Chapter 4

Modeling of ionospheric perturbations related to seismo-ionospheric coupling

Let us start by citing the famous quote by renowned seismologist: “Seismology has reached a stage where its lofty goals cannot be pursued by seismologists alone... A major interdisciplinary effort is needed to develop a prediction scheme based on multi-premonitory phenomena: it means that near-field of future focal zone must be first identified, and then monitored for electrical, magnetic, acoustic, seismic, and thermal precursors simultaneously and continually... Unless we launch a concentrated interdisciplinary effort, we shall always be surprised by next major earthquake” [BenBenahem, 1995]. For the past several decades, much efforts have been devoted in exploring the precursory signatures of earthquakes on atmosphere and ionosphere from ground based and satellite observations, but they have not been universally accepted for the low occurrence rate of large earthquakes making it difficult to develop a statistical database [Kamogawa, 2006].

In this Chapter, we will first discuss a possible coupling mechanism, named as Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) mechanism followed by a brief history of research in this area. Next, we will present results obtained from our approaches in investigating the atmospheric and ionospheric anomalies associated with the $M = 7.3$ Nepal earthquake in May, 2015. For that, we will first present the data used in our study accompanied by our modeling approaches. We will then produce results as obtained from simulation and finally, we will make concluding remarks.
4.1 Lithosphere-Atmosphere-Ionosphere Coupling due to Seismicity (LAICS)

The ionosphere may be influenced by various lithospheric processes such as gas-water diffusion, volcanic eruptions and seismicity. In this Thesis, we will discuss the processes related to seismicity alone and hence, to be precise, we named the coupling mechanism as Lithosphere-Atmosphere-Ionosphere Coupling due to Seismicity (LAICS) [Molchanov et al., 2004]. Numerous evidences of preseismic disturbances on atmosphere and ionosphere as well as preseismic geo-electric potential anomalies and ultra-low frequency (ULF) geomagnetic variations from ground-based observations have been reported in Uyeda et al. [2011] and references therein [Kamogawa et al., 2014]. A major problem is that most of the phenomena reported so far are transient ones accompanied by a dormancy phase before the main shock which makes it difficult to draw a correlation between the appearance of certain anomaly and occurrence of an earthquake. However, some of the anomalies grow in intensity as the main shock [Figure 4.1] is approached which support the concept of seismic nucleation processes subject to the pre-earthquake state [Kamogawa et al., 2014]. One such example was reported in Fraser-Smith [1990], where ULF geomagnetic variations were observed 7 kms away from the epicenter of the 1989 $M = 7.1$ Loma Prieta earthquake, USA. The anomalies started two weeks before the occurrence of the main event and intensified further just few hours before. This result is very significant, although there are some confusions arising from the fact that the signal variations could have been due to some instrument malfunctions [Thomas et al., 2009].

The coupling between lithosphere, atmosphere and ionosphere can be validated only if the causal phenomena responsible for such coupling can be identified. In Figure 4.2, we have summarized the possible mechanisms for energy-transport channels from lithosphere to atmosphere-ionosphere [Komagawa, 2006]. One of the possibilities is release of Radon and other radioactive gases from active tectonic faults around the earthquake epicenter few days prior to the earthquake day generating ions in the near-Earth region. These ions generate an electric field on or near the ground surface which may cause the ionospheric anomalies. Another well acclaimed phenomenon responsible for the ionospheric anomalies prior to earthquakes is the generation of Atmospheric Gravity Waves (AGWs) due to long-period ground oscillations or thermal anomalies. These AGWs can propagate up to ionospheric heights and disturb the ionosphere before earthquakes. This suggestion is inferred from
Figure 4.1: Two types of time-series of reported earthquake precursors [Adopted from Kamogawa et al., 2014]

co-seismic ground vibrations and tsunami-exciting AGWs which propagate into the ionosphere [Komagawa, 2006]. Although several reports have been made regarding preseismic anomalies in temperature, surface latent heat, longwave radiation, and radio observations, it is still difficult to explain the proper path through which the anomalies reach ionosphere through the atmosphere.

Pulinets proposed a so-called Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) Model in [Pulinets and Ouzonov, 2011] to explain the complex chain of physical processes responsible for the anomalies seen in various geochemical, atmospheric, ionospheric and magnetospheric properties few days to almost a month before the main shock within a prescribed zone of influence called the earthquake preparation zone [Dobrovolsky et al., 1979]. Although the first version of the model was presented in Pulinets et al. [1998; 2000], the current version is a much developed one where radon is considered to be the key element in driving the energy transformation processes within the atmosphere. In Figure 4.3, we show a schematic diagram of the LAIC model. Radon and other radioactive gases released from micro-fractures around the earthquake epicenter was considered to be the main source of ionospheric anomalies that are seen within the preparation area before the earthquake. Ions are produced by α particles from $^{222}$Rn decay. During the attachment of these ions
with water molecules, a large amount of thermal energy is emitted due to latent heat release which disturbs the entire energy budget of the atmosphere. Thermal anomalies can be seen at all levels, with a temporal delay from lower to upper levels. Some of the parameters for measuring such thermal anomalies are the surface latent heat, and the Outgoing Longwave Radiation (OLR) measured at the top of the atmosphere. These ions also play a role in changing the conductivity over the earthquake preparation area which modifies the parameters of the Global Electric Circuit (GEC). The change in atmospheric electricity induces variations in electron and ion concentrations which in turn modulates the radio wave propagation through the earth-ionosphere waveguide and is ultimately recorded as anomalies in the received signal strength [Pulinets and Ouzonov, 2011].

4.2 Earlier Works

The first evidence of seismo-ionospheric anomaly came from the works of Bolt [1964] after the famous Alaskan “Good Friday” earthquake in March, 1964. Immediately after this, Leonard and Barnes showed irregularities in the ionospheric reflection height occurring 20−30 minutes after the same Alaskan earthquake using Ionosonde measurements [Leonard and Barnes, 1965]. The signatures of seismo-ionospheric coupling were reported by several other authors in the following few years such as those by [Davis and Baker, 1965; Row, 1966, 1967; Yuen et al., 1969; Tanaka et al., 1984]. The critical frequencies of E and F layers of the ionosphere showed
anomalies just one day prior to the earthquake day during several earthquakes such as Norfolk, 1971, $M = 6.6$; Rome, 1980, $M = 6.7$; Milkvo, 1971, $M = 7.2$; and Tashkent, 1966, $M = 5.3$ [Gokhberg et al., 1984; Pulinets et al., 1988]. The critical frequencies in the F layer was found to be anomalous one to four days before the main shock as observed from Intercosmos-19 satellite. Anomalies in the received VLF signal was first presented by Gufeld and Marenko [Gufeld et al., 1992] during the Caucasus earthquake on December 30, 1983. They found significant anomalies in the nighttime VLF signals two days and one day before the earthquake. Similar VLF signal anomalies were also found for the famous Spitak earthquake ($M = 7.1$) that occurred in United States on December 7, 1988 [Sasmal, 2013]. Some other significant works are those by Calais and Minster [1995], Afraimovich [2001], etc.

In 1996, Hayakawa showed the most reliable VLF subionospheric signal effect related to seismic activity during the famous Kobe earthquake [Hayakawa et al., 1996]. They
used the terminator time (TT) method for analysis [Figure 4.4]. To understand the nature of such effects, Molchanov and Hayakawa performed a detailed statistical study during 10 other strong earthquakes ($M > 6$) [Molchanov and Hayakawa, 1998]. They suggested from their extensive study that such effects can be observed only for crustal earthquakes with the effects starting few days before the event and lasting for a few days or weeks after it. They also stated that the seismic influence on VLF signals may be due to the generation of AGWs during earthquakes [Molchanov et al., 2004; Rozhnoi et al., 2013]. Simple theoretical estimation of electron density anomalies before earthquakes were produced by [Hayakawa et al., 1996, Rodger and Clilverd, 1999] and a more detailed study including the TT method was presented by Soloveiv [2004].

Figure 4.4: (a) shows the path between Omega transmitter and the receiving location, Inubo, along with the earthquake epicenter. (b) shows the diurnal variation of VLF signal phase as received for the days from January 3, 1996 to January 23, 1996. The terminator times, both SRT and SST are found to clearly shift towards nighttime starting from three days prior to the day of the earthquake on January 17. [Adopted from Hayakawa et al., 1996]

During the tsunami in 2004, strong shifts in terminator times were reported in Chakrabarti [2005]. Sasmal et al. [2009] presented the diurnal variation of VLF signal amplitude during the period 2005-2008. A total number of 624 days were
considered and the signal was recorded for the VTX-Kolkata propagation path. Any shift in terminator times outside the standardized calibration curve was considered to be generated due to terrestrial (such as earthquakes) and extra-terrestrial events (such as solar activities). A good correlation between the shifts and occurrence of seismic activities was found and the maximum shift was found to happen a couple of days prior to the seismic event. The possibilities of any VLF anomalies due to seismic activities was studied during the Pakistan earthquake that took place on January 18, 2011 and have been presented in [Ray et al., 2013]. Four different propagation paths were considered, namely, DHO–IERC, VTX–Pune, VTX–ICSP, and NWC–IERC. For the DHO-IERC and VTX–Pune paths, the shift in terminator times was very strong and crossed the $3\sigma$ level, while for VTX–ICSP path, the shift was not so strong although it exhibited the shift four days before the event. For NWC–IERC propagation path, there were no considerable shifts in terminator times. They concluded that the proximity of the propagation paths DHO–IERC and VTX–Pune to the earthquake epicenter resulted in greater shifts in terminator times relative to the other places. The effect of 2011 Honshu, Japan earthquake on VLF signal was studied and presented in several papers such as in [Hayakawa et al., 2012; Sasmal et al., 2014]. In Sasmal et al. [2014], the paths studied were JJI-IERC and NWC-IERC. For JJI-IERC propagation path, significant shifts in SRT beyond $2\sigma$ level was seen to occur 2 days prior to the earthquake day. The D-Layer Disappearance Time (DLDT) also exhibited unusual enhancements. The path NWC-IERC was influenced by several solar flares and so, similar observations could not be achieved.

### 4.3 Data used in the study

For the present study, we considered the earthquake that took place in Nepal on May 12, 2015 at 12:50 PM local time (07:05 UT) with Richter scale magnitude $M = 7.3$ and depth 10 km (6.21 miles). The epicenter was located at southeast of Kodari (Latitude: 27.89°N, Longitude: 86.17°E) and the earthquake was followed by a major aftershock of magnitude $M = 6.7$ on May 16, 2015. To inspect any possibilities of seismio-ionospheric anomalies associated with this earthquake, we proceeded in two ways: first, we checked the Outgoing Longwave Radiation (OLR) data to probe the presence of any thermal anomalies and second, we scrutinized the VLF data collected at IERC to look for the presence of Atmospheric Gravity Waves (AGWs) and terminator shifts.
To study any thermal anomalies, we used the OLR data archived by the National Environmental Satellite Data and Information Service (NESDIS) of National Oceanic and Atmospheric Administration (NOAA). The data has been recorded by NOAA18 satellite which is functional from 09/01/2005 up till now and uses a 1355 equatorial crossing time. The data is archived onto 2.5°lat × 2.5°long grids with two grids per day corresponding to daytime and nighttime orbits. The major problem of this data is the presence of missing grids and missing values within grids. This is probably due to incomplete global coverage of the satellites, or any satellite and archival problems. These missing data are usually recovered by a nearest neighbor spatial interpolation which are flagged as negative [Liebmann and Smith, 1996]. The data is available in NOAA website which covers the whole span of the globe, from 90°N to 90°S and 0°E to 357.5°E [http://www.esrl.noaa.gov/psd/data/gridded/]. The user needs to specify the region of their interest and the temporal range to get the desired data in netCDF4-classic format.

The May earthquake was preceded by another major earthquake on April 25 with magnitude $M = 7.9$ and epicenter at 28.147°N, 84.708°E. Although our primary focus was to study the May earthquake, we analyzed the OLR data during the April earthquake also as the effects of that earthquake may get superimposed with the May earthquake. We took the data with a spatial coverage of 6° × 7° from 25°N to 31°N and 82°E to 89°E so that both the earthquake epicenters remain more or less at the center of our chosen grid. The temporal range was taken to be 45 days from April 16, 2015 - May 30, 2015.

To detect the presence of AGWs during the earthquake and look for any terminator shifts, we analyzed the VLF data collected at Ionospheric and Earthquake Research Centre (IERC), Sitapur. The data has been collected using SoftPAL antenna and receiver system (details in Chapter 2). Although the receiver is capable of recording signals from multiple stations (NWC, VTX, JJI), we concentrated on the JJI-IERC propagation path. This is because of the proximity of this propagation path to the earthquake epicenter suggesting more anomalies in the VLF data collected along this path in comparison to the other paths [Ray et al., 2013]. In Figure 4.5, we show the transmitter JJI (blue triangle), the receiver IERC (black circle), the wave paths between them, the location of the earthquake epicenters (red filled circles) and also the earthquake preparation zones (gray shaded circles). Here, by Eq1, we mean the first earthquake that occurred on May 12 and Eq2 denotes its major aftershock on May 16. In the inset, we have shown the corresponding earthquake preparation zones.
(EPZ) in a magnified way, the outer circle is for Eq1 and the inner for Eq2. EPZ is that region around an earthquake epicenter where the effects of an earthquake can be identified [Dobrovolsky et al., 1979]. According to the formula, earthquakes with magnitude \( M = 7.3 \) and \( M = 6.7 \) would have EPZ with radii 1370 and 760 km respectively. The propagation path is \( \sim 4355 \) kms long with high longitudinal variation (87.8°E to 130.82°E) and thus only \( \sim 1/3^{rd} \) of it lies within the EPZ.

![Figure 4.5: Position of the transmitter JJI (blue triangle), receiver IERC (black circle), the propagation path between them, the earthquake epicenters for May 12 (Eq1) and its aftershock on May 16 (Eq2) (red filled circles) and the earthquake preparation zones (gray shaded circles). In the inset, we have shown the preparation zones in a magnified way, the outer circle is for Eq1 and the inner circle is for Eq2 [Chakraborty et al., 2017].](image)

In Figure 4.6, we present the diurnal variation of VLF signal amplitude as received on May 9, 2015. Along x-axis, we plot the time (IST) in hours and along y-axis, we plot the amplitude in dB. SRT and SST correspond to the sunrise terminator time and sunset terminator time respectively. From the figure, we see a sudden fall in the data at around 5:00 IST and a subsequent return to its normal position at around 13:00 IST. We noticed this feature for all the days of our study. This part of the data clearly bears no signal characteristics and may be due to transmitter related issues. As we are dealing with nighttime data for detection of AGWs and
terminator times for numerically modeling any shifts, this part is away from our region of interest and so, we can safely ignore the variation.

![Figure 4.6: Diurnal variation of VLF signal amplitude as received for the JJI-IERC propagation path on May 9, 2015. Along x axis, we plot the time (IST) in hours and along y axis, we plot the signal amplitude in dB. The sunrise and sunset terminator times (SRT and SST) are indicated by the arrows [Chakraborty et al., 2017].](image)

To detect the presence of AGWs during the earthquake, we separated the nighttime data from 18:00 IST to 2:30 IST. In Figure 4.7, we present the nighttime data from May 7, 2015 to May 16, 2015. Due to some technical problems, data immediately outside this period range is not available and hence could not be used. Along x axis we plot the time (IST) in minutes and along y axis, we plot the signal amplitudes in dB. The amplitudes have been stacked with a relative shift of 15 dB for clarity.

We have checked the position of the terminators, both SRT and SST from May 7 to May 9 and found the position to not vary much. So, we assumed the data on those days as seismically quiet, i.e., free from any seismo-ionospheric influences. But to bring clarity to the plots, we have presented only the data on May 9 as representative of a seismically quiet data and compared the variations with reference to it. We extracted the data from May 9 to May 17 around the sunrise terminator time (left panel) and sunset terminator time (right panel) and presented in Figure 4.8. Along x axis, we plot the time in hours and along y axis, we plot the relative signal
amplitudes in dB with a shift of 10 dB for clarity. From the figure, we clearly see that the SRTs begin to shift towards nighttime from May 10, the maximum shift being on May 11. The value of normal day SRT was 03:56:00 IST. On May 12, the day of the main event, and May 13, the SRT shows a tendency to return back towards its normal value but on May 14, it again shifted night-ward and followed the trend on the next day as well. On May 16, it again began to move towards right. The maximum shift in SRT was found to be 17 minutes. In the right panel figure, we see a similar trend of movement of sunset terminator times towards nighttime, the maximum shift being 15 minutes. The value of normal SST was 16:30:00 IST. For the SST, we found some residual anomalies and so the signal took one more day to return to normal.

In Figure 4.9, we compared the variations of SRT (top panel), SST (middle panel) and VLF day length (bottom panel) obtained by subtracting the VLF data between SST and SRT. From the figure, we see the maximum shift in SRT to occur just 1 day before both the earthquakes Eq1 and Eq2, while for SST, the maximum shift before Eq1 occurred on the day before the earthquake day and for Eq2, the shift
was maximum 2 days before the earthquake day. The maximum increase in VLF day length was observed to be 32 minutes.

### 4.4 Data Analysis Procedure

#### 4.4.1 OLR data analysis method

Among the various methods available to detect anomalies in daily/monthly OLR data, we have adopted the method of ‘Eddy field calculation mean’ to find singularities in OLR data around the earthquake epicenter. It actually divides the whole area under study into small grids and then takes the value of OLR corresponding to a particular grid and subtracts it from the average of values of adjacent grids. In this way, it checks the weightage of OLR in that grid compared to its neighboring grids. Mathematically, it can be defined as the “total sum of the difference value” of the “measured value” of OLR between adjacent points [Xiong et al., 2010] and is expressed as

\[
S_d(x_{i,j}, y_{i,j}) = 4.S(x_{i,j}, y_{i,j}) - [S(x_{i-1,j}, y_{i,j})+S(x_{i,j}, y_{i,j-1})+S(x_{i+1,j}, y_{i,j})+S(x_{i,j}, y_{i,j+1})].
\]
Here, $S^*_d(x_{i,j},y_{i,j})$ is the daily Eddy field; $S(x_{i,j},y_{i,j})$ is the daily mean; $x$ and $y$ respectively represent latitudes and longitudes; and $i, j$ are integers representing number of grid points. Evidences of singularities in OLR data before some major earthquakes using this method have been presented by various authors like [Liu et al., 1999; Liu, 2000; Kang and Liu, 2001; Ouzonov et al., 2007 and Xiong et al., 2010].

The methodology we followed is described here. First, we have chosen a $6^\circ \times 7^\circ$ grid from $25^\circ N$ to $31^\circ N$ and $82^\circ E$ to $89^\circ E$ around the earthquake epicenters. The data has been downloaded in netCDF format from April 16 to May 30 and then converted into a matrix using the method of mesh grid. The columns of the matrix represent longitudes ($x$), the rows represent latitudes ($y$) and the corresponding
matrix elements \((i,j)\) are the daily mean of OLR \(S(x_{i,j},y_{i,j})\) of that particular point. The Eddy field has then been calculated using the equation and the results have been interpolated within the operational area to obtain a smooth 3d plot for a single day. The same procedure has been repeated for all other days and all the individual plots have been assembled into three figures, each containing 15 days data to compare variation in their values [Chakraborty et al., communicated, 2017].

4.4.2 VLF data analysis method

Detection of Atmospheric Gravity Waves (AGWs)

To detect presence of Atmospheric Gravity Waves (AGWs) due to the earthquake, we have taken only the nighttime part of the data. This is because during the daytime, any additional source of ionization arising from seismic activities will not be able to outweigh that due to solar radiation. We have carried out both Fourier and wavelet analysis of the data (details in Chapter 3). 8.5 hours of nighttime data, starting from 18:00:00 IST were taken for the days May 7 to May 16. The Fourier transform was performed using a rectangular windowed function and for wavelet analysis, Morlet mother wavelet function was used. The sampling period was taken to be 1 minute for both the analyses.

Numerical Simulation of terminator shifts

The propagation path under study, namely, the JJI-IERC propagation path has a special feature that it has a high spread over longitude (from 87.8° E to 130.82° E). As a result, the path is not illuminated homogeneously and experiences transverse movement of terminator boundary both during sunrise and sunset times. To deal with this problem, it is necessary to replace the homogeneous ionosphere by an inhomogeneous one [Chakraborty et al., 2017]. For this, at first we calculated the speed \((v)\) of the terminator at our location using the formula

\[
v = \frac{2\pi R_{\text{equator}} \cos(\text{latitude})}{24 \text{hr}},
\]

where we substituted latitude as 29° which is the latitude of the midpoint of the propagation path and thus obtained the value of \(v\) as 407 m/sec. This means that the terminator shadow will cover 25 km distance in 1 minute. In Figure 4.10, we show the movement of shadow boundary over the propagation path. The upper three figures are during sunrise times and the lower three figures are during sunset.
times. The top left figure shows the situation when the transmitter, JJI, is just illuminated while the remaining propagation path is still under darkness, the top middle figure corresponds to SRT at the receiving location and the top right figure is when the receiver, IERC is just illuminated. In the bottom panel figures, we present a similar situation during sunset times. This inhomogeneous nature of the solar illumination over the propagation path has then been incorporated into the LWPC programme by dividing the whole path into several segments depending upon the terminator position. Same $h'$ and $\beta$ values were chosen for either of the two regions (illuminated/dark) and a sharp change in their values was considered across the shadow boundary. With this convention, we determined the VLF signal corresponding to normal ‘non-seismic’ situation.

Next, to obtain the signal variation under ‘seismic’ situation, we made additional changes in the parameter values for only that portion of the propagation path that lied within the EPZ. For the region outside of the EPZ, the values were kept intact as under ‘non-seismic’ situation. We considered two conditions, one by raising the parameter values and the other by lowering them. The parameter values used in our study are enlisted in Table 4.1. Here the values under ‘Non-seismic’ correspond to the whole propagation path under normal (non-seismic) situation and the portion of the propagation path outside of EPZ under anomalous (seismic) situation, while the values under ‘Seismic’ correspond to only that portion of the propagation path that lies within the EPZ. For further ease of presentation, we will refer to lowering of ionospheric parameters within the EPZ by simply ‘lowering’, and similarly, raising the parameters within the EPZ by ‘raising’. The parameter values under normal ‘non-seismic’ situation and for that portion of the propagation path outside of EPZ will be referred to as ‘normal’.

Table 4.1: D region ionospheric parameter values used in numerical modeling [Chakraborty et al., 2017]

<table>
<thead>
<tr>
<th>Condition</th>
<th>Illuminated Region</th>
<th>Dark Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$[h'(km)/\beta(km^{-1})]$</td>
<td>$[h'(km)/\beta(km^{-1})]$</td>
</tr>
<tr>
<td>Non-seismic</td>
<td>75.0/0.35</td>
<td>85.0/0.55</td>
</tr>
<tr>
<td>Seismic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) Lowering</td>
<td>72.0/0.32</td>
<td>83.0/0.53</td>
</tr>
<tr>
<td>(ii) Raising</td>
<td>78.0/0.38</td>
<td>87.0/0.57</td>
</tr>
</tbody>
</table>

We also calculated the electron density as a function of height (h) with the parameter
values mentioned in Table 4.1 using the formula of electron density \((N_e(h, h', \beta))\) as defined in Wait’s two-component exponential lower ionosphere model [Wait and Spies, 1964].

\[
N_e(h, h', \beta) = 1.43 \times 10^{13} \exp(-0.15h') \exp[(\beta - 0.15)(h - h')],
\]

where \(N_e\) is in m\(^{-3}\).

## 4.5 Results

### 4.5.1 Outgoing Longwave Radiation (OLR)

We present the results of ‘Eddy field calculation mean’. As mentioned earlier, although our primary focus was to study the May 12, 2015 earthquake, we also analyzed the April 25, 2015 earthquake. This was done because the effects of numerous aftershocks that followed the April earthquake may get superimposed on the May earthquake. As a result, a total of 45 days of data were analyzed and the results are
arranged in three figures, Figure 4.11, Figure 4.12 and Figure 4.13, each containing 15 days data. Along x axis, we plot the longitude from 82°E to 89°E and along y axis, we plot the latitude from 25°N to 31°N. The colorbar denotes the intensity of mean Eddy field and runs from values 0 to 60. The country boundary and the plate tectonic boundary are shown by white and red lines respectively. The two earthquake epicenters are indicated by the initials A (for April) and M (for May). The two earthquake days April 25 and May 12 are indicated by red color.

From Figure 4.11, we see that from April 16 to April 20, the field activity is absolutely low with no high intensity around the epicenters. On April 21, we see some weak diffusive field like structures around the epicenter which intensified and spread towards it further on the next day (April 22). The day of the earthquake was April 25 and after that day, due to many aftershocks we see weak diffusive fields to be present around the epicenters. On May 1 to May 6, we see similar weak fields around the epicenters from Figure 4.12. On the next two days (May 7 and May 8), such fields become absolutely absent but suddenly on May 10, there is a strong intensification in the field with its further advancement towards the earthquake epicenters on the next day (May 11). On the day of the earthquake (May 12), the field somehow dissolves but it again regains its strength on May 13 and followed a similar trend of spreading towards the epicenter on the next two consecutive days (May 14 and May 15). After the occurrence of the aftershock on May 16, although the field exists, it loses its strength and shows a diffusive nature around the epicenter region [Figure 4.13].

From the above figures, we see that the intensification of the Eddy field is mostly spreaded over the western longitudes or towards the left side of the epicenters. These Eddy fields are obtained by calculations from direct observation of OLR from satellite data over a 6°×7° grid. The effects of earthquakes are extended over the plate boundary region rather than being confined to the epicenter alone and as a result, the OLR anomalies are not expected to be observed exactly on the top of the epicenter. In previous literatures also like those by Ouzounov et al., 2007; Chen et al., 2010 and Venkatanathan et al., 2014, there are evidences of maxima in OLR Eddy field at almost 1000 km away from the epicenter. There are no directional biasing of the OLR intensity. It is rather random in direction such as in our case the intensity is spreaded over the western longitudes. In Figure 4.14, we show the monthly mean of original OLR value for the month of May, 2015 as obtained from NOAA satellite. The plate tectonic boundary between the Eurasian plate and the Indian plate is shown by the red line and the colorbar denotes monthly mean OLR
values in $\text{W/m}^2$. From the figure, we see that the distribution of OLR is such that it is intense towards the western longitudes.

Next, to check whether the intensification of the Eddy field were associated with the earthquakes, we did the analysis during the month of January, 2015 which is a seismically quiet period. The results have been arranged in Figures 4.15 and 4.16, each containing 15 days data in the same manner as in Figures 4.11, 4.12 and 4.13. From Figures 4.15 and 4.16, we see the Eddy field activity to be reasonably low during the entire month of January as compared to the months of April and May. Thus, we conclude that the sudden strong intensification of the field few days prior to the earthquake days and its fading away after the events (both April and May) may be related to the large amount of energy released by the earthquakes.

4.5.2 Atmospheric Gravity Waves (AGW)

We present the results obtained from both Fourier and wavelet analysis of the nighttime part of the VLF amplitude data. In Figure 4.17, we show the normalized FFT spectrum for the days May 7 to May 16. Along x axis, we plot the period of the waves in minutes and along y axis, we plot the normalized Fourier amplitude. The colors correspond to spectrum for the days as mentioned in the inset. From the figure, we see a strong peak in the spectrum at 65 minutes on May 8. Two other less significant peaks at 45 minutes and 55 minutes are also seen on May 13 and May 16 respectively. For the other days, no such significant peaks above the background variation could be seen.

In Figure 4.18, we present the Wavelet Power Spectrum (WPS) for the days May 7 to May 16. Along x axis, we plot the time in hours after 18:00:00 IST and the period of the waves in minutes are plotted along y axis. The colorbar runs from values 0 to 8 indicating the intensity of the waves. The Cone of Influence (COI) is shown by the solid black curve (discussed in Chapter 3). From the figure, we see presence of strong waves with periods of the order of 16 minutes to 128 minutes on May 8 within the COI. On May 14 and May 16, we see some weak wave like structures within the COI, but for the other days, such waves within the cone are absent. Because any enhancements in the spectrum generated outside the COI are not solely due to seismic activities and the edge effects may remain superimposed on them, we concentrate only on the waves we find within the cone.
Figure 4.11: Daily Eddy field around the earthquake epicenters A and M from April 16, 2015 to April 30, 2015 with a spatial extent from 25°N to 31°N and 82°E to 89°E. Longitudes are plotted along x axis and latitudes along y axis and the earthquake epicenters are denoted by white filled circles, A for April Eq and M for May Eq. The colorbar runs from values 0 to 60 which indicates the intensity of the mean Eddy field. The days of occurrence of the earthquake is indicated by the red color. The country boundary and the plate tectonic boundaries are indicated by white and red lines respectively [Chakraborty et al., communicated, 2017].
Figure 4.12: Same as in Figure 4.11 but for the days May 1, 2015 to May 15, 2015. [Chakraborty et al., communicated, 2017].
Figure 4.13: Same as in Figure 4.11 but for the days May 16, 2015 to May 30, 2015 [Chakraborty et al., communicated, 2017].
Figure 4.14: Monthly mean of OLR over the Indian subcontinent for the month of May, 2015. The tectonic plate boundary between the Eurasian plate and the Indian plate is shown by the red line. The colorbar denotes the monthly mean OLR values. We see a general trend of intensification of the OLR values towards the western longitudes.
Figure 4.15: Same as in Figure 4.11 but for the days January 1, 2015 to January 15, 2015
Figure 4.16: Same as in Figure 4.11 but for the days January 16, 2015 to January 30, 2015
Along x axis, we plot the period of the waves in minutes and along y axis, we plot the normalized Fourier amplitude. The colors correspond to the spectrum for the days as mentioned in the inset. We see strong peak at \( \sim 65 \) minutes on May 8, whereas two less significant peaks at \( \sim 45 \) and 55 minutes can be seen on May 13 and May 16 respectively [Chakraborty et al., communicated, 2017].
Figure 4.18: Wavelet power spectrum (WPS) of the VLF data for the days May 7, 2015 to May 16, 2015. Along x axis, we plot the time starting from 18:00:00 IST and along y axis, we plot the period of the waves in minutes. The thick contour encloses regions with greater than 95% confidence and the cone represents the cone of influence (COI). Periodic wave structures with periods of the order of minutes to hours within the COI are seen on May 8, May 12 and May 14 [Chakraborty et al., communicated, 2017].
Next, to examine whether the peaks we observed in both the Fourier and wavelet power spectrum were really associated with the earthquakes, we checked the geomagnetic activity of the Sun by measuring the $Kp$ index. In Figure 4.19, we show the $Kp$ index values for the days of our analysis starting from May 5 to May 20. We found the $Kp$ values to be reasonably low ($< 5$) during the period of our study, except on May 13, when it rose to $\sim 4.9$. On May 8, it was even below 1.5 and for the other two days (May 14 and 16), it was less than 2. So, the strongest wave-like structure we observed on May 8 from both FFT and wavelet analysis and the relatively weak wave-like structures on May 14 and 16 may be associated with the seismic activities while that on May 13 may be an indication of the precursory effects along with the geomagnetic activity of the Sun.

![Figure 4.19: Daily average $Kp$ values for the days of our analysis starting from May 5, 2015 to May 20, 2015. For all the days, we find the $Kp$ values to be below 5 which indicate a geomagnetically quiet situation [Chakraborty et al., 2017].](image)

### 4.5.3 Terminator shifts

In Figure 4.20, we present the VLF signal amplitude as obtained from simulation around SRT from 02:00:00 IST to 05:00:00 IST. Along x axis, we plot the time (IST) in hours and along y axis, we plot the signal amplitude in dB. The black curve corresponds to normal condition while the green and red curves correspond to the signal obtained by respectively lowering and raising the parameter values within
the EPZ (for parameter values, see Table 4.1). The vertical dotted lines indicate the corresponding SRTs. From the figure we see that raising the ionosphere within the EPZ produces the observed shift in SRT towards nighttime. The shift obtained from simu

![Simulated VLF signal amplitude around sunrise terminator time (SRT) under normal non-seismic situation (black curve), lowering the ionosphere (green curve) and raising the ionosphere (red curve) within the EPZ. Along x axis, we plot the time (IST) in hours and along y axis, we plot the simulated signal amplitude in dB. The three vertical dotted lines mark the corresponding terminator times. The parameter values used under three different ionospheric conditions are mentioned in Table 4.1. We see that raising the ionosphere within the earthquake preparation zone resulted the observed nightward shift of SRT [Chakraborty et al., 2017].](image)

In Figure 4.21, we present the VLF signal amplitude as obtained from simulation around SST from 03:00:00 IST to 06:00:00 IST. The choice of axes and other parameters are the same as in Figure 4.20. Here also, we find that raising the ionospheric parameters within the EPZ resulted in the shift of SSTs towards nighttime. The shift as obtained from simulation is 15 minutes that matches exactly with our observation. Thus, the overall day length increase observed is 32 minutes, while the same obtained from simulation is 25 minutes.
Figure 4.21: Same as in Figure 4.15 but around sunset terminator time (SST). Here also, we see that raising the ionosphere within the earthquake preparation zone resulted the observed nightward shift of SST [Chakraborty et al., 2017].

In Figure 4.22, we present the height profile of electron density as obtained from simulation. Along x axis, we plot the electron density ($m^{-3}$) in logarithmic scale and along y axis, we plot the ionospheric height in km. The figures in the top panel are for transmitter (T) location, the middle panel figures are for the midpoint (M) of the propagation path and the bottom panel figures are for the receiving location (R). The left column figures correspond to SRT and the right column figures correspond to SST. From the figure, we find that raising the ionosphere within the EPZ implies a decrease in electron density.
Figure 4.22: Height profile of electron density (m\(^{-3}\)) as obtained from simulation at the transmitter T (top panel figures), mid-point of the propagation path M (middle panel figures) and receiver R (bottom panel figures). Along x axis, we plot the electron densities in logarithmic scale and along y axis, we plot the ionospheric height in km. The colors have been chosen with the same convention as in Figures 4.20 and 4.21. The left column are for sunrise terminator times (SRTs) and the right column are for sunset terminator times (SSTs). We see that raising the ionosphere within the earthquake preparation zone implies a reduction of electron density [Chakraborty et al., 2017].
4.6 Effects of varying location of earthquake epicenter on VLF signal amplitude

4.6.1 Aim of the study

So far, we considered a single propagation path for a single earthquake. The effects of a particular earthquake event on multiple propagation paths have also been studied in Ray et al., [2013] and Sasmal et al., [2014]. In both these cases, it was concluded that proximity of a path to earthquake epicenter is favorable for producing considerable modulations in the received VLF signal. Contrary to the earlier works, here we study the effects of two different earthquakes on a single propagation path. For this, the path chosen is JJI-IERC and the two earthquakes are the 2011 Honshu, Japan earthquake and 2015 Nepal earthquake. The reason behind such choice is the location of the two epicenters related to the propagation path: the Honshu earthquake is located near the transmitter (JJI) end while the Nepal earthquake is located near the receiver (IERC) end. This facilitated us to deal with two different scenarios: one when the signal is highly perturbed initially and then propagates through a perturbed earth-ionosphere waveguide towards the receiving end (for Honshu earthquake) and second when the signal initially propagates through a normal unperturbed waveguide and then suddenly enters a region of strong perturbation near the receiving end (for Nepal earthquake). Hereafter, we will use the notations H-eq and N-eq for Honshu and Nepal earthquakes respectively [Ghosh, Chakraborty et al., communicated, 2017]. In Figure 4.23, we show the location of the two earthquakes, H-eq and N-eq (red circles), the transmitter JJI (blue triangle), the receiver IERC (green circle), and the wave path between them. The detailed information of the two earthquakes are given in Table 4.2.

Table 4.2: Basic earthquake informations [Ghosh, Chakraborty et al., communicated, 2017]

<table>
<thead>
<tr>
<th>Eq</th>
<th>Epicenter</th>
<th>Richter Scale Magnitude</th>
<th>Depth (km)</th>
<th>Date and Time (IST)</th>
<th>Distance (km) from JJI</th>
<th>Distance (km) from IERC</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Eq</td>
<td>38.322°N, 142.369°E</td>
<td>9.0</td>
<td>29</td>
<td>11/03/2011 11:16:24</td>
<td>1180</td>
<td>5438</td>
</tr>
<tr>
<td>N-Eq</td>
<td>27.89°N, 86.17°E</td>
<td>7.3</td>
<td>10</td>
<td>12/05/2015 12:35:19</td>
<td>4392</td>
<td>621</td>
</tr>
</tbody>
</table>
4.6.2 Modeling approach

The propagation path, JJI-IERC has a high longitudinal extent and so, the illumination over it is variable rather than uniform. As our primary focus is to examine the effects of varying location of the earthquake epicenter relative to the propagation path, so, instead of considering precise variation of illumination over the path as we considered before, we followed a more general approach where we replaced the homogeneous ionosphere by an effective one defined by the parameters $h'_{\text{eff}}$ and $\beta_{\text{eff}}$. The VLF amplitude has been normalized to values corresponding to the unperturbed ionosphere as suggested by LWPC. For this approach, we used RANGE and EXPONENTIAL subprogrammes of the main LWPC program. We first provided the location of the transmitter, receiver, and information of the propagation path, such as bearing angle and path length into the RANGE subprogram. The VLF amplitude variation around SRT for a single day have then been calculated by varying the values of the parameters $h'_{\text{eff}}$ and $\beta_{\text{eff}}$ into the EXPONENTIAL subprogram. The same process has been repeated to obtain the signal variation for a few days around the earthquake days. In Figure 4.24, we present the daily variation of sunrise terminator time (SRT) during the earthquake days for both H-eq (left

Figure 4.23: Position of the transmitter JJI (blue triangle), receiver IERC (green circle), the wave path between them and the two earthquake epicenters N-eq and H-eq (red filled circles).
panel) and N-eq (right panel). The data for H-eq around sunset terminator time (SST) is very noisy. So we have produced only the SRT variations for comparative study. Along x axis, we plot the time (IST) in hours and along y axis, we plot the relative amplitude in dB, which are shifted by 10 dB each for clarity. The red curves indicate the respective earthquake days. To reproduce these signal variations, the parameter values taken in our study were within the range 0.4 to 0.55 km$^{-1}$ for $\beta_{\text{eff}}$ and 78 to 82.5 km for $h_{\text{eff}}'$. LWPC defines a normal ionospheric-day condition by the parameter values $h' = 74.0$ km and $\beta = 0.3$ km$^{-1}$, while $h' = 87.0$ km and $\beta = 0.6$ km$^{-1}$ represent a complete night. So, our choice of parameter values were well within this prescribed range and were also sufficient to represent the mixed day-night situation over the path. We also calculated the height profile of electron density at respective SRTs using the well-known Wait’s formula [Wait and Spies, 1964].

Figure 4.24: VLF amplitude data around the sunrise terminator times (SRTs) for the Honshu earthquake (left panel) and Nepal earthquake (right panel). Along x axis, we plot the time (IST) in hours and along y axis, we plot the signal amplitude in dB with a relative shift of 10 dB. The SRTs are indicated by arrows and the earthquake days are highlighted by the red curves [Ghosh, Chakraborty et al., communicated, 2017].

4.6.3 Results obtained

Here, we present the results as obtained from numerical simulation for both H-eq and N-eq and compare our results with observations. In Figure 4.25, we present the VLF amplitude variation around SRTs from both (a) observation and (b) simulation for H-eq during the days March 8 to 15, 2011. Due to some technical problems,
data on March 12 to 14 could not be procured and hence not presented. The time span taken is from 04:00:00 IST to 06:00:00 IST and is plotted along the x axis in hours. The amplitudes are plotted along y axis and the arrows indicate the respective SRTs. The red curves represent the day of the earthquake. Here, March 8, 2011 is considered to be a seismically quiet day. As the true time-to-time variation of VLF signal amplitude under disturbed as well as normal conditions is very difficult to reproduce theoretically because of the complex geophysical and chemical processes taking place continuously within the ionosphere, we concentrate on the signal variation and levels of deviation rather than measuring their individual values. From the figure, we find the signal variations as obtained from simulation to match satisfactorily with observed values. The maximum shift of SRT from normal position is found to occur on March 11 with a value $\sim 18.4$ minutes, whereas the same obtained from simulation is $\sim 20.2$ minutes.

Figure 4.25: VLF amplitude variation around sunrise terminator times (SRTs) for the Honshu earthquake as obtained from (a) observation and (b) simulation. Along x axis, we plot the time (IST) in hours and along y axis, we plot the signal amplitude in dB with a relative shift of 10 dB. The SRTs are indicated by arrows and the earthquake days are highlighted by red curves. The maximum shift in SRT from normal position as observed is $\sim 18.4$ minutes whereas the same obtained from simulation is $\sim 20.2$ minutes. The simulated amplitude variation is also found to display good agreement with observation [Ghosh, Chakraborty et al., communicated, 2017].

In Figure 4.26, we present the VLF amplitude variation around SRTs from both (a) observation and (b) simulation for N-eq during the days May 9 to 13, 2015. As
in the present case, our main target is to have a comparative study of the influences of varying location of epicenters with respect to a propagation path on the signal amplitude, we focused only on the earthquake on May 12 and excluded its aftershock on May 16. The choice of the axes and other parameters are similar to what is in Figure 4.25. Here, May 9, 2015 is taken as a normal day. In contrary to the H-eq case, we find the changes for N-eq to be quite gradual with the maximum shift on May 11, just one day before the earthquake day with value $\sim 17$ minutes. The same as obtained from simulation is $\sim 20.4$ minutes. Here, we see that the recombination processes have already been initiated in the ionosphere from the day of the earthquake and the VLF-SRTs begin to return to its original value, but for H-eq, we observed a different situation where the recovery phase started almost 2−3 days after the main shock [Figure 4.25]. This may be probably due to the location of the two epicenters in reference to the receiving location, IERC.

![Figure 4.26: Same as in Figure 4.25, but for the Nepal earthquake. Here, the maximum shift in SRT from normal position as observed is $\sim 17$ minutes whereas the same obtained from simulation is $\sim 20.4$ minutes. The simulated amplitude variation is also found to match well with observation [Ghosh, Chakraborty et al., communicated, 2017].](image)

In Figure 4.27, we present the height profile of electron density for (a) H-eq and (b) N-eq as obtained from calculations using Wait’s formula. Along x axis, we plot electron density ($m^{-3}$) in logarithmic scale at the time of SRT on March 8, 2011 and May 9, 2015 which are taken as normal days for H-eq and N-eq respectively. Along y axis, we plot the ionospheric height in km. The colors correspond to the values for the days as mentioned in the inset. From the figure, we see that the electron density decreases as one approaches the earthquake day. For H-eq, on March 11, the
electron density reduced by $\sim 40\%$ at 82 km altitude compared to that on March 8 and interestingly, on that day, the VLFSRT shift was also maximum ($\sim 20.4$ minutes). During March 11 to 15, the electron density did not show much change which may be probably due to a series of aftershocks that followed the main event and prevented the ionosphere from returning to its normal condition. For N-eq, we find the change in electron density to be more gradual. Here, at 82 km altitude, the shift in electron density was found to be maximum on May 11 with value $\sim 76\%$ after which it showed a tendency to return to its initial value and on May 13, it almost got back to the pre-event value.

Figure 4.27: Height profile of electron density ($m^{-3}$) for (a) H-eq and (b) N-eq. Along x axis, we plot the electron density in logarithmic scale and along y axis, we plot the ionospheric height in km. The colors correspond to the values for the days mentioned in the inset. We see that the electron density decreases as one approaches the earthquake days. For H-eq, the changes are sudden while for N-eq, the changes are gradual ones [Ghosh, Chakraborty et al., communicated, 2017].

4.7 Discussions and Conclusions

In this Chapter, we presented results of our attempts to understand seismo-ionospheric coupling during the 2015 Nepal earthquake. The earthquake took place in Nepal on May 12, 2015 with magnitude $M = 7.3$ followed by a major aftershock on May 16 with magnitude $M = 6.7$. Among the various channels which are responsible for coupling the lithosphere with atmosphere and ionosphere during seismic activities, we considered the thermal channel, acoustic channel and electromagnetic channel. For studying the thermal channel, we chose the parameter Outgoing Longwave Ra-
radiation (OLR) which is usually measured at the top of the atmosphere (10-12 km altitude). For studying acoustic channel, we analyzed the VLF signal received by our ICSP-VLF network to examine the presence of any small-scale wave-like disturbances associated with generation of Atmospheric Gravity Waves (AGWs) and for studying electromagnetic channel, we tried to detect and numerically simulate the VLF terminator shifts in the received signal amplitude. By calculating the Eddy fields around the earthquake epicenter using the method of ‘Eddy field calculation mean’, we found intensification of the field in daily OLR data around the earthquake epicenter just two days prior to the earthquake day (May 12) and its fading away after the major aftershock on May 16. Another strong earthquake with magnitude $M = 7.9$ took place in Kathmandu, Nepal on April 25 and was accompanied by a large number of aftershocks. The two earthquake epicenters were only hundreds of kilometers apart from one another compared to several thousand kilometers of preparation area. For this reason, we analyzed the OLR data during the April earthquake and found a similar trend of intensification of Eddy field around the epicenter just three days prior to the earthquake day and presence of weak diffusive fields due to the aftershocks that followed the main event. So radiation was always present in our grid but it became strongest only before the main event on May 12. To relate the intensification of the Eddy fields during the earthquake days with the events, we also analyzed the OLR data for the whole month of January, 2015 which was a seismically quiet period and found the Eddy field to be reasonably low during the entire month. Thus, such intensification of the field before the earthquake days are concluded to be due to the earthquakes and also, as the process of preparation of the earthquake and its after effects are continuous events rather than discrete ones, the presence of weak diffusive fields during the period of analysis may be justified by the preparation mechanisms [Chakraborty et al., communicated, 2017].

To detect the presence of AGWs during the earthquake on May 12, we took only the nighttime part of the VLF data collected for JJI-IERC propagation path. This is because any additional ionization due to seismic activities will not be able to surpass that due to solar radiation during daytime. We performed both Fourier and wavelet transforms of the data and found strong waves with periods of the order of few minutes to hours on May 8. We also found some less significant waves with lesser periods on May 14 and 16. Next, to examine whether these wave-like structures are associated with the earthquake on May 12 and its aftershock on May 16, we monitored the solar geomagnetic activity by checking the $Kp$ index and found it to be reasonably low during the days of our analysis. So, the waves excited on those
days may be associated with the earthquake on May 12 and its major aftershock on May 16.

We then coupled the well-known LWPC code with the true variation of illumination over the entire propagation path to numerically simulate the shifts in terminator times. The necessity to consider such a situation arose due to the special feature of the propagation path. It has a high longitudinal extent with different illuminated/dark conditions. We considered the true movement of terminator shadow over the path starting from calculation of its speed and incorporation into the LWPC code to obtain the VLF signal variation under normal ‘non-seismic’ situation. Then, to obtain the signal variation under anomalous ‘seismic’ scenario, we made additional changes in the parameter values for only that portion of the propagation path that lied within the earthquake preparation zone (EPZ). For regions outside of EPZ, the parameter values were kept unchanged. From this approach, we found a good agreement between our simulated results and observations regarding the amount of terminator shift. We also found that raising the ionosphere within the EPZ resulted in our observed shift of terminators, both SRT and SST towards nighttime, thereby increasing the overall VLF day length. From observation, we found the maximum increase in day length to be 32 minutes whereas the same obtained from simulation was 25 minutes. The electron density was also found to decrease before the earthquake day as calculated from the Wait’s formula. Using several satellite and ground based measurements, Trigunait et al., [2009] also found a similar reduction in overall ionospheric electron content before the Bhuj earthquake. Thus, we conclude that from our modeling approaches, we have at least been able to reproduce the trend of terminator shifts and the values thus obtained also matched satisfactorily with our observations. But still there are some mismatches which arise out of our consideration of a sharp change in the parameter values across the EPZ boundary that is not the true realistic scenario but still a justifiable approximation to make.

Finally, to consider a different aspect, we examined the situation when two earthquakes are situated at two terminating ends of a VLF propagation path. For this, we chose the same JJI-IERC propagation path and the two earthquakes were the 2011 Honshu earthquake which was at the transmitter end and the 2015 Nepal earthquake which was at the receiver end. We found from our simulation results that for the Honshu earthquake, for which the signal got initially perturbed and then propagated through a perturbed waveguide, the changes are sudden, while for the Nepal earthquake, for which the signal initially traveled through an unperturbed
waveguide and then suddenly suffered strong perturbation near the receiving end, the changes are rather gradual. Also, the decrease in electron density as seen at 82 km altitude for Honshu earthquake was only 40% while that for the Nepal earthquake was 76%. Thus, it was found that the location of the epicenter with respect to a propagation path has genuine influence on the level of VLF signal modulations.

To summarize, we conclude that although the results thus obtained are quite satisfactory and match our observations to a considerable extent, a concrete theory supporting the atmospheric and ionospheric anomalies associated with earthquakes is still far from complete. The coupling between lithosphere, atmosphere and ionosphere prior and during seismic activities is a multi-parametric process and thus, it is very difficult to pin-point a single mechanism responsible for such coupling. Some more detailed observation with several receivers and transmitters and more thorough modeling is necessary to better understand this coupling mechanism. This we hope to do in future.