Chapter 2

Very Low Frequency (VLF) Radio Waves: Tool to probe the Ionosphere

In the previous Chapter, we learned the propagation mechanism of radio waves through the Earth-Ionosphere Waveguide (EIWG) and the theories available in literature that can predict the signal strength at some point within the waveguide. Radio waves, precisely Very Low Frequency (VLF) radio waves (3 − 30 kHz) and Extremely Low Frequency (ELF) radio waves (< 3 kHz) suffer reflection from the lower ionospheric layers during its propagation. They carry information about any anomalies in that region and thus can serve as useful experimental tools in probing the ionosphere.

In this Chapter, we will discuss about the VLF radio wave and its advantages over other probing techniques. We will also discuss about networks of VLF transmitters across the globe and the types of VLF receivers, the ICSP-VLF network and the characteristics of a diurnal signal variation as received on a quiet unperturbed day. Knowing how the signal behaves on a time scale of 24 hours under normal conditions will help us in detecting the modifications arising from extra sources of ionization.

2.1 Very Low Frequency (VLF) radio waves

Very Low Frequency (VLF) radio waves are the waves corresponding to frequencies 3 − 30 kHz and respective wavelengths 100 − 10 km. The VLF band is used for radio navigation services and secure military communications. The history of VLF dates back to the time of the Second World War. The urge to develop radio research came from the experience gained in the war about the importance of radio in communications and navigation [Buder, 1999]. These waves have large skin depths of about
10 – 40 meters (30 – 130 feet) in salt water depending on the incident frequency and salinity of the water and hence they were and still are used to communicate with submarines under sea water. This need for navigation and secure global military communication with submarines was the thrust behind the development of this particular area of theoretical and experimental research for the past several decades [Barr et al., 2000].

The region 50 – 250 km of the Earth’s atmosphere can be studied neither by sending balloons because it is too high for them nor by satellites because it is too low for satellites. Rocket-borne experiments can be performed, but they are too costly to execute and also the information obtained from such experiments would be of very short duration (few minutes). To understand this region VLF radio waves are used which reflect from the lower ionospheric D and E layers during its propagation and any anomalies in that region get imprinted on the received signal. This is why VLF radio waves have gained popularity in studying the lower regions of the ionosphere.

The origin of VLF transient signals can be due to both natural and artificial sources. Lightning discharges from thunderstorms, volcanic eruptions, dust storms and tornados are some of the natural sources. Among them, lightning discharges are the most significant noise producing sources on a global basis. On the other hand, to produce electromagnetic waves artificially and efficiently, an antenna with dimensions of the order of wavelength of the radiation is required. As the wavelength of VLF waves is between 100 – 10 km, it suggests that the antenna should be sufficiently large to be efficient [Barr et al., 2000].

### 2.2 VLF Transmitting Antennas

The major problem in constructing a full size resonant VLF antenna is the wavelength of the waves (100 – 10 km). Vertical antennas are to be built as the VLF waves are vertically polarized, but a quarter-wave vertical antenna transmitting at 30 kHz would be 2.5 km high. So, in reality, vertical antennas are electrically short with height equivalent to only a small fraction of a wavelength. These antennas are also inefficient, radiating only 10% to 50% of the transmitting power at frequencies above 10 kHz. The remaining power is dissipated in the antenna/ground system.

Transmitting antennas for VLF frequencies are large wire antennas consisting of
radio masts interconnected to each other at the top by cables. The whole system covers miles of area, and looks like an umbrella. Either these radio masts themselves or vertical wires connected at the top of them serve as monopole radiators and the horizontal cables form a capacitive topload to increase efficiency of the antenna. In order to prevent power dissipation to the ground, the radio masts are provided with radial networks of copper cables extending radially outwards from the radio masts from few feet above the ground [Figure 2.1]. VLF antennas have often been seen to be constructed making use of natural geographic structures to provide support, like the ones strung across the fjord in Norway and in extinct volcanoes in Hawaii [Barr et al., 2000]. There are numerous antennas all across the globe transmitting at various VLF frequencies. The primary function of these VLF transmitters is to communicate with submarines. The global network of VLF transmitters is presented in Table 2.1 (Source: https://sidstation.loudet.org/stations-list-en.xhtml).
Table 2.1: List of VLF transmitters across the globe (Source: https://sidstation.loudet.org/stations-list-en.xhtml)

<table>
<thead>
<tr>
<th>Call Sign</th>
<th>Frequency (kHz)</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTX1</td>
<td>16.3</td>
<td>South Vijayanarayanam, India</td>
<td>8° 23' 13.25&quot;N</td>
<td>77° 45' 9.94&quot;E</td>
</tr>
<tr>
<td>JXN</td>
<td>16.4</td>
<td>Novik, Norway</td>
<td>66° 58' 27.67&quot;N</td>
<td>13° 52' 25.02&quot;E</td>
</tr>
<tr>
<td>VTX2</td>
<td>17.0</td>
<td>South Vijayanarayanam, India</td>
<td>8° 23' 13.25&quot;N</td>
<td>77° 45' 9.94&quot;E</td>
</tr>
<tr>
<td>SAQ</td>
<td>17.2</td>
<td>Grimeton, Sweden</td>
<td>57° 06' 47.42&quot;N</td>
<td>12° 23' 50.20&quot;E</td>
</tr>
<tr>
<td>VTX3</td>
<td>18.2</td>
<td>South Vijayanarayanam, India</td>
<td>8° 23' 13.25&quot;N</td>
<td>77° 45' 9.94&quot;E</td>
</tr>
<tr>
<td>VTX4</td>
<td>19.2</td>
<td>South Vijayanarayanam, India</td>
<td>8° 23' 13.25&quot;N</td>
<td>77° 45' 9.94&quot;E</td>
</tr>
<tr>
<td>GBZ</td>
<td>19.58</td>
<td>Anthorn, UK</td>
<td>54° 54' 41.91&quot;N</td>
<td>3° 16' 42.44&quot;W</td>
</tr>
<tr>
<td>NWC</td>
<td>19.8</td>
<td>Harold E. Holt, North West Cape, Exmouth, Australia</td>
<td>21° 48' 58.78&quot;S</td>
<td>114° 09' 56.11&quot;E</td>
</tr>
<tr>
<td>ICV</td>
<td>20.27</td>
<td>Isola di Tavolara, Italy</td>
<td>40° 55' 23.26&quot;N</td>
<td>9° 43' 51.64&quot;E</td>
</tr>
<tr>
<td>FTA</td>
<td>20.9</td>
<td>Sainte-Assise, France</td>
<td>48° 32' 40.68&quot;N</td>
<td>2° 34' 45.94&quot;E</td>
</tr>
<tr>
<td>NPM</td>
<td>21.4</td>
<td>Pearl Harbour, Lualualei, HI</td>
<td>21° 25' 12.60&quot;N</td>
<td>158° 09' 4.10&quot;W</td>
</tr>
<tr>
<td>HWU</td>
<td>21.75</td>
<td>Rosnay, France</td>
<td>46° 42' 47.26&quot;N</td>
<td>1° 14' 42.89&quot;E</td>
</tr>
<tr>
<td>GQD</td>
<td>22.1</td>
<td>Skeiton, UK</td>
<td>54° 43' 54.48&quot;N</td>
<td>2° 52' 58.92&quot;W</td>
</tr>
<tr>
<td>JJI</td>
<td>22.2</td>
<td>Ebino, Japan</td>
<td>32° 04' 55.50&quot;N</td>
<td>130° 49' 40.66&quot;E</td>
</tr>
<tr>
<td>DHO</td>
<td>23.4</td>
<td>Rhauderfehn, Germany</td>
<td>53° 04' 44.04&quot;N</td>
<td>7° 36' 54.00&quot;E</td>
</tr>
<tr>
<td>NAA</td>
<td>24.0</td>
<td>Cutler, ME</td>
<td>44° 38' 41.77&quot;N</td>
<td>67° 16' 53.90&quot;W</td>
</tr>
<tr>
<td>NLK</td>
<td>24.8</td>
<td>Oso Wash, Jim Creek, WA</td>
<td>48° 12' 12.55&quot;N</td>
<td>121° 55' 0.58&quot;W</td>
</tr>
<tr>
<td>unid25</td>
<td>25.0</td>
<td>Mokpo, South Korea</td>
<td>34° 40' 44.65&quot;N</td>
<td>126° 26' 43.38&quot;E</td>
</tr>
<tr>
<td>NML</td>
<td>25.2</td>
<td>La Moure, ND</td>
<td>46° 21' 57.56&quot;N</td>
<td>98° 20' 8.30&quot;W</td>
</tr>
<tr>
<td>TBB</td>
<td>26.7</td>
<td>Bafa, Turkey</td>
<td>37° 24' 45.81&quot;N</td>
<td>27° 19' 24.03&quot;E</td>
</tr>
</tbody>
</table>
Chapter 2. VLF radio waves

2.3 VLF Receiving Antennas

The main purpose of an antenna is to convert electromagnetic radiation in space into electrical currents in conductors or vice-versa depending on whether it is used for receiving or transmitting. The characteristics of a transmitting antenna remains almost unchanged when it is used for receiving, and thus we can use the analysis of a transmitting antenna to understand a receiving antenna.

2.3.1 Loop antenna

A loop antenna is sensitive to the magnetic field of electromagnetic radiation and hence it is also called magnetic loop antenna. It is actually a winding of copper wires around a frame (for air-core loops) or around ferromagnetic materials (for ferrite loops). A loop antenna gives an output voltage proportional to the magnetic field and frequency of the signal, whose amplitude is maximum in the plane of the frame and theoretically zero in the plane normal to the frame. The performance of the antenna is dependent on number of turns and area of each loop. According to Faraday’s law of induction (or the law of electromagnetic induction), the electromotive force \( e(t) \) induced in a closed loop is directly proportional to the time rate of change of magnetic flux \( \Phi(t) \) through it

\[
e(t) = -\frac{d\Phi(t)}{dt}.
\]

This equation is only valid for electrically short antennas which is true for antennas for VLF frequencies.

Let us define

\[
B(t) = B(t)u
\]

as the vector of magnetic induction, \( u \) being the unit vector,

\[
S = S.n
\]

as the normal vector to the frame surface, \( n \) being the unit vector,

\[
u.n = \cos \theta,
\]

where \( \theta \) is the angle between the magnetic field lines and the frame normal.

The magnetic flux is defined as the quantity of magnetism passing through an antenna due to a given magnetic induction

\[
\Phi(t) = B(t).S.
\]
For a sinusoidal magnetic field uniform over the surface \([B(t) = B_0 \cos \omega t]\), where \(B_0\) is the strength of magnetic induction, and \(\omega\) is the angular frequency of the magnetic field, the amplitude of \(B(t)\) projected on \(n\) is

\[B(t) \cdot n = B(t)u \cdot n,\]

or

\[B(t) \cdot n = B_0 \cos \omega t \cos \theta.\]

We can then write

\[\Phi(t) = B(t)S u \cdot n,\]

or

\[\Phi(t) = B_0 \cos \omega t S \cos \theta.\]

For a loop with \(N\) turns, each of area \(A\), we have \(S = NA\), so that

\[\Phi(t) = NAB_0 \cos \omega t \cos \theta,\]

and then

\[e(t) = NAB_0 \omega \sin \omega t \cos \theta.\]

Since \(\omega = 2\pi f\), the r.m.s (root mean square) value of the electromotive force at the output of the antenna will be

\[V_{rms} = 2\pi NAf B_{rms} \cos \theta.\]

**Expression of the induced voltage as a function of the electric field**

The efficiency of an antenna is defined through the effective height parameter as

\[V_{rms} = h_e E_{rms},\]

where

- \(h_e\) is the effective height of the antenna in m, and
- \(E_{rms}\) is the r.m.s value of the electric field in V/m.
Now as $f = c/\lambda$ and the electric field is related to the magnetic induction through the relation $E = cB$, we get

$$h_e = \frac{V_{rms}}{E_{rms}},$$

or

$$h_e = \frac{2\pi NA \cos \theta}{\lambda},$$

where $\lambda$ is the wavelength of the wave, in m.

When using a ferrite antenna, the magnetic induction through the antenna is modified by the relative permeability of the medium ($\mu_r$) and then the expression of effective height changes to

$$h_e = \frac{2\pi N A \mu_r \cos \theta}{\lambda}.$$

**Expression of the induced voltage as a function of the magnetic field**

The inductive magnetic field across the loop depends on the magnetic component of the electromagnetic wave (called H or the magnetic field strength) and on the magnetic permeability of the loop core. The relation between the inductive magnetic field $B$ and magnetic field strength $H$ is given by

$$B_{rms} = \mu_0 \mu_r H_{rms},$$

where

- $B_{rms}$ is the r.m.s value of the magnetic induction,
- $\mu_0$ is the permeability of vacuum,
- $\mu_r$ is the relative permeability, and
- $H_{rms}$ is the r.m.s value of the magnetic field strength.

For the case of an air-core loop, $\mu_r = 1$, but for a ferrite loop, the field lines are affected by the ferromagnetic properties of the core, and then the rms value of the output voltage is given by the expression

$$V_{rms} = 2\pi \mu_0 \mu_r NA f H_{rms} \cos \theta.$$
2.3.2 Vertical dipole antenna

The simplest vertical antenna is a short dipole antenna with length \( l \) much smaller than one wavelength \( \lambda \) of the wave. The radiation from a dipole depends on frequency, and so let us consider a driving current \( I \) that varies sinusoidally with angular frequency \( \omega = 2\pi \nu \)

\[
I = I_0 \cos(\omega t),
\]

where \( I_0 \) is the peak current going into each half of the dipole. If we replace the trigonometric function \( \cos(\omega t) \) with its complex exponential equivalent, we can write

\[
I = I_0 e^{-i\omega t},
\]

where only the real part represents the driving current. Now, electric current is defined as the time derivative of electric charge

\[
I = \frac{dq}{dt},
\]

or

\[
I = \frac{dq}{dz} \frac{dz}{dt},
\]

or

\[
I = \frac{dq}{dz} v,
\]

considering the wire along z axis and where \( v \) is the instantaneous flow velocity of the charges. The coordinate system used to describe the vertical dipole antenna is shown in Figure 2.2

From the derivation of Larmor’s formula, we have

\[
E_\perp = \frac{q \dot{v} \sin \theta}{rc^2},
\]

so in the short dipole

\[
E_\perp = \int_{z=-l/2}^{+l/2} dq \frac{dz}{dz} \frac{\dot{v} \sin \theta}{rc^2}.
\]

For a sinusoidal driving current

\[
\dot{v} = -i \omega v,
\]
This implies that the radiated electric field strength $E_{\perp}$ is proportional to the integral of the current distribution along the antenna. The current at the center is the driving current itself which gradually decreases towards the end of the antenna, where the conductivity becomes zero. For a short antenna, we can approximate the current to decrease linearly from the center towards the ends so that

$$I(z) = I_0 e^{-i\omega t} \left[ 1 - \frac{|z|}{l/2} \right].$$

Then

$$\int_{-l/2}^{+l/2} I dz = \frac{I_0 l}{2} e^{-i\omega t},$$

and

$$E_{\perp} = \frac{-i \omega \sin \theta}{rc^2} \frac{I_0 l}{2} e^{-i\omega t}.$$
Substituting $\omega = 2\pi c/\lambda$, we get

$$E_\perp = \frac{-i2\pi c \sin \theta}{\lambda r c^2} \frac{I_0 l}{2} e^{-i\omega t}$$

$$E_\perp = \frac{-i\pi c \sin \theta}{\lambda} \frac{I_0 l}{r} e^{-i\omega t}.$$  The time-average Poynting flux which measures the power per unit area is given by

$$\langle S \rangle = \frac{c}{4\pi} \langle E_\perp^2 \rangle,$$

since $|H_\perp| = |E_\perp|$. Then

$$\langle S \rangle = \frac{c}{4\pi} \left( \frac{I_0 l \pi}{\lambda c} \right)^2 \sin^2 \theta \left( \frac{1}{2} \right),$$

because $\langle \cos^2(\omega t) \rangle = 1/2$. The received power thus depends only on the projected length $(l \sin \theta)$ of the dipole. The time-averaged total power emitted is obtained by integrating the Poynting flux over the surface area of a sphere of any radius $r >> l$ with its center on the antenna

$$\langle P \rangle = \int \langle S \rangle dA = \frac{c}{4\pi} \left( \frac{I_0 l \pi}{\lambda c} \right)^2 \left( \frac{1}{2} \right) \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \sin^2 \theta r \sin \theta d\phi d\theta,$$

$$\langle P \rangle = \frac{c}{4\pi} \left( \frac{I_0 l \pi}{\lambda c} \right)^2 (1/2) 2\pi \int_{\theta=0}^{\pi} \sin^3 \theta d\theta.$$  Since $\int_{\theta=0}^{\pi} \sin^3 \theta d\theta = 4/3$, we get

$$\langle P \rangle = \frac{c}{4\pi} \left( \frac{I_0 l}{\lambda} \right)^2 \frac{\pi^2}{c^2} \left( \frac{1}{2} \right) 2\pi \left( \frac{4}{3} \right),$$

$$\langle P \rangle = \frac{\pi^2}{3c} \left( \frac{I_0 l}{\lambda} \right)^2.$$  The effective area of a receiving antenna

Let us imagine an ideal antenna that is capable of collecting all the radiation incident on it from a distant point source and converts it to electrical power. It is more like a ‘rain gauge’ for collecting photons. So, the total spectral power collected by it will be the product of its geometrical area $A$ and the incident spectral power per
unit area, or flux density $S$. If any real antenna collects spectral power $P_\nu$, then its effective area $A_e$ is defined as

$$A_e = \frac{P_\nu}{S_{(matched)}},$$

where $S_{(matched)}$ is the flux density in the “matched” polarization. For an unpolarized radiation, $S_{(matched)} = \frac{S}{2}$.

**Polarization of an antenna**

The polarization of an antenna is defined by the orientation of the electric field component of the electromagnetic radiation with respect to the Earth’s surface. It is defined as “the sum of the E-plane orientations over time projected on an imaginary plane perpendicular to the direction of radio wave propagation”. Polarization is determined by the orientation of the antenna: a simple straight wire antenna will have different polarizations when mounted vertically and horizontally. For line-of-sight propagation or ground wave propagation, vertically or horizontally transmitted signals remain in more or less the same state of polarization at the receiving end. But for sky waves, that suffer reflection from the ionosphere, a consistent polarization cannot be expected. Polarization can be predicted from the antenna’s geometry, e.g., a vertical whip antenna is capable of transmitting or receiving vertically polarized waves only.

**2.3.3 Vertical monopole antenna**

Monopole antennas consist of a single vertical rod behaving as a conductor mounted on ground or an artificial conducting surface acting as a ground plane. One end of the cable from receiver or transmitter is connected to the conductor and the other end is connected to the ground. This is simply one half of a dipole antenna above a ground plane, the other half is its reflection in the “mirror” provided by the ground. Such antennas have almost twice the gain of an equivalent dipole as the radiation is concentrated in a half-space. Some examples of such monopole antennas are the whip antennas, mast radiator, and inverted F.
2.4 ICSP-VLF network

Indian Centre for Space Physics (ICSP) has its own observatory at Sitapur, West Midnapore, West Bengal, India named Ionospheric and Earthquake Research Centre (IERC). It has four VLF receivers, namely, ICSP-made Gyrator-III type receiver, Stanford made AWESOME receiver, SoftPAL receiver and UltraMSK receiver which monitor VLF signals regularly. Although these receivers are capable of recording signals from multiple transmitters, we mainly focus on signals from VTX, NWC, and JJI (for transmitter details, see Table 2.1). Figure 2.3 shows the ICSP-VLF network where the receiving location, Sitapur is indicated by IERC (green circle) and the three transmitters by their call signs (red triangles). We also show the Great Circle Paths (GCPs) between these transmitters and the receiving station IERC.

![Figure 2.3: The ICSP-VLF network. The receiving location is denoted by IERC (green circle) and the three transmitters by their respective call signs (red triangles). The Great Circle Paths (GCPs) between the transmitters and the receiving location are also shown.](image-url)
2.4.1 ICSP-made Gyrator-III type receiver

This is a ‘loop antenna’ capable of recording fluctuations in the magnetic field of
the signal. It is built on a square frame consisting of four GI pipes, each 2.5 ft
long. They are interconnected in the middle by a four-way metal cross connector
and are provided with four ‘T’ junctions on the opposite ends. This whole structure
is wrapped with insulated copper wire on the outside which provide an inductance
of almost 2$mH$. Signals first received by this antenna are fed into a ‘resonant
 circuit box’. This box contains capacitances whose adjustments help in tuning the
frequency to match with the inductance of the VLF antenna to achieve resonance.
This is defined by the working formulae:

\[
\omega_0 = \frac{1}{\sqrt{LC}},
\]

or,

\[
f_0 = \frac{1}{2\pi\sqrt{LC}},
\]

where $f_0$ is the transmitting frequency. Signals after passing through this ‘resonant
box’ are received by the receiver and are finally stored into computer in ASCII
format. The receiver consists of two types of circuits, one is a gyrator tuning circuit
and the other is an amplifier circuit. The gyrator circuit is a simple LC circuit
where the inductance $L$ can be changed with a variable resistance and the amplifier
circuit is used to change and control the gain of the signal with a 10K POT. The
data thus stored is processed with Spectrum software [Ray, 2013]. Figure 2.4 shows
the antenna and receiver systems.

Figure 2.4: The ICSP-made Gyrator-III type (1) antenna and (2) receiver. The data
acquisition using a laptop and Spectrum software is shown in (3).
2.4.2 AWESOME receiver

The ‘Atmospheric Weather Electromagnetic System for Observation, Modeling and Education’, more popularly known as the ‘AWESOME’ receiver was designed by Morris Cohen and Justin Tan of Stanford University. It is a medium cost widely used ultra-sensitive VLF receiver. Figure 2.5 shows the block diagram of an AWESOME receiver which consists of three main components: antenna, preamplifier and line receiver.

![Block diagram of the AWESOME antenna and receiver system.](image)

The antenna is a ‘loop antenna’ capable of recording magnetic fields orthogonal to the plane of the loop. Generally, two loops are used which are orthogonal to each other and also to the ground. This helps in recording the horizontal (i.e., parallel to the Earth’s surface) magnetic field at any location [Cohen et al., 2009]. Usually, one loop is aligned in the North/South direction, while the other in the East/West direction. The size of the loops may vary, larger loops implying better sensitivity. The resistance of the wire loop is chosen to be 1 Ω and the inductance 1 mH. The next component is the pre-amplifier. It is usually placed inside a NIMA-4 rated weather proof box for protection as it is normally kept outdoors [Ray, 2013]. The pre-amplifier is connected to the line receiver via a cable. This connecting cable has four pairs of conductors: two for the antenna signals, one for the power signal, and one for the calibration signal. The line receiver helps in signal processing, digitization control, GPS management, power management, and system calibration [Ray, 2013]. The line receiver is placed close to the computer system and preferably far away from the antenna to ensure that there is no coupling between the radiation emitted by it into the antenna. Time-stamp to the recorded signal is provided by a GPS receiver. We use MATLAB software for data acquisition and data analysis purpose. The AWESOME setup we use is shown in Figure 2.6.
2.4.3 SoftPAL receiver

SoftPAL or ‘Software Phase and Amplitude Logger’ is a PC based software VLF receiver that uses coherent detection and optimal demodulation of Minimum Shift Keying (MSK) and Interrupted Continuous Wave (ICW) signals to measure and record their phase (relative to GPS time) and amplitude up to frequencies of about 45 kHz. It is the successor to DSP based AbsPAL and OmniPAL systems. The hardware of this system consists of five components: antenna, pre-amplifier, a GPS antenna and engine (a single unit), a service unit (SU) and a computer. The antenna is a vertical whip antenna capable of recording vertically polarized electric field fluctuations of the incoming radiation mounted generally at rooftop or equivalent heights. The signal thus received is then passed through the pre-amplifier first and then the GPS antenna adds time information to it. It is then logged into the computer via the service unit (SU). The SU generally fits into a slot of the computer and we need operating systems like Windows XP, Vista or Windows 7 to run the software. Labchart software is used for data acquisition and data analysis purpose. The SoftPAL antenna installed at IERC is shown in Figure 2.7.
2.4.4 UltraMSK receiver

UltraMSK is a VLF radio receiver suitable for recording both amplitude and phase of the signal. It can receive both 100 and 200 band MSK signals and is capable of monitoring multiple stations simultaneously at arbitrary recording time resolutions. It can run on Linux platform and the output is stored in text format. A typical UltraMSK hardware setup consists of: VLF antenna and pre-amplifier, a power supply for the pre-amplifier and a GPS signal with a 1PPS signal output, a computer and a sound card to run the UltraMSK software [Figure 2.8].

The antenna is a simple vertical whip antenna, usually made of PVC pipes. There is no restriction on the height of the aerial component of the antenna system. The antenna needs to be installed at roof tops or on a mast at the edge or corner of a building as the VLF electric field is usually much larger at the edge than in the centre of a flat roof. It should also be taken care of that the antenna is away from other electrical equipment such as heating, ventilation or Air-Conditioning (AC) units because they can generate considerable noise at VLF. The preamplifier contains filters, amplification and a balanced signal output suitable for long cable runs. The preamplifier unit must be mounted outside at the base of the antenna. As it is placed outdoors, we need a waterproof enclosure that should have a temperature rating matching the expected environmental range. Polycarbonate plastic enclosures can protect from temperatures with a wide range: from $-40^\circ C$ to $+120^\circ C$. Power to
this pre-amplifier is provided by the power supply unit which receives balanced VLF radio signals via 1:1 isolation transformers. An AC to DC converter generates an isolated ±12 V DC power supply to the pre-amplifier from the USB input power. A GPS receiver provides a 1PPS signal. The 1PPS signal is then connected to the 1st input channel and the VLF signal to the second input channel of the computer sound card. Finally, to check the connections and signal quality, we use ‘Audacity’ software. Our UltraMSK setup is shown in Figure 2.9.
2.5 VLF Data acquisition modes

There are two modes of VLF data acquisition. They are:

1) Broadband,
2) Narrowband.

2.5.1 Broadband data acquisition

In broadband data acquisition mode, we can record full range VLF amplitude data time series, which can later be transformed into frequency domain using Fourier transform mechanism. Such data gives us a dynamic VLF spectrum which is usually recorded in synoptic mode. Broadband data helps us in studying lightning strokes and their associated waveforms. It also helps us to deduce the VLF reflection height between the source of the signal and a receiver by analyzing its dynamic profile [Lay and Shao, 2011]. Besides these, we also get the information about the propagation path and distance from the receiver from the signal’s broadband spectrum. In Figure 2.10, we present a typical broadband data as received at IERC on a solar quiet day.

![Sample broadband data as received at IERC on a normal unperturbed day. The horizontal red lines above the blue background correspond to the fixed-frequency transmitters and the few vertical lines are due to sferics/lightning.](image)

2.5.2 Narrowband data acquisition

Narrowband data acquisition, on the other hand, selects a particular frequency from a broadband spectrum, which corresponds to a transmitter located anywhere on the
globe and records the amplitude and phase of the signal in that frequency. Figure 2.11 shows a sample narrowband data, both amplitude (red curve) and phase (blue curve) variation over a timescale of 24 hours as recorded at IERC under a normal unperturbed condition.

Figure 2.11: Sample narrowband data, both amplitude (red curve) and phase (blue curve) as received at IERC on a normal unperturbed day. Along x axis we plot time (IST) in hours and along y axis, we plot the amplitude in dB (for red curve) and phase in degrees (for blue curve).

2.6 Characteristics of a normal diurnal VLF signal

In Figure 2.12, we present a typical diurnal variation of VLF signal amplitude (and phase for phase stable transmitter NWC) under normal quiet condition as received at IERC. Along x-axis, we plot the time (IST) in hours and along y-axis, we plot the amplitude in dB (and phase in degree, for NWC data). We see two minima in the daily signal variation, one at around local sunrise and the other at around local sunset. These two minima are called the Sunrise Terminator time (SRT) and the Sunset Terminator time (SST) respectively which mark the formation of the D region and disappearance of it. At night, in the absence of solar radiation, the D region disappears and the E region also becomes weak. The VLF radio waves then reflect from higher regions of the ionosphere. At dawn, with the incidence of solar radiation, ions begin to form gradually and the VLF radio waves then have to pass through a newly formed weak region of ionization before suffering reflection. This
initiates attenuation of the signal strength and the amplitude begins to fall. With time, as more and more solar rays enter into the atmosphere, the rate of ionization increases and the D region begins to form. The VLF signal then reflects from the D region and throughout the day, it follows the variation of incoming solar flux with solar zenith angle. The amplitude is found to be maximum around the local noon when the electron production rate in the ionosphere reaches its peak value [Pal, 2013]. We can also see some fluctuations around SRT and SST which arises from modal interference due to sudden change in VLF reflection height across the terminator boundary. For the phase variation, we can see an almost 360° phase change around the local sunset time and a similar dip in the phase variation around sunrise. We named them the SRT$_p$ and SST$_p$ following Pal et al. [2017].

![Figure 2.12: Typical diurnal variation of the VLF signal amplitude (and phase for the phase stable transmitter NWC) as received at IERC. Along x-axis, we plot time (IST) in hours and along y axis, we plot amplitude (dB) (and phase in degrees for NWC signal). SRT (SRT$_p$ for phase) and SST (SST$_p$ for phase) are the Sunrise Terminator Time and Sunset Terminator Time respectively which indicate the formation of the D region and disappearance of it.](image)

The signal pattern even changes with the propagation path, for ‘East-West’ propagation path, the night-time amplitude is found to be much weaker compared to the day-time amplitude, whereas for ‘West-East’ propagation path, this feature is
completely opposite. The reason behind such an observation may be attributed to
the magnetic field effects. These features have been extensively studied, modeled
and presented in previous works such as those by Chakrabarti et al. [2012a], Ray
et al. [2013].