,ndst)$ is a four dimensional matrix (dxmxsxD). Figure 3.20 shows this matrix.

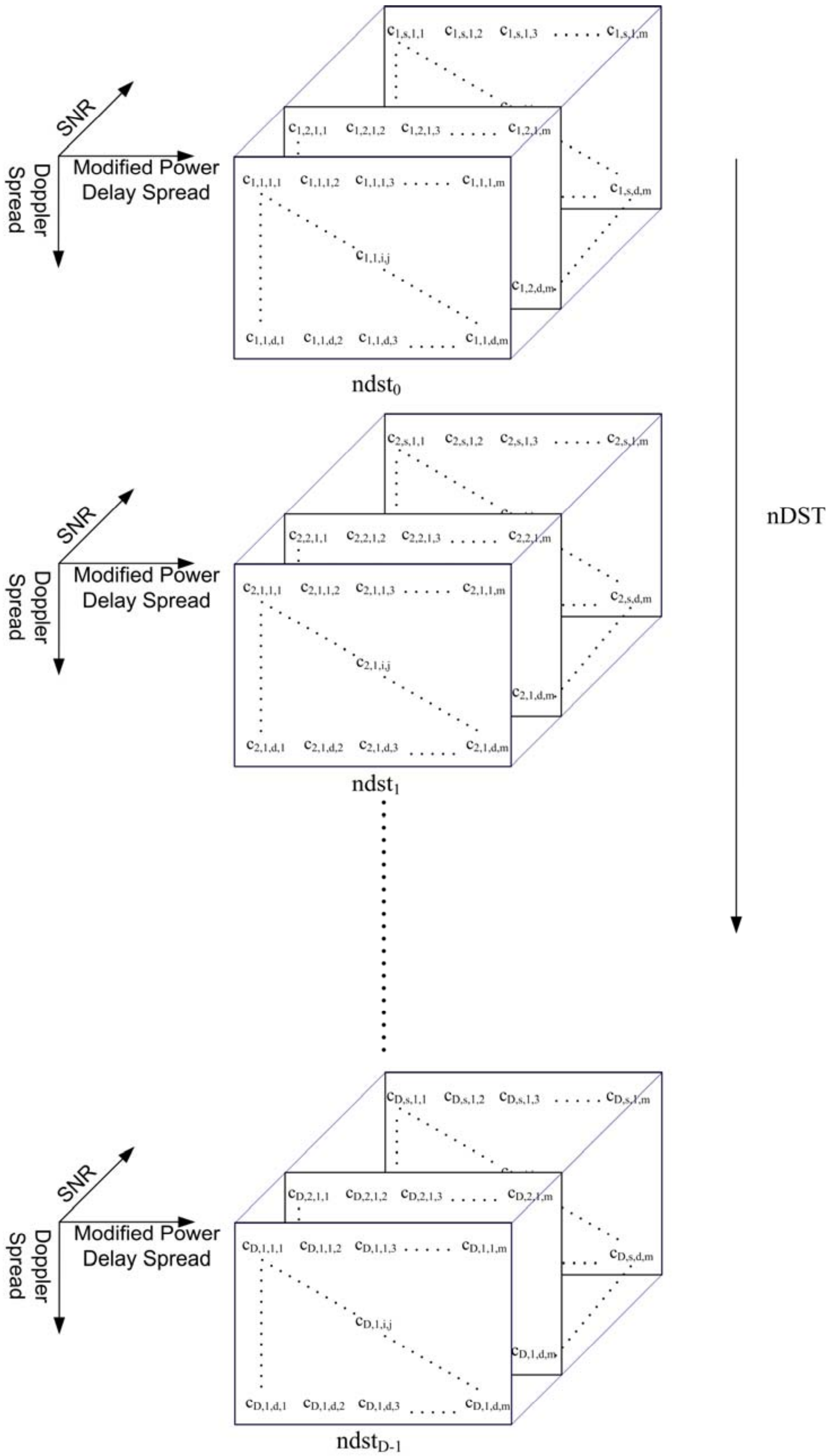


Figure 3.20: $f_{DOPSPREAD,MPSPREAD,SNR,|nDST}(dopspread,mpspread,SNR,ndst)$

$$\sum_i \sum_j \sum_k \sum_l c_{i,j,k,l} = 1 \tag{3-12}$$

$f_{DOPSPREAD,MPSPREAD,SNR|nDST}(dopspread,mpspread,SNR|ndst=ndst_0)$ is the normalized version of one of the three-dimensional cubes seen in Figure 3.20. Let's define *c'* as

$$c'_{j,k,l} = \frac{c_{j,k,l}}{\sum_j \sum_k \sum_l c_{j,k,l}} \tag{3-13}$$

than

$$\sum_j \sum_k \sum_l c'_{j,k,l} = 1 \tag{3-14}$$

$f_{DOPSPREAD,MPSPREAD,SNR|nDST}(dopspread,mpspread,SNR|ndst=ndst_0)$ is a three dimensional (sxdxm) matrix as seen in Figure 3.21.

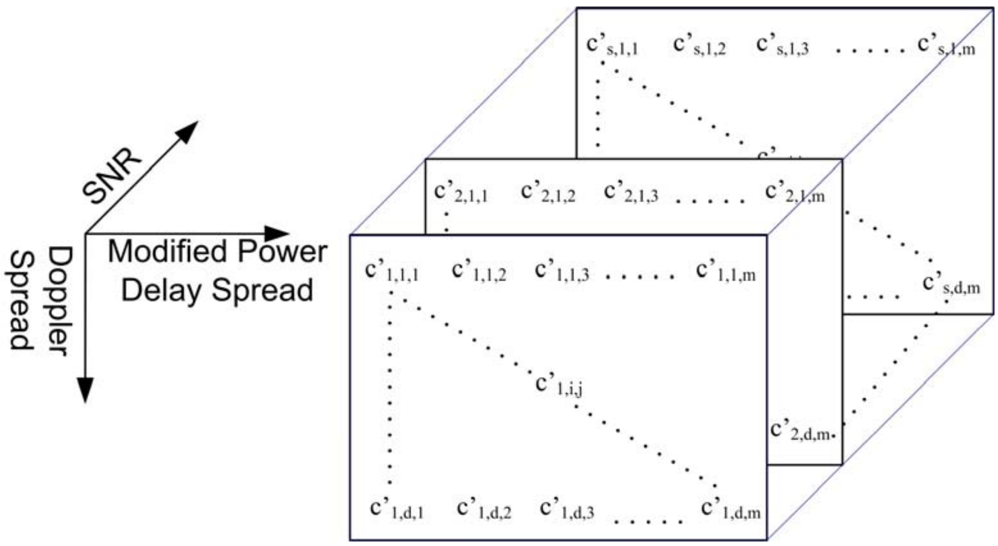


Figure 3.21: $f_{DOPSPREAD,MPSPREAD,SNR|nDST}(dopspread,mpspread,SNR|ndst=ndst_0)$

3.3.8.2 Conditional Probability:

Conditional probability which is nothing but the modem availability probability is evaluated as

$$Modem\_availability\_probabilty = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=L}^{s} c'_{j,k,l} \qquad (3\text{-}15)$$

where

J: Maximum allowed Doppler Spread

K: Maximum allowed Modified Power Delay Spread

L: Minimum allowed SNR

As an example of calculation of the conditional probabilities, the approximated SNR surface for the STANAG 4539 requirements as defined in Table-2.3 is used.

Tables 3.2, 3.3, 3.4, 3.5 and 3.6 show the probability of modem availability for different data rates and frequencies.

Table 3.2: Modem Availabilities with DST=0.

DST=0	2400 bps	1200 bps	0600 bps	0300 bps	0150 bps	0075 bps
04 MHz	0	0	0,004	0,983	0,974	1
06 MHz	0	0,026	0,245	0,891	0,869	0,983
10 MHz	0,288	0,472	0,576	0,978	0,978	0,991
11 MHz	0,179	0,424	0,533	0,987	0,974	1
14 MHz	0,122	0,258	0,380	0,987	0,978	0,996
18 MHz	0,153	0,183	0,253	1	0,991	1

Table 3.3: Modem Availabilities with DST=-025.

DST=-025	2400 bps	1200 bps	0600 bps	0300 bps	0150 bps	0075 bps
04 MHz	0	0	0,071	0,973	0,965	0,991
06 MHz	0,009	0,124	0,301	0,982	0,973	0,982
10 MHz	0,354	0,434	0,460	0,991	0,991	0,354
11 MHz	0,283	0,398	0,433	0,982	0,965	0,991
14 MHz	0,071	0,177	0,292	1	0,991	1
18 MHz	0,124	0,168	0,168	1	1	1

Table 3.4: Modem Availabilities with DST=-050.

DST=-050	2400 bps	1200 bps	0600 bps	0300 bps	0150 bps	0075 bps
04 MHz	0	0	0,04	1	0,96	1
06 MHz	0	0	0,12	0,96	0,92	1
10 MHz	0,32	0,4	0,56	1	0,96	1
11 MHz	0,2	0,4	0,56	1	0,92	1
14 MHz	0,08	0,2	0,28	1	0,92	1
18 MHz	0,16	0,2	0,2	1	0,96	1

Table 3.5: Modem Availabilities with DST=-100.

DST=-100	2400 bps	1200 bps	0600 bps	0300 bps	0150 bps	0075 bps
04 MHz	0	0	0	1	1	1
06 MHz	0	0,2	0,2	1	1	1
10 MHz	0,4	0,8	0,8	1	1	1
11 MHz	0,6	0,6	0,6	1	1	1
14 MHz	0,4	0,6	0,6	1	1	1
18 MHz	0,2	0,2	0,2	1	1	1

Table 3.6: Modem Availabilities with DST=-150.

DST=-150	2400 bps	1200 bps	0600 bps	0300 bps	0150 bps	0075 bps
04 MHz	0	0	0	1	1	1
06 MHz	0	0	0	1	1	1
10 MHz	0	0	1	1	1	1
11 MHz	0	0	0	1	1	1
14 MHz	0	0	0	1	1	1
18 MHz	0	0	0	1	1	1

It should be noted that the precision of the modem availability values are different in Tables 3.2-3.6. This is due to the availability of different number of data points for each condition. There are large number of data with DST=0, while there are much less amount of with DST=- 150. This situation is beyond the control of the author.

If Tables 3.2-3.6 are investigated it can easily be noted that the highest probability values of each table are found on the rows of 10 MHz and 11 MHz. It can be commented that this is due to the MUF to be around these values during the experimental study.

CHAPTER 4

CONCLUSIONS and FUTURE STUDIES

4.1 Summary and Conclusions

HF Channel is considered as a system composed of various physical and chemical processes.

A new approach to model the Ionospheric HF channel is submitted. HF Ionospheric Channel is expressed by the three parameters for an HF model to work with desired BER. These parameters are SNR, Doppler Spread and Delay Spread.

In this study, data of these three parameters over the year 2001 are obtained from an experiment held between Leicester (U.K.) and Uppsala (Sweden). DST index of the same interval is obtained from National Geophysical Data Center's database [34].

In the beginning of the study, the dependences between DST and SNR, DST and Doppler Spread, DST and Delay Spread are presented. Secondly, four dimensional conditional probability density functions are obtained. Finally the probability of modem to be available for the selected DST value is calculated.

As shown with DST example this method considers the channel as a system and models the channel to asses modem/channel availability under Ionospheric Disturbances.

In this study, only DST index is used. However it is easy to use other magnetic indices. However it should be noted that DST is a planetary index and is unique over the Earth. If any local index like PC index is to be used then the correct local value should be selected. Obviously the local parameter should characterize the mid-point of the selected communication path (channel).

It should be noted that the proposed method is not limited with the use of one parameter. More than one ionospheric parameter can be used and consequently more than four dimensional conditional probability density functions can be obtained. There is no restriction of the modeling method concerning the number of magnetic parameters. Actually the inclusion of more ionospheric parameters will give more precise solutions. This is similar to the use of more than one input parameters in neural network models which are mostly used to forecast ionospheric critical frequency and Total Electron Content (TEC) Maps [37], [38],[39],[40].

Since the model has a stochastic approach depending on experimental data the conditional probability density function can be updated continuously.

The method is general and can be applied to industrial or other types of systems with similar characteristics. HF Channel is considered in this study as an interesting and involved example. The approach is also interesting in the sense that it deals with the effects of space weather on communication. Space Weather is a new concept which is attracting a great deal of attention in the international scientific and technological circles [37].

4.2 Future Work

Two or more relevant indices can be included and the improvements can be examined. The effects of including local magnetic indices can also be investigated. For the year 2001 and the experimental path such data could not be obtained within reasonable time.

A new experiment can be held to include local indices or global indices. As the data is increased (as the duration of the experiment gets longer), the conditional density function will be updated for better sensitivity

.

The study can be repeated with other Modem standards or with the values defined in particular Modem specifications.

The experimental data and the results can be statistically evaluated. By using dynamic estimation techniques, model can be updated to a dynamic model.

The study can be applied to systems other than HF Channel where required.

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