INVESTIGATION OF MAGNETIC FIELD MEASUREMENTS RECORDED BY LOW EARTH ORBITING SATELLITES

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UNDER THE GUIDANCE OF
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dedicated to mummy and daddy ...
STATEMENT BY THE CANDIDATE

As required by the University Ordinances 770, I wish to state that the work embodied in this thesis titled “Investigation of magnetic field measurements recorded by Low Earth Orbiting satellites” forms my own contribution to the research work carried out under the guidance of Dr. Geeta Vichare at the Indian Institute of Geomagnetism, New Panvel, Navi Mumbai. This work has not been submitted for any other degree of this or any other University. Wherever references have been made to previous works of others, it has been clearly indicated as such and included in the Bibliography.

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I hereby declare that the work described in the thesis has not been submitted previously to this or any other University for Ph.D or any other degree.

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“Whether the work is based on the discovery of new facts by the candidate or of new relations of facts observed by others, and how the work tends to the general advancement of knowledge”.

The first chapter gives a brief introduction to the variations in the geomagnetic field associated with solar terrestrial interactions in particular the quiet time ionospheric currents, disturbed time magnetospheric phenomena like storms and substorms and geomagnetic pulsations. Chapter two discusses the techniques and tools used in the study. In chapters three to six, the original work done by the candidate is described. This includes the new results of the identification of daytime Pi2 oscillations in the topside ionosphere and its wave characteristics. The first time observation of background frequencies present in LEO measurements, which can alter the Pc4-5 and Pi2 pulsations at satellite are presented. We also establish that these frequencies are due to the spatial structures of ionospheric currents monitored by the satellite. The new results concerning the disturbed time and quiet time magnetic field variations obtained from recent LEO mission Swarm are addressed. In the final chapter, the results are summarized and scope for future work is discussed.

The major findings of the present work are listed below:

- The occurrence of daytime Pi2s in the topside ionosphere is established, however its detection at polar LEO satellite is found to depend on Pi2 frequency.
• A combination of fast cavity-mode oscillations and an instantaneous transmission of Pi2 electric field from high to low-latitude ionosphere is proposed to be the responsible mechanisms for the daytime Pi2 oscillations.

• The presence of dominant background frequencies < 15 mHz are consistently observed in CHAMP compressional magnetic field. These background frequencies are found to alter daytime Pc4-5 and Pi2 oscillations at CHAMP.

• The characteristic features of these frequencies suggest its dependence on the low latitude ionospheric currents. The observed frequencies are therefore attributed to the spatial structures of ionospheric currents monitored by CHAMP and hence inherent to satellite observations. The present study strongly recommends the consideration of these background frequencies while studying geomagnetic pulsations using LEO.

• The global features of the EEJ is derived using Swarm satellites.

• The magnetic field variations caused by the geomagnetic storms, estimated from various passes of Swarm (Alpha) satellite are found be consistent with SymH variations, for the entire profile of storm and hence can be used as a proxy for disturbed time index, such as Dst.

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Statement No. 3

"The source from which this information has been derived and to the extent to which she has based her work on the work of others, and shall indicate which portion or portions of her thesis she claims as original”.

The information mentioned here is derived by the candidate during the course of the research. Some of the results presented in this thesis are reported in the following research
articles published in international journals.

- **Papers Published and Communicated in Journals**


  (2) **Neethal Thomas**, G. Vichare, and A. K. Sinha, Spatial frequencies associated with the latitudinal structures of various ionospheric currents seen by CHAMP satellite, *Astrophysics and Space science* (Accepted).


- **Papers presented in conference/symposium**


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- **Trainings and Workshops attended**

  (1) Workshop on YOUTHSAT Data Utilization for Ionospheric Studies and Hands-on Training *held at Space Physics Laboratory, VSSC, ISRO, during 13-14 October 2011*

  (2) Training in Pi2 pulsation studies under the supervision of **Prof. Kazuo Shiokawa at ISEE, Nagoya University, Japan** through SCOSTEP’s Visiting Scholar (SVS) scholarship program *during 17 January 2016 - 20 February 2016*

- **Lectures Delivered**

  (1) Daytime Pi2 Pulsations, *at Kyoto University, Japan, on 26th January 2016*

  (2) Low latitude Pi2 pulsations observed by CHAMP satellite, *at Nagoya university, Japan on 29th January 2016*
“Where a candidate presents joint work, she shall clearly state the portion which is her own contribution as distinguished from the portion contributed by her collaborators.”

The computation, analysis and the presentation of the works discussed in chapter 3, 4, 5 and 6 are done by the candidate. Problems addressed in this thesis are formulated by Dr. Geeta Vichare, the thesis supervisor.

(Dr. Geeta Vichare)  
Guiding Teacher

(Neethal Thomas)  
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Neethal Thomas
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Chapter 1

Introduction

In this chapter we will introduce the fundamental concepts that are used in this thesis, such as the Earth’s magnetic field, ionospheric layer, magnetospheric regions, various ionospheric and magnetospheric current systems, geomagnetic quiet and disturbed time variations, geomagnetic pulsations, specifications of low earth orbiting satellites etc.

1.1 Earth’s magnetic field and its components

The history of magnetism dates back to first century BC, during when the ancient Greeks and Chinese were known to have used the naturally occurring mineral magnetite called loadstone. Like gravitation, magnetism is also a fundamental property in the universe and is generated in matter at microscopic levels by the spin and orbital motion of electrons within the atoms. William Gilbert in 1600 performed the first scientific study on magnetism and establishes the fact that Earth itself is a huge magnet.

The region surrounding the magnet where another magnetic object can experience an attractive or repulsive force is termed as the magnetic field. The Earth being a giant magnet also
has magnetic lines of force surrounding it and is known as the geomagnetic field. These field lines originate deep within the Earth and extend to much higher altitudes in the interplanetary space. The Earth’s magnetic field is nearly dipolar with the magnetic field directed from southern hemisphere to northern hemisphere.

At any point in space the magnetic field can be expressed by its strength and direction and hence is a vector quantity. In northern hemispheric mid-latitude location, a magnet suspended freely will set itself along the total field vector ($\vec{B}$), which point towards north dipping downwards (Figure 1.1). The plane in which the magnet comes to rest is called the magnetic meridian which makes an angle with the geographic meridian (plane containing geographic north and south poles). This angle between the magnetic and geographic meridian is called declination ($D$). The vector $\vec{B}$ can be resolved into two components, $\vec{H}$ in the horizontal plane and $\vec{Z}$ in the vertical plane. The angle $\vec{B}$ makes with $\vec{H}$ is called Dip or Inclination ($I$). The horizontal component $\vec{H}$ can also be further decomposed into two components $\vec{X}$ and $\vec{Y}$, along geographic north and east respectively. The set of elements $B$, $D$, $I$ or $H$, $D$, $Z$, or $X$, $Y$, $Z$ used to describe the magnetic field at a location are called magnetic field components. Figure 1.1 depicts the relationship between these 7 elements and is mathematically described as follows.

\[ B = \sqrt{H^2 + Z^2} \]  \hspace{1cm} (1.1)

Where, \[ H = B \cos(I), \quad Z = B \sin(I) \] \quad and \quad \[ I = \tan^{-1} \frac{Z}{H} \]  \hspace{1cm} (1.2)

\[ H = \sqrt{X^2 + Y^2} \]  \hspace{1cm} (1.3)

Where, \[ X = H \cos(D), \quad Y = H \sin(D) \] \quad and \quad \[ D = \tan^{-1} \frac{Y}{X} \]  \hspace{1cm} (1.4)
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1.2 Ionosphere and its structure

The ionized part of the Earth’s upper atmosphere that contains significant number of free electrons and ions is termed as ionosphere. The high temperature in this region and consequently the ionized state of the gas is explained by the absorption of ultra violate (UV) and extreme ultra violate (EUV) radiation from the sun. These highly energetic solar radiations have sufficient energy to ionize the neutral atmosphere. The ionosphere is also called as partially ionized plasma as it contains a large number of residual neutral atoms and molecules. Even though electrons and ions are minor constituents in comparison to neutral gas, they exert a great influence on the medium’s electrical properties and hence have significant importance. Based on the electron density profile the ionosphere itself is again divided into four regions.
namely D, E, F1, F2. The typical electron density profiles of ionosphere is shown in Figure 1.2

Figure 1.2: The typical electron density profiles of ionosphere during both day and night hours. Dotted line shows the monthly median solar index which relates to activity at Sun (taken from: http://roma2.rm.ingv.it/)

D region is the lowest part of the ionosphere, which lies in the altitude range of 60-90 km. It is a relatively weakly ionized layer. Although D region ionization is low, it has great impact on radio waves, which results in the loss of wave energy. E- Region, which starts above 90 km, has ionization peaks at a height of about 110 km. It is formed by the absorption of longer wavelength ultraviolet radiations by the dominant molecular species like O₂ and NO. It is a very important layer as the strong electric currents in this region that are generated by the dynamo process greatly affects the physical processes here. Above E region there lies a well separated region called the F region. It has an ionization peak at about 300 km, which is a region of highest plasma density in the ionosphere. Atomic oxygen plays a major role in the
ionization of this layer. During day time the F-region splits into two layers, the F1-region at around 200 km, and the F2-region around 300 km height.

As ionization is a balance between production and recombination of ions, during night time the production of ions is sharply curtailed as the source is absent. As a result D and E regions, which are mainly constituted by molecular ions disappears completely at night. The increased recombination rate of the molecular ions together with the higher gas density is responsible for the faster recombination of the charged particles in these regions. Where as in F-region where the constituents are mainly atomic ions, the ionization can survive the night conditions. This is because of the longer life time of atomic ions than molecular ions and less frequent collisions due to reduced neutral density. Hence the existence of F region at night clearly mirrors the change in atmospheric composition with altitude.

1.3 Ionospheric Conductivity

As we have seen, the terrestrial ionosphere consists of partially ionized plasma, where the neutral density dominates that of the charged particles. Frequent collisions between the charged and neutral particles, in the presence of strong magnetic field cause a finite anisotropy in the conductivity of this layer. This anisotropy leads to a variable conductivity profile, which acts as the major controlling factor for the existence of various current systems in different layers of the ionosphere. The three major conductivities in this region are Parallel conductivity ($\sigma_o$), Pederson conductivity ($\sigma_p$) and Hall conductivity ($\sigma_H$).

The specific conductivity depends on local time as it depends on the number densities of charged particles. They are functions of altitude also. At the altitude range where the collision frequency of electrons and ions are greater than their gyro frequencies, the particle motions are essentially determined by the collisions with the neutrals. Because of the high collision frequency all the three conductivities in this region will be small. As the conductivity is too
low, practically no current flows in this region. This altitude range lies mainly below 70 km which is the D layer. Now in the altitude range between 70 and 130 km, i.e., E layer where the collision frequencies of electrons with the neutrals are lesser and that of ions are higher than their respective gyro-frequencies, all the three conductivities are high and the corresponding currents are mainly electron currents as the ions are heavily retarded by the collisions with the neutrals. In the high altitudes above 130 km, i.e., the F region, where the plasma density is high, the electron and ion motions are greatly controlled by magnetic field as the collisions with neutrals are relatively unimportant. Here the parallel conductivity $\sigma_o$ will be infinitely high as collision frequency is extremely low. But the pederson and hall current densities will be practically zero. Thus the only current that can be substantial in the F region is the parallel or field aligned current supported by $\sigma_o$. From this it is clear that the substantial current that flows in the ionosphere is in the E region.

1.4 Magnetosphere

Magnetosphere of the Earth is a cavity formed when a stream of charged particles emanating from the Sun’s upper atmosphere called solar wind interacts with the intrinsic magnetic field of the Earth. As Earth is immersed in a magnetic environment imposed by the solar wind, its magnetic field unlike expanding infinitely into the universe, gets confined to a limited space. This space surrounding the Earth where the magnetic field is confined is called the magnetosphere of the Earth and the boundary is the magnetopause. The shape of the magnetosphere is determined by the Earth’s internal magnetic field, the solar wind plasma and the interplanetary magnetic field (IMF). The magnetosphere of Earth therefore stands as an obstacle for the solar plasma by preventing it from entering directly into the Earth’s atmosphere. Since the solar wind hits the obstacle with supersonic speed, a bow shock wave is generated, where the plasma is slowed down and a substantial fraction of the particle’s kinetic energy is converted into thermal energy. The region of thermalized subsonic plasma behind the bow shock is called the magnetosheath [Baumjohann and Treumann, 1997].
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The interaction of the Earth’s dipolar field with the solar wind deforms its shape by compressing it at the dayside and stretching it to form a tail like structure in the night side, which extends far beyond the orbit of moon. The outer parts of the magnetotail, which occupies two large bundles of nearly parallel magnetic field line north and south of the equator are called magnetotail lobes. The two tail lobes are connected magnetically to the polar regions of the Earth with the magnetic field directed towards the Earth in the northern lobe and away from the Earth in the southern lobe. The tail lobes are separated by a region called plasma sheet. Typically, plasma sheet is 4-8 Earth radii ($R_E$) thick and it consists of relatively dense hot (having plasma pressure larger than magnetic pressure) low energy plasma [Kivelson and Russell, 1995]. The region earthward of the inner edge of plasma sheet is the radiation belt, which contains highly energetic charged particles which are trapped in the magnetic fields. There are inner (located between 0.5-2 $R_E$) and outer belts (located between 3-10 $R_E$) which are toroidaly shaped and encircles the planet [Hess, 1968]. Well inside the magnetosphere there is a region called plasmasphere. It is a doughnut-shaped region located just outside the ionosphere at a few Earth radii at mid- to equatorial latitudes. Plasmasphere contains dense,
cold plasma which is primarily of ionospheric origin. Unlike the plasma of the central plasma sheet, which flows sunward toward the dayside magnetopause, the cold, dense plasma of the plasmasphere is trapped on magnetic field lines and thus co-rotates with the Earth. The outer boundary of the plasmasphere is the plasmapause and is relatively sharp. Both the sharpness and location of the plasmapause vary with geomagnetic activity, with plasmapause located closer to Earth and sharper during times of high geomagnetic activity. Figure 1.3 summarizes the different regions of the magnetosphere.

1.5 Geomagnetic field variations

The geomagnetic field at any location on Earth is a combination of the magnetic field originating from different sources internal and external to the Earth’s surface. The magnetometers located on Earth respond to all the fields reaching the local environment, add them together and therefore gives a net magnetic field value at that location. The magnetic field recorded by these magnetometers exhibit variations having time scale ranging from few seconds to years. Based on the period, the magnetic field variations are classified into secular and transient variations. The secular variations are periodic variations of the Earth’s magnetic field which occur over years due to the changes in the geodynamo process by which the field originate within the Earth. The transient variations on the other hand occur over shorter time scales and are the reflections of physical processes taking place in the space around the earth. The present thesis mainly deals with the transient variations, which are further classified into quiet time and disturbed time variations. These variations are discussed below in sub-sections.

1.5.1 Quiet time variations

During the periods of low solar activity, the Earth’s magnetic field undergoes a regular smooth variation with a fundamental periodicity of 24 hour, in accordance with the position of the Sun
and hence is known as solar quiet variations. These variations are basically caused by the non uniform heating of the Earth’s upper atmosphere at ionospheric E-region altitude by the solar EUV radiations. This differential heating sets up pressure gradients and therefore the thermal tides in the atmosphere, which drags the atmospheric constituents (electrons and ions) across the Earth’s magnetic field. This dynamo action gives rise to currents which flow at right angles to the direction of the magnetic field and the motion of the charged particles. These ionospheric currents which are generated by the dynamics in the E region form dominant current system during daytime, when the E-region conductivity is high. The quiet time E-region dynamo currents are 1. Sq current, 2. Equatorial Electrojet (EEJ) and 3. Counter Electrojet (CEJ)

- **Solar quiet (Sq) Current**

![Solar quiet (Sq) Current](image)

Figure 1.4: Global view of average Sq current system [Baumjohann and Treumann, 1997]

It is a two cell current pattern circulating around focal points centered at local noon and 30° magnetic latitude north and south of the equator. The tidal motions in the atmosphere
create circular current patterns in the both northern and southern hemisphere and these two current vortices touch each other at the geomagnetic equator. A fixed amount of current flows between two consecutive streamlines. Therefore the current is more intense where the lines are more crowded. These lines are more crowded in the dip equator and less as we go higher latitude. Hence we have an intense current at the dip equator and of gradually decreasing amplitude at higher latitudes. Since the E region disappears in the nighttime, the Sq currents are concentrated at the day side region. A global view of the average Sq current system is shown in Figure 1.4

- **Equatorial Electrojet (EEJ)**

An interesting feature over equatorial latitudes is a rapid increase in the surface component of the geomagnetic field at and in the vicinity of the dip equator during daytime. This enhancement in the magnetic field results from an intense eastward electric current flow in the ionospheric E region along the dip equator and is known as equatorial electrojet (EEJ). The EEJ is most intense around local noontime and appears to be more stable than other ionospheric current systems. The prime reason for the high current density is the geomagnetic field geometry, exhibiting horizontal lines of forces in these latitudes. This special geometry of the magnetic field at the equator together with the nearly perpendicular incidence of the solar radiation causes an equatorial enhancement in the effective conductivity that is the cowling conductivity, which leads to an amplification of the jet current.

The generation of this enhanced current can be explained by a slab geometry in the ionospheric E-region as illustrated in Figure 1.5. During daytime, the E-region dynamo is active and controls the ionospheric dynamics at this time. The tidal winds in the E-region sets up the zonal electric field (eastward electric field) at the equator. This eastward electric field and the northward magnetic field will cause a small Pederson current (Sq current) to flow along the electric field direction \( \vec{E} \). Also the crossed electric and magnetic fields cause the electrons to drift vertically upward causing a hall current \( \sigma_H E_y \) to flow downward. The downward flowing hall current cannot cross the boundary, because of a non conducting atmosphere at
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Figure 1.5: Enhancement of the effective conductivity at the magnetic equator [Baumjohann and Treumann, 1997]

the bottom and effectively collisionless plasma at the top. This will lead to an accumulation of the charges at the two boundaries, i.e., the negative charge at the top and positive charge at the bottom of the E region, which in turn generates a vertical polarization field ($E_z$). In a steady state in this slab model no vertical current may flow, and the vertical Pederson current must exactly cancel the Hall current.

\[ \sigma_H = \sigma_P = 0 \]

\[ \sigma_H > \sigma_P > 0 \]

\[ \sigma_H = \sigma_P = 0 \]

\[ J_x = \sigma_P E_x + \sigma_H E_z \]

\[ \sigma_H = \sigma_P = 0 \]

\[ i.e., \quad \sigma_H E_x = \sigma_P E_z \] (1.5)

\[ hence, \quad E_z = \left( \frac{\sigma_H}{\sigma_P} \right) E_x \] (1.6)

Since $\sigma_H > \sigma_P$, the vertical electric field component exceeds the zonal electric field component. This vertical electric field component creates a secondary Hall current in the eastward direction. The zonal current is now given by

\[ J_x = \sigma_H E_x + \sigma_P E_x \] (1.7)

\[ J_x = \left[ \left( \frac{\sigma_H}{\sigma_P} \right)^2 + 1 \right] \sigma_P E_x = \sigma_C E_x \] (1.8)

Where $\sigma_C$ is called cowling conductivity. This Hall current enhances the original Pederson current, thereby resulting in a ne jet current along eastward direction called equatorial
electrojet. This strong jet current causes a magnetic field disturbances, which enhances the horizontal component of the Earth’s magnetic field. The typical disturbance fields at ground near the noon equator is around 50-100 nT.

- **Counter Electrojet (CEJ)**

As discussed early, the intense current flowing in the equatorial regions i.e., EEJ will result in an increase in the surface magnetic field components. If \( \Delta H \) is the incremental change in the horizontal component of the surface level geomagnetic field with reference to the night time level of \( H \), then an abnormal decrease or reversal of the daytime \( \Delta H \) which is confined predominantly to the EEJ latitudes is taken as the manifestation of reverse electrojet phenomenon. This decrease in \( \Delta H \) is due to the existence of the westward directed current mainly in the morning and/or evening hours. Such a current in the equatorial region is called as counter electrojet (CEJ).

### 1.5.2 Disturbed time variations

- **Geomagnetic storm**

Geomagnetic storm is the disturbance caused in the Earth’s magnetic field due to enormous energy input into Earth’s inner magnetosphere from the Sun. During certain period, large magnetic structures called coronal mass ejections (CMEs) which contain huge amount of solar corona are erupted from the Sun’s surface into the heliosphere. Those CMEs which are Earth directed hits the Earth’s magnetosphere with supersonic speed and compresses the magnetopause in the dayside. On normal days the, the solar wind plasma approaching the Earth interacts with the terrestrial magnetosphere and cause the deflection of the electrons and ions into opposite directions. With the Earth’s magnetic field directed northward, the Lorentz force acting on the incoming solar wind particles will deflect the ions to east and electrons to west resulting in a net eastward current flow. This current is known as **Magnetopause current** or **Chapman-Ferraro current**. With an impact of CME, the magnetopause currents
enhances significantly and therefore the additional magnetic field caused by these currents will add to the Earth’s magnetic field thereby causing an abrupt increase in the H component of the magnetic field at equatorial to mid latitudes. This sudden increase in the magnetic field is called sudden impulse (SI). Under the favorable condition of southward IMF Bz, the terrestrial magnetic field reconnects with the IMF and are then swept back to the night side by the solar wind causing a transfer of magnetic flux to the magnetotail. The energetic particles of solar wind can now go into the magnetosphere, along magnetic field lines, yielding an injection of plasma in the night-side of the magnetosphere. With IMF Bz southward for prolonged period, the incoming solar plasma enhances the dawn-dusk electric fields which result in the enhanced convection in the magnetosphere. The plasma injected in the tail is convected back to the inner magnetosphere, where they get trapped in the magnetic fields. These highly energetic particles (energy of about 3-300 KeV) undergo gradient and curvature drifts, which are charge dependent and therefore results in the differential motion of ions and electrons. The ions drift westward and electrons eastward resulting in a net westward current known as ring current, which extends from 4 to 8 R\textsubscript{E}. The ring current will produce magnetic field variations opposite to the Earth’s magnetic field causing in a large depression in the H component (< −50 nT) of the Earth’s magnetic field at equatorial and mid latitudes, which last for a few days. [Daglis et al., 1999]. These events are observed during the periods when IMF Bz turn southward (<-5) for a prolonged period of 2-3 hours.

A typical geomagnetic storm observed on ground has various distinct phases namely SI, initial phase, main phase and recovery phase and is shown in Figure 1.6. The sudden increase in the H component due to magnetopause currents, when supersonic solar wind hits the Earth’s magnetopause is termed as SI. After SI, the time duration for which the H values are dominated by the magnetopause currents is the initial phase. Once the ring current strength enhances significantly, it will dominate over the magnetopause currents resulting in a large decrease in the H value below the normal quiet conditions which last for few hours to days. This period is considered as the main phase of a storm. Finally the ring current decays and the field reach back to the normal values during the recovery phase.
• Geomagnetic substorm

A substorm is the ordered sequence of events that occurs in the magnetosphere and ionosphere when IMF turns southward and increased energy flow from the solar wind into the magnetosphere [Akasofu, 1979; McPherron, 1979]. It can be regarded as the unloading of solar wind energy into near geo-space environment. The geomagnetic signatures of substorm are marked with a sharp drop in the H component (-100 to -2000 nT) at night time auroral latitude.

Figure 1.6: Magnetic field depression during a geomagnetic storm [Tsurutani et al., 2006]

Figure 1.7: Deviation of cross tail currents to auroral ionosphere at the time of substorm onset (Image courtesy: http://www.issibern.ch)
The substorm process initiates with the increase in the rate of the reconnection due to southward turning of IMF Bz. During dayside reconnection, the large amount of flux is eroded from the dayside and is transported to the tail of the magnetosphere. A part of this flux gets reconnected in the night side and is convected back to the dayside, whereas the remaining flux gets added to the tail lobes. Due to the difference between the adjoining magnetic fields in two tail lobes, by Ampre’s law an electric current flows in the neutral sheet, which is directed from dawn to dusk. This current is called the **cross-tail current or neutral sheet current**. Therefore, as the magnetic flux in the tail lobe increases, the cross-tail current also increases, which results in the stretching of the plasma sheet into more tail like configuration. The period during when more and more flux gets loaded to the tail is known as substorm growth phase. When the flux accumulated becomes too much, the tail becomes unstable and stored field lines gets reconnected in the tail releasing enormous amount of energy toward the Earth. This period is substorm onset and beginning of expansion phase. The substorm expansive phase witness the sudden disruption of the cross tail current caused by the reconnection of field lines in the tail. A new current system called the **substorm current wedge (SCW)** [Atkinson, 1967; McPherron et al., 1973] is then formed as the tail current is diverted through a circuit consisting of earthward (downward) **field aligned currents (FACs)** on the eastern side of the wedge (dawn side), a westward auroral electrojet in the ionosphere, and tailward (upward) FACs on the western side of the wedge (dusk side). At this time, substorm currents in the auroral ionosphere enhances and the auroral arc (a region around the globe at $60^\circ - 70^\circ$ magnetic latitude where auroral emissions will be visible) suddenly brightens. The enhanced auroral activity is associated with the increase in the particle precipitation. Final phase of the substorm is the recovery phase. Typically a substorm last for about 2-3 hours. The schematic diagram showing the SCW formation is shown in Figure 1.7
Table 1.1: Different pulsation classes, its period and frequency range

<table>
<thead>
<tr>
<th>Pulsations</th>
<th>Pc1</th>
<th>Pc2</th>
<th>Pc3</th>
<th>Pc4</th>
<th>Pc5</th>
<th>Pi1</th>
<th>Pi2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (mHz)</td>
<td>200-5000</td>
<td>100-200</td>
<td>22-100</td>
<td>7-22</td>
<td>1-7</td>
<td>25-1000</td>
<td>6.6-25 mHz</td>
</tr>
<tr>
<td>Time Period (s)</td>
<td>0.2-5</td>
<td>5-10</td>
<td>10-45</td>
<td>45-150</td>
<td>150-600</td>
<td>1-40</td>
<td>40-150</td>
</tr>
</tbody>
</table>

1.6 ULF Pulsations

Geomagnetic pulsations are ultra low frequency (ULF) oscillations of Earth’s magnetic field, which are the manifestation of Magnetohydrodynamic (MHD) waves produced by various processes in the Earth’s magnetosphere and solar wind. ULF waves are therefore considered as an essential element in the magnetospheric physics and a useful tool for diagnostic and space weather studies. The ideas which lead to the quantitative study of the ULF waves can be attributed to Hannes Alfvén who gave us the set of equations that describes these oscillations and and James W. Dungey who recognized the structure of waves in space that is observed on the Earth’s surface. The geomagnetic pulsations have frequencies ranging from approximately 1 mHz to 1Hz and can be observed in the magnetometer data recorded at the Earth’s surface, in the ionosphere and in the magnetosphere. The waves with the lowest frequencies have wavelengths which are comparable to the size of the magnetosphere.

These waves as seen on the ground are in general grouped into two classes:

1) Pulsation continuous (Pc), which are quasi-sinusoidal oscillations.
2) Pulsations irregular (Pi), which has waveforms that are more irregular.

Depending on frequency or time period continuous pulsations are further subdivided into Pc1, Pc2, Pc3, Pc4 and Pc5 and irregular ones into Pi1 and Pi2 [Jacobs et al., 1964]. Different classes of pulsations together with its period and frequency range are shown in Table 1.1. The present thesis investigates the Pi2 oscillations in detail and hence this category of the pulsations is discussed separately.
• MHD waves

MHD deals with the study of the electrically conducting fluids like plasma. Plasma can be considered as a fluid where waves similar to sound waves can exist. Plasma being electrically conducting, its electromagnetic properties also play an important role together with its mechanical properties like density and pressure. Therefore the waves in plasma are different from the electromagnetic and mechanical waves and are called MHD waves. In MHD, the low frequency waves whose frequencies are lower than natural frequencies of plasma are referred to as ULF waves. In a collision less plasma where the plasma gyrates around the field, any change in the charged particles can move magnetic field and also vice versa. This concept enabled Hannes Alfvén to describe a simple process that creates a low frequency wave in plasma called Alfvén waves that propagates along a magnetic field line.

In cold plasma (where the magnetic pressure dominates the plasma pressure, $\beta \ll 1$), two modes of MHD waves exist. They are

**Compressional Fast mode:** Fast mode carries no current along the ambient magnetic field (B) line, but magnetic perturbations in general have a component parallel to B, so the fast mode can transmit pressure variations. The wave energy propagates in the direction of poynting flux which has an arbitrary direction relative to B. These waves are therefore isotropic in nature as it can transport energy in any direction. The dispersion relation that describes this mode is given by $\omega^2 = k^2 V_A^2$, where $k = 2\pi/\lambda$ is the wave vector, $V_A$ is the Alfvén speed and is given by $V_A = \frac{B}{\sqrt{\mu_0 \rho}}$ with B as the magnitude of ambient field and $\rho$ plasma density.

**Shear Alfvén Mode (Guided Mode):** In comparison to compressional fast mode wave, the shear mode can carry a finite current along the field line. But here the magnetic perturbations are always perpendicular to B. So this mode carries no pressure perturbations. The group velocity and hence the energy propagation of the shear mode is always parallel to the B. For this reason this mode is known as guided mode, as energy is guided along the ambient magnetic field. The dispersion relation associated with this mode is given by $\omega^2 = k_{\parallel}^2 V_A^2$. 
Some mechanisms of ULF wave generation

ULF waves are created by a variety of processes in magnetized plasma. Similar to different magnetospheric phenomena we discussed in the previous section, the energy for pulsations is also ultimately derived from the solar wind. In 1960’s, the scientists in their search for sources of pulsations looked for correlations between solar wind parameters and the properties of pulsations observed on the ground. An important consequence of this early work was the realization that different classes of pulsation have different sources. Some of the important external source mechanisms responsible for the generation of ULF waves are 1. Kelvin-Helmholtz (K-H) instability and 2. upstream waves.

Kelvin-Helmholtz instability is mainly cause by the convective flow of plasma in the magnetosphere, resulting in large shear in the plasma velocity between field lines moving tailward in the boundary layer and other field lines returning to the dayside [Axford and Hines, 1961]. K-H instability is also known to be caused by reconnection [Dungey, 1961] at the magnetopause. Reconnection being transient and localized can produce transient plasma waves in the magnetosphere.
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The upstream waves (UWs) on the other hand are waves generated in the Earth’s foreshock region. These waves are driven by a wave-particle interaction between the backscattered ions (mainly protons), gyro-rotating around the interplanetary magnetic field (IMF) and the fast magnetosonic waves propagating upstream along the IMF [Barnes, 1970; Gary, 1991; Krauss-Varban, 1994; Le and Russell, 1994; Yumoto et al., 1984]. This process is called the ion-cyclotron instability.

Apart from the afore mentioned exogenous source mechanisms there are also other endogenous sources responsible for these pulsations and are the magnetospheric or plasmaspheric compressional cavity mode [Kivelson, 1986; Kivelson and Southwood, 1985; Takahashi and Anderson, 1992], the field line resonances (FLRs). The most striking property of this resonance is its latitude dependence, while the frequency of pulsations associated cavity resonances depends on the size of the magnetospheric or plasmaspheric cavity (with plasmapause as the outerboundary and ionosphere as inner boundary).

1.6.1 Pi2 pulsations

Pi2 pulsations are short leaved (few minutes), ULF pulsations having period 40-150 sec excited by a source in the nightside magnetosphere. Pi2s pulsations are known for their occurrence at the time of substorm onset and intensification. In low-latitudes, Pi2s are observed over a wide range of longitude other than night side and are therefore considered as a proxy for substorm onset.

Pi2s are regarded as transient hydromagnetic signals associated with sudden changes in the state of the magnetosphere during substorm onset [Southwood and Stuart, 1979]. These sudden changes are caused by a short circuiting of the cross-tail current to the auroral ionosphere via field-aligned currents at the time of tail current disruption, i.e. by the formation of the substorm current wedge. These field-aligned currents suddenly switched on in the magnetotail are transferred into the auroral ionosphere via Alfven waves, as it is the only wave mode
which can carry field-aligned currents.

The arrival of the kinetic Alfvén waves at the ionosphere is signaled by the brightening of auroral arc. In addition to the Alfvén waves, at the time of substorm onset, compressional waves are also launched in the near Earth plasma sheet, which then moves across field line radially inward toward Earth.

Oscillations in the current wedge field-aligned current produce the high-latitude and mid-latitude Pi2 signals. Whereas, the compressional wave travelling into the inner magnetosphere excite low-latitude Pi2s. All these waves are manifested at ground as impulsive oscillations which resembles each other and occur concurrently within a few minutes. Pi2s can thus be regarded as a class of pulsations and that all of the members of the class are generated by the same event, i.e., the onset of field-aligned currents and compressional waves in the near-Earth plasma sheet associated with substorm onsets.

Some of the characteristic features of Pi2 are

**Location:** Ground Pi2 pulsations can occur at all longitudes and at latitudes from the dip equator (L = 1) up to and even inside the polar cap in the nightside. However, the occurrence of Pi2 at specific latitudes depends on the longitude (or magnetic local time). At low latitudes (L<2), Pi2 pulsations have been recorded at all longitudes, including the dayside [Li et al., 1998; Sutcliffe and Yumoto, 1989]. At middle latitudes (2<L<5) they occur over most of the nightside [Yeoman et al., 1994], and at high latitudes (L>5) they occur within a few hours of local time from the center of the SCW [Gelpi et al., 1985; Singer et al., 1983].

**Period:** Pi2 period varies with geomagnetic activity as measured by the AE and Kp indices [Saito and Matsushita, 1968]. Increased activity corresponds to shorter period. However, the Pi2 period also vary with latitude and longitude during the same time interval, with high latitude Pi2s having longer period compared to low latitude ones.

**Amplitude:** A characteristic Pi2 feature is amplitude variation with latitude and longitude. The amplitude can range from less than 1 nT at low latitudes to over 100 nT at high latitudes
(auroral zone) where it reaches its maximum [Jacobs and Sinno, 1960; Rostoker and Samson, 1981; Saito, 1969]. The largest Pi2 pulsations are found near magnetic midnight at high latitudes. As one moves far from the midnight meridian the Pi2 amplitude fades.

## 1.7 Geomagnetic Indices

In the earlier sections we have seen that the transient variations in the geomagnetic field result from the changes in the Earth’s electromagnetic environment caused by the solar terrestrial interactions. The disturbances in the geomagnetic field are therefore the reflections of various processes taking place in the upper atmosphere. Hence by regularly monitoring these variations at ground, one can get information/insight about the complex electrodynamic processes taking place in the near Earth space. In order to account for different solar terrestrial processes which cause changes in the Earth’s magnetic field at various latitudes and in different time intervals, different geomagnetic indices are formulated. Magnetic indices can be defined as simple measures of magnetic activity that occurs, typically over periods of time scales less than a few hours and which is recorded by magnetometers at ground based observatories. Some indices have been designed specifically to quantify idealized physical processes while others work as more generic measure of magnetic activity. These indices are compiled and disseminated by International Association of Geomagnetism and Aeronomy (IAGA).

The simplest index of activity would be the **daily range** of the magnetic field component relevant to the location of observation, say H at equatorial, low-mid latitudes and Z at high latitudes.

\[
\text{Daily range} = (\text{Largest hourly mean value} - \text{Lowest hourly mean value})
\]

### K and Kp indices

The K-index is quasi-logarithmic local index of the 3-hourly range introduced by Bartels to quantify the disturbances in the horizontal component of Earth’s magnetic field with an integer
ranging between 0 and 9. It gives a measure of the daily average level for geomagnetic activity, with 1 indicating quiet geomagnetic condition and 5 and above indicating a geomagnetic storm. The K index is designed to be insensitive to long term magnetic variations, including those associated with the overall evolution of magnetic storm, the normal quiet time diurnal variation and geomagnetic secular variation. K index is calculated separately for each observatory and therefore with an ensemble of K indices from different observatory site, ground level magnetic activity can be quantified.

Kp index is the planetary scale magnetic activity index, which is derived by the averaging the K indices from the selected 13 observatories in sub-auroral latitudes for each 3 hourly interval. The scale of K and Kp indices is logarithmic. Other indices related to K and Kp are A and Ap, which are the linear versions of K and Kp.

**AE (Auroral Electrojet) Index**

Auroral latitudes are locations were most of the energy from the outer magnetospheric domain is transferred during a magnetic disturbance. The Auroral Electrojet Index, AE is designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. Ideally, it is the total range of deviation at an instant of time from quiet day values of the horizontal magnetic field (H) around the auroral oval.

AE index is computed using the horizontal magnetic field at 12 observatories located between 60° and 70° geomagnetic latitude (which is believed as a location of auroral oval) in the northern hemisphere. As the energy transfer process at auroral latitudes are so frequent and rapidly fluctuating, the magnetic field values are averaged over 1 minute interval. For each stations, the variation in H from a quiet time base level is determined. The largest and lowest deviations are designated as AU (Auroral Upper) and AL (Auroral Lower). Then,  \[ AE = AU - AL \]  and  \[ AO = AU + AL \]. Where, AU represent the eastward and AL represent the westward electrojet currents flowing in the auroral ionosphere. AL index
represents the westward electrojet, which intensifies during substorm activity. Therefore it is often used as a proxy for substorm phenomenon.

**Dst Index**

During geomagnetic storm, there is a remarkable flow of the westward ring current in the Earth’s equatorial belt roughly \( \pm 30^\circ \). This westward current cause magnetic field which is directed opposite to the Earth’s natural magnetic field. The depression in H observed during a storm is the signature of this westward current and the steady recovery of H indicates the ring current decay. Dst is a global index which gives a measure of the strength of the symmetric westward ring current encircling the Earth during geomagnetic storm. Dst index utilizes H component values from 4 low-latitude ground observatories, which are sufficiently away from the influence of both equatorial and auroral electrojets. Dst is then computed by averaging the hourly values of the deviations in the horizontal (H) component from its quiet time values from these 4 observatories. The index similar to Dst is SymH, which gives average H variations in every 1 minute interval.

**Wp index**

Wp (wave and planetary) is a substorm index recently developed by Nosé et al. [2012], which gives the Pi2 wave power at low-latitudes. This index employs high resolution (1 second) geomagnetic field data from 11 low latitude ground stations longitudinally distributed around the globe. These ground stations are selected in such a way that at least one station will always fall in the night side. As Pi2 are clearly observed at low- and mid-latitude ground stations at the time of substorm, Wp index gives an estimate of substorm activity by calculating the Pi2 wave power at low-latitudes. Since Pi2s have dominant power in the night side, the stations falling in the night side (18:00-04:00 magnetic local time (MLT)) are only used for calculating Wp index. Using 1 sec H component data from the night time ground station, the Pi2 wave power is estimated using wavelet analysis.

Traditionally, AL index is used to identify the substorm phenomenon, although it may not
represent the activity always [Nosé et al., 2009]. The location of auroral oval is highly dependent on the level of geomagnetic activity, hence its position changes with the intensity of the event and may not strictly lie within 60°-70° latitude. Thus the stations used for calculating AE index may happen to lie out of the oval and hence may not capture the activity correctly. This limitation of AL index can be overcome by the Wp index, as Pi2s (and hence Wp) are one of the proxies of substorm activity. With multiple ground stations distributed longitudinally around the globe, Pi2 can be detected at any given UT. As a result, Wp can ensures the detection of the substorm onset without fail.

1.8 Polar Low Earth Orbiting Satellites

Satellites are celestial bodies which orbit a planet or a star. There are two kinds of satellites: natural and artificial satellites. The moon orbiting around the Earth is an example of natural satellite. Artificial satellites or usually referred to as simply ”satellites” are machines that are launched into space and moves around Earth or another body in space. Satellites are launched into different orbits based on its purpose. Among different satellites, the low Earth orbiting ones are launched to an orbit at altitude less than 2000 km from the Earth’s surface. One of the important orbital parameters which describes the shape and orientation of a celestial orbit is its inclination. Inclination can be defined as the angular distance the orbital plane makes with a plane of reference, which is usually the equatorial or ecliptic plane. The LEO satellites having inclination >85° are called polar LEO satellites. With high inclination orbit, a polar LEO satellite moves from Earth’s one pole to other at orbital altitude closest to the Earth. For polar LEO satellites having a perfectly circular orbit, the altitude of the satellite nearly remains constant, whereas for non-circular orbits, its altitude varies depending on the perigee (the closest point to Earth) and apogee (the farthest point to Earth) of the satellite. The orbital specifications of a polar LEO satellite is as follows.

The polar LEO satellite have an orbital period of 90-100 min, i.e., it completes one complete
orbit around the Earth in 90-100 min. Therefore in one day, the satellite makes nearly 15 orbits round the Earth, with the half orbit over daylight side of the Earth and other half over night. Except at poles, the local time of the satellite remains nearly constant in its transit as the satellite moves over nearly identical longitude. With Earth rotating below, the longitude of polar LEO shifts by $\sim 23^\circ$ west after every complete orbit round the Earth. With this constant shift in longitude in every 100 min, on a given day, the polar LEO satellite witness nearly same LT for all 15 day and night passes. The satellite orbit drifts in local time by approximately 1 minutes each day and hence the satellite visit all LT sectors in nearly four months duration.

With this orbital specifications, a polar LEO satellite can visit all longitudes on a single day at fix LT in both day and night sector. This makes the satellites specially advantageous in studying various geomagnetic processes and its global features. As it flows in the ionospheric altitudes, these satellites have special importance in the study of ionospheric E-region and F-region dynamics. In fact it provides the only means of getting the longitudinal variability of these processes by quickly visiting all longitudes at a specific local time. Monitoring the Earth continuously from lowest possible altitudes, these satellite collect valuable information on the Earth’s internal and crustal fields and its spatial variations. This makes LEO magnetic field measurements a valuable data set for geomagnetic field modeling.

The era of polar LEO satellites started with the launch of OGO (Orbiting Geophysical Observatory) satellite series in the 1960s with an objective to obtain a better understanding of the Earth-Sun relations and of the Earth as a planet. The POGO (Polar Orbiting Geophysical Observatory) mission within OGO program includes three satellite series OGO 2, 4 and 6 which are low altitude polar orbiting satellites having inclination $>80^\circ$ and perigee and apogee heights of 400 and 1510 km respectively above the Earth. These POGO satellites are launched in succession every two years starting from 1965 with a prime aim of measuring Earth’s magnetic field for developing geomagnetic field models.

POGO was followed by Magsat (Magnetic Field Satellite) satellite, a joint mission by U.S.
Geological Survey (USGS) and NASA. The Magsat spacecraft was launched on October 30, 1979, into a dawn-dusk, sun-synchronous orbit with inclination $96.76^\circ$. The satellite had an elliptical orbit with perigee 352 km and apogee 561 km. The primary objectives of the Magsat mission were to obtain data for improved modeling of the time-varying magnetic field generated within the core of the earth, and to map variations in the strength and vector characteristics of crustal magnetization. Also, the dawn-dusk orbit of the satellite makes it particularly useful for studying the ionospheric processes taking place in the terminator hours. With flux-gate magnetometers on board, Magsat became the first satellite of its kind to give vector magnetic field measurements, providing valuable data for geomagnetic field modeling. It is therefore considered to be one of the important Science/Earth orbiting satellites launched till date. After collecting data for a six-month period, Magsat mission came to an end in the spring of 1980.

Twenty years after the Magsat mission, the Ørsted satellite was launched by Danish Meteorological Institute on February 23, 1999. Ørsted has a slowly drifting elliptical orbit with perigee 655 km, apogee 857 km and inclination $96.5^\circ$. The orbital period of satellite is 100 min. After 4 years in space, perigee and apogee of satellite decreased to 640 and 845 km respectively. The main scientific objective of the spacecraft was to map the Earth’s magnetic field and collect data to determine the changes occurring in the field. The magnetic field measurements are recorded by the on-board Overhauser proton magnetometer and fluxgate vector magnetometers. After more than seventeen years in orbit, the Ørsted satellite is still operational, and continues to measure the Earth’s total magnetic field. The Ørsted satellite thus constitutes a very valuable set of magnetic field modeling.

**SAC-C satellite** was launched in November 2000 into a sun-synchronous circular orbit at an altitude of $\sim430$ km. The satellite lasted in orbit till 2013. The science objectives of the SAC-C spacecraft was to study the structure and dynamics of the Earth’s atmosphere, ionosphere and geomagnetic field.

This thesis utilizes magnetic field measurements from two important satellite missions namely
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CHAMP and Swarm. The orbit specifications and the science objectives of these missions are detailed below.

1.8.1 CHAMP (Challenging Mini Satellite Payload) satellite

CHAMP is a German satellite launched on 15 July 2000 into near circular orbit with an inclination of 87.3° and an initial altitude of \(~450\) km. The mission lasted for ten years till September 2010 during when the satellite altitude descended to \(~250\) km. The satellite had an orbital period of \(~92\) min. Drifting in LT by \(~<1\) min, CHAMP visited all LTs in four month duration.

CHAMP carried high resolution scalar and vector magnetometers which gives magnetic field measurements of unprecedented accuracy. The other high precise payload elements on board CHAMP are accelerometer (to measure directly the non-gravitational orbit perturbations such as air drag, solar and Earth radiation pressure), star sensor (for precise inertial orientation information), GPS receiver (for satellite-to-satellite tracking between CHAMP and the high-flying GPS satellites), laser retro reflector (for additional tracking from ground) and ion drift meter (to measure the electrical field vector along the orbit). With these multi-functional and complementary payloads and its orbit characteristics, CHAMP generated highly precise gravity and magnetic field measurements over 10 year period, which allows the tracing of spatial and time variations of both magnetic and gravity fields for a long time.

The main objectives of CHAMP mission are:

1) Mapping of the Earth’s global long to medium wavelength gravity field and its temporal variations with applications in the geophysics, geodesy and oceanography.

2) Mapping of the Earth’s global magnetic field and temporal variations with applications in geophysics and solar terrestrial physics.
3) Atmosphere/ionosphere sounding with applications in global climate studies, weather forecasting, disaster research and navigation.

**1.8.2 Swarm mission satellites**

It is the latest ongoing polar LEO missions launched by the European Space Agency (ESA). Swarm consist of a constellation of three satellites A-Alpha, B-Bravo and C-Charlie orbiting in two different near polar orbits, with two of them flying side by side at an altitude of 450 km and the third at an altitude of 530 km. The three satellites were launched together on 22 November 2013 into a near-polar (87.5° inclination) orbit at an altitude of about 500 km. After a commissioning of the scientific instruments, the spacecraft were maneuvered into their final orbits from middle of January 2014 onward. On 15 April 2014 Swarm had achieved its final constellation. Two satellites, Swarms-A and -C, are flying side by side in orbits separated by only 1.4° in longitude and at an altitude of about 460 km. The third spacecraft, Swarm-B, orbits the Earth at about 520 km with a somewhat higher inclination. With a higher inclination orbit, Swarm-B drifts longitudinally from Swarm-A and C by 20° in every year.

One of the main objectives of the Swarm mission is to provide the best-ever survey of the geomagnetic field and its temporal evolution together with the electric fields measurements in the upper atmosphere using high precision magnetometers and electric field instruments. Using simultaneous measurements at different altitudes and local times, the Swarm mission will allow better separation of internal and external sources, thereby improving geomagnetic field models. In addition to internal field, Swarm mission is aimed in getting a better estimate of the external magnetic field contributions caused by magnetospheric currents to facilitate the space weather research.

The other research topics to be addressed by the Swarm mission are Earth’s internal processes including core dynamics, geodynamo, and core mantle interaction (to improve the models of
the core field dynamics), the lithospheric magnetization and its geological interpretation and 3-D electrical conductivity of the mantle.

1.9 Scope of Thesis

As mentioned in the previous section, the orbital specifications of the LEO satellite facilitate to study ionospheric currents during quiet and disturbed period. As these satellites cruise through the topside ionosphere it can also monitor various magnetosphere-ionosphere coupling processes taking place during solar terrestrial events.

Till date the magnetic field measurements from various LEO satellites have been extensively used by several researchers to carry out studies on the spatial distribution of different ionospheric processes such as E-region currents [Jadhav et al., 2002; Lühr et al., 2004][Alken and Maus, 2007] and F-region currents [Lühr et al., 2015; Lühr and Maus, 2006] and ionospheric irregularities [Park et al., 2009a; Stolle et al., 2006].

LEO satellites have also made significant contribution to the geomagnetic pulsations studies Balasis et al. [2012]; Heilig et al. [2007]; Jadhav et al. [2001]; Ndiiitwani and Sutcliffe [2009]; Sutcliffe and Lühr [2003]; Vellante et al. [2004]. One of the distinct advantages of using LEO satellites for pulsation study is to understand the effect of ionosphere on these oscillations. As different pulsations manifest itself in different components such as compressional and poloidal above the ionosphere [Takahashi et al., 1994; Yumoto et al., 1984], it can easily be separated and identified at satellites. Whereas, on the ground, due to the effect of ionosphere on these oscillations they show up in the H (magnetic north) component [Nishida, 1978; Takahashi et al., 1994] and hence cannot be distinguished directly using observations from ground alone. As different wave modes have different characteristics above and below the ionosphere the study of these pulsations using polar LEO observations in conjunction with ground can provide better insights to the different wave modes and the mechanisms by which these pulsations propagation from magnetosphere to ground.
Attempts have been made by previous researchers [Balan et al., 2011; Lühr and Liu, 2006; Manoj et al., 2013; Sivla and Okeke, 2011] in investigating magnetospheric process such as geomagnetic storm and its effect on thermosphere/ionosphere system using polar LEO observations. These studies are mainly centered around the electron density measurements and wind drag information derived from LEO observations. However magnetic field measurements from polar LEO satellites have been less explored in studying geomagnetic storms.

Present thesis is dedicated to the studies of various solar terrestrial phenomena exclusively using magnetic field measurements from polar LEO satellites. This thesis addresses one of the important problems about substorm associated geomagnetic pulsation named Pi2. Through this study we have attempted to resolve a long lasting question on the existence of Pi2s in the topside ionosphere during daytime and the limitations imposed by LEO satellites in observing them. The present thesis also studies quiet time E-region ionospheric current flowing along the dip equator (EEJ) using multi satellite mission Swarm. The thesis presents the results of geomagnetic storms, which has been done for the first time using magnetic field measurements from polar LEO satellite.

The main topics covered are

- Ionospheric currents during geomagnetic quiet period
- Magnetospheric currents during during geomagnetic storm
- Pi2 pulsation associated with substorm activity

A brief summary of the work carried out in each chapter is discussed below.

Chapter 2

In chapter 2, the methods and tools used in investigating the magnetic field measurements from polar LEO satellites are detailed. As the focus of the thesis is to investigate the transient magnetic field variations recorded by the satellite, the ambient field present in satellite measurements has to be accurately predicted and removed at each point of observation. This is
achieved using a geomagnetic field model. This chapter firstly gives a basic introduction to the mathematical formalism for the spherical harmonic representation of the Earth’s magnetic field and the different geomagnetic field models in use. As a first step towards this thesis, I have calculated the ambient field at each satellite location by employing a suitable geomagnetic field model. The ambient field estimated are then subtracted from the satellite observations to get the residual fields at satellite. This is performed by developing a FORTRAN code. The different steps involved in estimating the residual field are detailed with the help of a flow chart. This chapter also discusses the different spectral analysis tools extensively used in investigating the residual magnetic field at satellite to study different geomagnetic processes.

Chapter 3

Chapter 3 discusses the characteristics of EEJ current derived using the vector magnetic field measurements from Swarm satellites (Bravo ’Swarm-B’ and Charlie ’Swarm-C’) obtained during the quiet days ($\sum Kp \leq 10$) of the years 2014-2015. In this study the EEJ parameters such as peak current density, total eastward current, width of EEJ, position of the electrojet axis etc are obtained by fitting an empirical model for EEJ to the satellite observations. For more realistic estimates, in the present study the model is fitted separately for both the hemispheres unlike previous studies [Jadhav et al., 2002] where they consider the current to be symmetric in both the hemispheres. The return currents of EEJ is also calculated and its linear dependence on forward current is determined. The longitudinal and local time variation of some of the electrojet parameters are also investigated and is discussed in this chapter.

Chapter 4

Chapter 4 investigates the magnetic field variations recorded by Swarm satellite during geomagnetic storms. The results of three storm events of solar cycle 24 representing major, moderate and weak storms are presented. The satellite observations are compared with the model estimates predicted using Tsyganenko model. The amplitude of maximum variation
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during storm-time obtained from satellite and model matches well with that obtained from SymH index, during all three storms. The study suggests that the model estimates considering magnetopause, ring, partial ring current (PRC), magnetotail, region1 (R1), region2 (R2) currents are not able to produce the observed asymmetry during moderate and weak storms, while during major storms, model predictions are better.

Chapter 5

Chapter 5 investigates the occurrence of substorm associated Pi2 (6.6-25 mHz) pulsations in the low latitude topside ionosphere using vector magnetic field measurements from LEO satellite CHAMP. Although the daytime occurrence of Pi2s at ground stations is well reported in literature [Shinohara et al., 1997; Sutcliffe and Yumoto, 1989], its simultaneous occurrence in the topside ionosphere remained a topic of debate [Han et al., 2004; Sutcliffe and Lühr, 2010]. Present study primarily investigates the simultaneous occurrence of daytime Pi2s in LEO and underneath ground observations. It is shown that the identification of daytime Pi2s at CHAMP (compressional component) depends on the frequency of Pi2 oscillation, i.e., Pi2s with higher frequencies (>15 mHz) are more suitable for the detection in the topside ionosphere using polar LEO satellites. The presence of a dominant non-Pi2 power in the lower frequencies (<15 mHz) of Pi2 band, is consistently observed in the CHAMP observations during daytime and are found to contaminate Pi2 pulsations having frequency <15 mHz. Through case and statistical studies, the present study demonstrates that the signatures of daytime Pi2s are possible to observe at CHAMP, provided that contribution from background frequencies at satellite is eliminated.

Chapter 6

The background frequencies uniquely observed in CHAMP while studying daytime Pi2 pulsations are investigated in detail in Chapter 6. The CHAMP total magnetic field variations during international quiet days of the years 2008-2009 are utilized here. The present study investigates the source mechanism responsible for the occurrence of these background frequencies in CHAMP and are identified to be inherent to polar LEO satellite observations.
These frequencies were found to have serious impact on pulsation studies and is demonstrated in this chapter through a case study.

**Chapter 7**

This chapter summarizes the scientific outcomes of this thesis. The scope for future work is also briefly discussed here.
Chapter 2

Earth’s Magnetic Field Models and methods of Signal processing

2.1 Introduction

The magnetic lines of force which surround the Earth are termed as the geomagnetic field. The geomagnetic field is a superposition of the fields generated both internal and external to the Earth’s surface. The major part of the geomagnetic field is generated deep inside the Earth due to the electric current flow in the convecting liquid outer core by geodynamo action. It accounts for 97% of the Earth’s total magnetic field. This internal field from the Earth’s core is termed as the main field. The other internal source is the crustal field and is caused by the remanent magnetization of the rocks in the crust and upper mantle, and by the induced magnetization due to the currents flowing above the Earth’s surface. The crustal field contributes to 2 – 3% of the total field. The remaining (1%) contribution comes from the external field which is caused by the currents flowing above the Earth’s surface in the ionosphere and magnetosphere. The core and crustal field which accounts for the 99% of the Earth’s magnetic
field undergoes a slow temporal or secular variation of 1% in every year. Whereas, the external field although contributes less, varies in a time scales of few seconds to day and can cause the near Earth field to vary from fraction of nT to thousands of nT.

As discussed in the previous chapter, the focus of the thesis is to investigate the Earth’s magnetic field recorded by polar LEO satellites to study various ionospheric and magnetospheric processes. A polar LEO satellite moving at high inclination orbits monitors the geomagnetic field distribution over the entire range of latitudes spanning from one pole to another at all longitudes round the globe. Orbiting at altitudes a few hundred kilometers above the Earth’s surface, the magnetic field recorded by these satellites has sources both internal and external to the Earth’s surface. Therefore in order to study any variations in the magnetic field resulting from sources external to the Earth’s surface, one has to remove other contributions such as the internal core and crustal fields and static external fields caused by magnetospheric currents. Unlike ground observatories, the satellite being a moving entity, its location (latitude, longitude and altitude) changes constantly with time. Since the ambient magnetic field is different at different locations and at different epoch, it is very much essential to accurately estimate the magnetic field values at each locations of the satellite at a given time, in order to remove these contributions from satellite observations. This can be achieved with the help of an appropriate geomagnetic field model, which predicts the magnetic field value at different locations at different time.

The present chapter firstly details the spherical harmonic representation of the Earth’s magnetic field and introduces different geomagnetic field models developed based on it. As the thesis mainly concentrates on the magnetic field variations obtained from different platforms, the investigation of the time series of these variations is an important aspect of the thesis. Different signal processing tools extensively used in analyzing the time series are therefore greatly discussed in the second half of this chapter.
2.2 Spherical Harmonic representation of Earth’s magnetic field

Considering Earth to be a perfect sphere, the best mathematical formalism for the geomagnetic field is the spherical harmonic expansion. It was Gauss in 1838, who first developed the spherical harmonic analysis to model the Earth’s main field in a global scale and it continued to be used as the most convenient tool to illustrate the important properties of geomagnetic field. Spherical harmonics are a series of special functions defined on the surface of a sphere. It can be defined as the angular portion of a set of solutions to Laplace’s equation in three dimensions.

The Maxwell’s equations governing the magnetic field are

\[
\nabla \cdot \vec{B} = 0 \hspace{1cm} (2.1)
\]

\[
\nabla \times \vec{B} = \mu_0 J + \mu_0 \frac{\partial D}{\partial t} \hspace{1cm} (2.2)
\]

Where, \( \vec{B} \) is the magnetic field, \( J \) is the current density, and \( \partial D/\partial t \) is the electric displacement current density. The surface of the Earth can be considered as a source free region for the magnetic field as it is reasonable to assume that there is negligible electric flow across the boundary between the surface of the Earth and the atmosphere.

Hence, on the Earth’s surface, \( J \) and \( \partial D/\partial t \) can be considered to be zero. Therefore, by Eq.(2.2) \( \nabla \times \vec{B} = 0 \), indicating that the vector field \( \vec{B} \) is conservative in the considered area and it can be expressed as

\[
\vec{B} = -\nabla V \hspace{1cm} (2.3)
\]

Where, \( V \) is the scalar potential and therefore satisfies the Laplace equation,

\[
\nabla^2 V = 0 \hspace{1cm} (2.4)
\]
In spherical coordinates the Laplace equation can be represented as,
\[
\frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial V}{\partial \theta} \right) - \frac{1}{\sin^2 \theta} \frac{\partial^2 V}{\partial \theta^2} = 0
\]  \hspace{1cm} (2.5)

Where, \( r \), \( \theta \), and \( \phi \) are the geographic coordinates representing the radial distance, co-latitude and longitude respectively. A complete solution of \( V \), which is a sum of internal \( (V_{int}) \) and external \( (V_{ext}) \) field contributions, i.e., \( V = V_{int} + V_{ext} \) is given by spherical harmonics as
\[
V(r, \theta, \phi) = R \sum_{n=1}^{\infty} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} \left[ (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m \cos \theta \right] + \\
R \sum_{n=1}^{\infty} \left( \frac{r}{R} \right)^{n+1} \sum_{m=0}^{n} \left[ (q_n^m \cos m\phi + s_n^m \sin m\phi) P_n^m \cos \theta \right]
\]  \hspace{1cm} (2.6)

Where, \( R \) is the radius of the Earth. \( (g_n^m, h_n^m) \) and \( (q_n^m, s_n^m) \) are the Gauss spherical harmonic coefficients, which can be considered as the magnetic field sources for internal and external fields respectively. These values are obtained by the prolonged magnetic field observations from ground and satellite. \( P_n^m(\cos \theta) \) are the Schmidt semi-normalized associated Legendre polynomials. The first term of Eq.(2.6) corresponds to the internal field with degree, \( n=1 \) representing the dipolar structure of magnetic field and higher degrees corresponding to multi-polar structure. Therefore by increasing \( n \) from 1 to higher and higher values, one can obtain magnetic field contributions from core to crust. The main field dominates the values for degrees less than 13 (i.e., long wavelengths), whereas the crustal field dominates for degrees larger than 15 (wavelengths smaller than 2500 km). As the Earth’s internal magnetic field changes over time (in the time scale of years), the corresponding field coefficients are also time dependent. The secular variation (SV) of the internal magnetic field can be accounted by adding the potential term for SV, and is represented as
\[
V_{SV} = R \sum_{n=1}^{\infty} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} (t - T_0) \left[ (\dot{g}_n^m \cos m\phi + \dot{h}_n^m \sin m\phi) P_n^m \cos \theta \right]
\]  \hspace{1cm} (2.7)
Where, \((\hat{g}_n^m, \hat{h}_n^m)\) are the time derivatives of the internal Gauss coefficients. \(T_0\) denotes the reference time (i.e., the epoch of the main field model), and \(t\) is the considered epoch.

## 2.3 Geomagnetic field models

Geomagnetic field models are the empirical models which gives the estimate of magnetic field values at any point above or below the Earth’s surface using spherical harmonics. These models are based on extended magnetic field measurements from different observational platforms. Different models use spherical harmonic representation to various degrees and orders in order to obtain the magnetic fields at different wavelengths. So, based on the purpose, which demands different level of accuracy in predicting the magnetic field values, the choice of the field models vary. Most of the main field models give an estimate of the secular variation of the Earth’s magnetic field for the years following from their release date. The secular variation is the slow annual to decadal change of the Earth’s magnetic field caused by the flow of liquid in the outer core, deep inside the Earth. This change of the field is not easily predictable due to the complex geodynamo action by which the magnetic field is generated. The estimates of SV given by the main field models are mainly based upon linear extrapolation of the magnetic field from the observed change in the previous few years. However, the estimate is often relatively inaccurate at the end of the epoch of the model. Therefore, these models are updated traditionally in every 5 years in order to account for the changing magnetic field. There are different geomagnetic field models available based on magnetic field measurements from different observational platforms. Some of them are listed below.

### International Geomagnetic Reference Field (IGRF)

IGRF is a series of mathematical models of the Earth’s magnetic field and its annual rate of change (secular variation) produced and released by the International Association of Geomagnetism and Aeronomy (IAGA) working Group V-MOD for scientific use. It was introduced in
response to the demand for a standard spherical harmonic representation of the Earth’s main field. IGRF is meant to give a reasonable approximation of the Earth’s magnetic field, which has its origin inside the surface. The model is developed and regularly revised every 5 years for epochs starting from the 1955 to present (1955.0, 1960.0, 1965.0 etc.), in order to follow the continuous temporal changes of the geomagnetic field. At any one epoch, the IGRF generation specifies the Gauss coefficients of a truncated spherical harmonic series. For dates until 2000 the truncation is at $n=10$, with 120 coefficients, but from 2000 the truncation is at $n=13$, with 195 coefficients. Apart from this, each generation also provides the models for SV to predict the time variation of the large-scale geomagnetic field for the 5 years following the latest revision of the IGRF and a Definitive Geomagnetic Reference Field (DGRF) for the previous epoch. The latest model is the $12^{th}$ generation released in December 2014.

**Enhanced Magnetic Model (EMM)**

EMM is a geomagnetic field model with higher spatial resolution. It calculates the magnetic field for both the Earth’s internal magnetic field as well as the crustal field. It extends to degree and order 720, resolving the magnetic anomalies down to smaller (56 km) wavelength. It is also updated for the latest model coefficients in every 5 year epoch. This model is compiled from satellite, marine, aeromagnetic and ground magnetic surveys. The latest version is EMM 2015, which includes data from the recently deployed Swarm satellite mission of ESA.

**High Definition Geomagnetic Model (HDGM)**

HDGM is also a main field model with higher spatial resolution similar to that of EMM including Earth’s internal magnetic field as well as the crustal field to degree and order 720 for the years 1900 to present. But unlike EMM, HDGM also includes a basic model for external fields and is updated annually to model the secular variations correctly.
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**Ørsted Initial Field Model (OIFM)**

It is a model derived from scalar magnetic field data obtained by Ørsted satellite collected during the quiet (Kp ≤ 1+) period between December 1999 and January 2000. This model accounts for both the internal and the external fields up to degree 19 and 2 respectively. The spherical harmonics expansion for the scalar potential V is given as:

\[
V(r, \theta, \phi) = R \sum_{n=1}^{19} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} \left[ (q_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m \cos \theta \right] + \\
R \sum_{n=1}^{2} \left( \frac{r}{R} \right)^{n} \sum_{m=0}^{n} \left[ (q_n^m \cos m\phi + s_n^m \sin m\phi) P_n^m \cos \theta \right] + \\
R \cdot D_{st} \cdot \left[ \left( \frac{r}{R} \right)^2 + Q_1 \left( \frac{R}{r} \right)^2 \right] \cdot \left[ \tilde{q}_1^0 P_1^0 \cos \theta + \left( \tilde{q}_1^1 \cos \phi + \tilde{s}_1^1 \sin \phi \right) P_1^1 \cos \theta \right] 
\]  
(2.8)

The \(q_n^m\)s and \(s_n^m\)s are the Gauss coefficients for external field and \(\tilde{q}_1^0\), \(\tilde{q}_1^1\) and \(\tilde{s}_1^1\) are the Gauss coefficients for the time varying Dst dependent part of the external field. This time varying external field induces currents on ground, which further gives rise to secondary internal fields. The induced field on ground caused by this Dst dependent field is represented here via the factor \(Q_1 = 0.27\), a value found from Magsat satellite data by Langel and Estes [1985]. Therefore, the first term in Eq.(2.8) represent the internal field with expansion up to degree 19; the second term represents the external field with degree 2 and the third term the Dst dependent part of the external field together with its internal induced counterpart up to degree 1 [Olsen et al., 2000]. The model is further revised by Langlais et al. [2003] and Olsen [2002] to higher spherical harmonic expansion of the static field up to \(n \leq 29\) and the linear secular variation up to, \(n \leq 13\).
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CO2 model

CO2 is an initial official CHAMP main magnetic field model that utilizes magnetic field measurements of all three satellites, viz., Ørsted, CHAMP and SAC-C as well as ground observatory data. This is again an epoch based model, which employs data collected during the period between July 2000 and December 2001 including higher geomagnetic activity up to Kp=2, thereby including more data compared to OIFM model. Unlike OIFM, CO2 also accounts for the SV of Earth’s magnetic field. The latest CO2 model includes internal field coefficients up to order 49, with the main field secular variation up to 13 and the external field correction is up to order 2 Holme et al. [2003]. The complete expression for scalar potential is given as

\[
V(r, \theta, \phi) = R \sum_{n=1}^{49} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} \left[ \left( g_n^m \cos m\phi + h_n^m \sin m\phi \right) P_n^m \cos \theta \right] + \\
R \sum_{n=1}^{13} \left( \frac{R}{r} \right)^{n+1} \sum_{m=0}^{n} \left( t - T_0 \right) \left[ \left( \dot{g}_n^m \cos m\phi + \dot{h}_n^m \sin m\phi \right) P_n^m \cos \theta \right] + \\
R \sum_{n=1}^{2} \left( \frac{r}{R} \right)^{n} \sum_{m=0}^{n} \left[ \left( q_n^m \cos m\phi + s_n^m \sin m\phi \right) P_n^m \cos \theta \right] + \\
R \cdot D_{st} \cdot \left[ \left( \frac{r}{R} \right) + Q_1 \left( \frac{R}{r} \right)^2 \right] \cdot \left[ \tilde{q}_1^0 P_1^0 \cos \theta + \left( \tilde{q}_1^1 \cos \phi + \tilde{s}_1^1 \sin \phi \right) P_1^1 \cos \theta \right]
\] (2.9)

CHAOS model

CHAOS describes the near-Earth static (core and crustal) magnetic field up to spherical harmonic degree \( n = 50 \), and up to \( n = 18 \) for the first time derivative (SV) using more than 6.5 years of high-precision geomagnetic measurements from the three satellites Ørsted, CHAMP and SAC-C. The mathematical expression for the internal part is same as previous models,
with only difference in the expansion coefficients and the maximum degree of spherical harmonic expansion.

CHAOS provides an improvised estimate of the external field by calculating the contributions from different magnetospheric currents separately. Unlike the previous models, it evaluates the effects of the magnetotail current together with the external field correction from the time varying magnetospheric ring currents and the secondary field at ground due to its induced counterpart. Among these the Dst dependent ring current contribution is evaluated in Solar Magnetic (SM) coordinates and the magnetospheric tail current contribution is evaluated in Geocentric Solar Magnetospheric (GSM) coordinates. The external magnetic field potential, $V_{ext}$ describing large-scale magnetospheric contributions from the near magnetosphere sources (magnetospheric ring current) and from far magnetospheric current systems (tail currents) are expressed as

$$V_{ext} = R \sum_{n=1}^{2} \left( \frac{r}{R} \right) \sum_{m=0}^{n} \left( q_{n}^{m} \cos mT_{D} + s_{n}^{m} \sin mT_{D} \right) P_{n}^{m} \cos \theta_{D} +$$

$$\sum_{m=0}^{1} \left( \tilde{q}_{1}^{m} \cos mT_{D} + \tilde{s}_{1}^{m} \sin mT_{D} \right) \cdot \left\{ E_{st} (t) \left( \frac{r}{R} \right) + I_{st} (t) \left( \frac{R}{r} \right)^{2} \right\} P_{1}^{m} \cos \theta_{D} +$$

$$R \sum_{n=1}^{2} q_{n}^{0} R_{n}^{0} (r, \theta, \phi)$$

(2.10)

Where, $R_{n}^{0} (r, \theta, \phi) = \left( \frac{r}{R} \right)^{n} P_{n}^{0} \cos \theta_{GSM}$

Where, $\theta$ and $T_{D}$ are dipole co-latitude and dipole local time, respectively, which are co-latitude and longitude in the solar magnetic coordinates system. Est and Ist are time series of the components of the Dst-index, which is decomposed into external and induced parts as $\text{Dst}(t) = \text{Est}(t) + \text{Ist}(t)$ [Olsen et al., 2005]. The functions $R_{n}^{0}$ are modified Legendre functions to account explicitly for induced field contributions due to the variation of the GSM z-axis with respect to the Earth’s rotation axis.
POMME model

POMME (Potsdam Magnetic Model of Earth) is a main field model which is based on extensive satellite magnetic field measurements. It utilizes vector field from CHAMP and total field measurements from Ørsted satellites. The latest model in the POMME series (POMME-9) also includes vector magnetic field data from Swarm satellites for a period from December 2013 to January 2015. Similar to CHAOS, POMME model provides the coefficient values for the internal field, its secular variation and acceleration and external field, with the internal field contributions evaluated in geographic (GEO) coordinates, the magnetospheric tail current in Geocentric Solar Magnetospheric (GSM) coordinates and the Dst dependent ring current and magnetopause currents in Solar Magnetic (SM) coordinates. Mathematical expressions of POMME is similar to that of CHAOS.

Swarm Initial Field Model (SIFM)

SIFM is a very recent magnetic field model of Earth derived using the data from the first year of Swarm satellites in orbit. In addition to the conventional magnetic field observations provided by each of the three Swarm satellites, the advantage of the three satellite constellation is taken by including east-west magnetic intensity gradient information from satellites in the lower altitude. Along-track differences in magnetic intensity provide further information concerning the north-south gradient. Use of this gradient data improves the determination of both the static field and its secular variation. SIFM accounts for internal field expansion up to degree and order 70 and SV up to 13. The external part of the field model is identical to that of the CHAOS-4 model, with magnetospheric sources (magnetospheric ring current) in the Solar Magnetic (SM) coordinate system having an expansion of n=2, the time varying Dst-dependent field correction with n = 1 and of the remote magnetospheric sources (e.g., magnetotail and magnetopause currents) in GSM (n = 2 and m = 0).

However, in SIFM the external contributions to the Earth’s magnetic field are not accurately
modeled. An improved version of SIFM is CHAOS-5, which additionally utilizes ten months of Swarm observations and ground observatory monthly means together with the data sources previously used to construct CHAOS-4 which includes 14 years of magnetic field measurements from 3 different satellite missions Ørsted, SAC-C and CHAMP and ground observatory monthly means.

2.4 Estimation of the residual fields at satellite

In order to study the magnetic field variations caused by ionospheric and magnetospheric processes using polar LEO satellites, the first step is to get the residual fields by removing the dominant internal and static external magnetic fields. In order to obtain the residual fields at satellite, a FORTRAN code is developed which makes use of a geomagnetic field model. The present thesis utilizes POMME main field model to remove the dominant ambient field contributions in the satellite observations. Using POMME model, the magnetic field values are estimated for each satellite locations at which observations are made. The basic steps involved in the process are detailed below.

**Step 1:** Get the basic inputs required for the program, which includes the vector magnetic field measured by the polar LEO satellite at a location (latitude, longitude and altitude) and at a particular instant of time. The observations are recorded by satellite in GEO coordinates.

**Step 2:** Calculation of internal field

1. Read Gauss coefficients of the internal field \((g_n^m, h_n^m)\) for \(n=1\) to \(N_{\text{max}}\), \(m=0\) to \(n\), and SV \((\dot{g}_n^m, \dot{h}_n^m)\) for \(n=1\) to \(N_{\text{max SV}}\), \(m=0\) to \(n\) given by the model. The coefficients for internal field and its SV are given in GEO.

2. Calculate the Schmidt semi-normalized Legendre polynomial \(P_n^m(\cos \theta)\) with \(n=1\) to \(N_{\text{max}}\) and \(m=0\) to \(n\) for a given \(\theta\), the co-latitude of satellite.
3. Calculate the vector magnetic field components $B_X$, $B_Y$, $B_Z$ of the internal field at the given satellite location using POMME internal coefficients and the calculated $P_m^n(\cos \theta)$ values.

**Step 3:** Calculation of external field due to different current systems oriented in different coordinate systems

1. Convert latitude and longitude of satellite from GEO to geomagnetic (GM) coordinates.

2. Calculate magnetic local time (MLT)
   
   (a) Calculate sidereal time and the location (latitude and longitude) of sun such as its right ascension, declination, ecliptic longitude and obliquity of ecliptic. These values in the celestial coordinate system are best aligned in geocentric equatorial inertial (GEI) frame.

   (b) Convert Sun’s right ascension and declination from GEI to GM.

   (c) Calculate MLT by taking the difference between the longitudes of satellite and Sun in GM coordinates.

3. Calculate $P_m^n(\cos \theta)$ for $n=1$ to 2 and $m=0$ to $n$, get for $\theta$ (satellite co-latitude) in GM colatitudes.

4. Calculate $B_X$, $B_Y$, $B_Z$ separately for GSM and SM coordinate systems using the estimated $P_m^n(\cos \theta)$ values and POMME external coefficients.

5. Calculation of the external field due to time varying ring current and its induced part on ground.

   (a) Obtain Dst values for the concerned time and calculate Est and Ist values from it.

   (b) Read POMME coefficient for the time varying field, $q_0^\theta$ in SM coordinates.
(c) Calculate $B_X$, $B_Y$, $B_Z$ in SM frame using $q_i^0$ and the Legendre polynomial $P_l^0 (\cos \theta)$ ($\theta$ is the co-latitudes of satellite in GM coordinates).

**Step 4:** Convert external fields calculated in GSM and SM coordinates to GEO.

**Step 5:** Add the contributions from internal and external field to get the net field predicted at a particular location using POMME model.

**Step 6:** Subtract the estimated magnetic field from that observed by the satellite to get the residual fields.

**Step 7:** Repeat the steps 1 to 6 for each time at which satellite observations are available.

The flowchart detailing these steps is shown in Appendix A.

### 2.5 Selection of geomagnetic field model

The geomagnetic field models are developed for a certain time period in which it can give the best prediction of magnetic field values at a certain location. We have seen in the earlier section that there are different geomagnetic field models available which are based on magnetic field values obtained from different platforms and based on observations made over different time period i.e., some use a few months data while some other utilize magnetic field data over many years. As Earth’s magnetic field is not constant but changing constantly over years, a geomagnetic field model based on a particular epoch cannot accurately predict the field values in another epoch due to the model limitation in precisely estimating the SV of Earth’s magnetic field. So when employing geomagnetic field model for predicting magnetic field, the correct choice of the model has an important impact in the estimated values. Since the calculation of the residual fields at satellite, highly relies on the accurate estimation of ambient field, the appropriate choice of the model and its epoch is of prime importance. The
improper removal of ambient field from satellite observations can result in large residual field values which can give erroneous results unless treated properly. The residual fields obtained at satellite for different epochs using POMME 6.1 (2005 epoch) model is shown in Figure 2.1.

Figure 2.1: Residual field estimation at CHAMP and Swarm satellites using POMME 6.1 model for different epochs.

The top panels displays the magnetic field observed by CHAMP (Figure 2.1a) and Swarm (Figure 2.1b) satellites (blue line) during a quiet time pass (Kp<1) at different epochs over nearly identical longitude (∼200°E) and nearly same local time (LT: 10.5 h) together with the magnetic field values predicted using POMME 6.1 model (blue line). The curves of the model predictions and actual observations look identical with the scales of ambient magnetic field tens of thousands of nT. It is not possible to view any smaller scale deviations in those
plots and hence we plot the difference between the observations and model predictions in the bottom panels. For residual fields at CHAMP (Figure 2.1c), the values are of the order of tens of nT and depicts the ionospheric currents. But for Swarm, over similar longitude at similar LT and during similar geomagnetic conditions, the residual field showed an increase in value by one order. These additional contributions at Swarm are caused by the improper removal of geomagnetic main field by POMME model which is developed for 2000-2009 epoch. This shows the inaccuracy of the model in predicting the changes in the main field at a time beyond the model epoch.

2.6 Methods of signal processing

A signal is a piece of information regarding a phenomenon that is evolved over time or space. The signal or information recorded at regular time interval is known as time series. The study of time series is basically intended to understand the underlying process that leads to the observed data points. Signal processing involves techniques to analyze such data points to get the information contained in the signal. The present thesis utilizes a few data analysis techniques to get the information encrypted in the time series of magnetic field measured by the polar LEO satellites which are discussed below.

2.6.1 Power Spectral Density

The spectral analysis deals with the estimation of the frequency content encoded in a time series (that forms a signal), by giving the distribution of the power over frequency. The power spectral density (PSD) $S_x(f)$ of a time series, $x(t)$ of infinite length is defined as

$$S_x(f) = T \sum_{k=-\infty}^{\infty} R_{xx}(k)e^{-j2\pi fkT}$$  \hspace{1cm} (2.11)
Where, \( R_{xx}(k) \) is the auto correlation function (ACF), i.e., the correlation of a signal with itself at different points in time, and \( T \) is the sampling interval. This equation is called Wiener-Khinchin theorem, which implies that the PSD is the Fourier transform of the ACF. There are different spectral analysis tools in use for discretely sampled signals. The classical one is the Fourier method which assumes the validity of Wiener-Khinchin theorem. The Fourier series method describes the power spectrum as the magnitude square of the Fourier transform of the data. The basic idea behind Fourier approach is to construct an artificial time series by summing up sines and cosines with different amplitudes that best resembles the actual time series. When the data and sinusoids match, the power spectrum of a data at a particular frequency \( f_j \) is large and when data and sinusoids do not match, the power at frequency \( f_j \) is small. In FFT method, the data set is considered to be finite which repeats periodically and an integer number of periods fill the acquisition time interval, i.e., the signal is assumed to be periodically repeating beyond the known interval. As mostly the measured signal isn’t periodic, it can result in a truncated waveform with characteristics different from the original continuous-time signal, which is a major limitation of FFT method. Also as the frequency resolution of PSD in FFT method is the reciprocal of time interval, it may not appropriate for short duration signals as it reduces the spectral resolution.

One of the popular non Fourier methods for spectral analysis is the ‘autoregressive modeling’ method or ‘all pole’ model. Autoregressive (AR) model is a representation of a stochastic (random) process which specifies that a value or a realization at a time \( t \) depends linearly on its own previous values and on uncorrelated random variables with zero mean and variance \( \sigma^2 \), which is essentially the white noise. An AR process of order \( p \) can be written as

\[
X_t = \sum_{j=1}^{p} \phi_j X_{t-j} + Z_t \tag{2.12}
\]

Where, \( \phi \) is the AR coefficient. The conventional method of estimating power spectrum from a measured autocorrelation function (indirect Fourier method) assumes that correlation
function is zero at times for which no information is available. In an attempt to avoid this shortcoming of the conventional PSD estimator, Burg [1968, 1967] introduced an estimator based on the principle of maximum entropy. The maximum entropy (MEM) spectral estimation method is based on the extrapolation of the known autocorrelation of a process $X_t$, by maximizing the entropy of the corresponding probability density function. Here, the idea is to choose a spectrum that corresponds to the most random or the most unpredictable time series whose autocorrelation function agrees with the known values.

Entropy is a measure of uncertainty described by a set of probabilities or in other words it can be regarded as a measure of the ignorance about the actual structure of a system. The probability of occurrence of an event, $P_i$ is related to information as $I = k \ln \left( \frac{1}{P_i} \right)$, where $k$ is a constant. Then the total information about the system which is observed for a time interval $T$ can be expressed as,

$$I_{total} = k \left( p_1 T \ln \frac{1}{p_1} + p_2 T \ln \frac{1}{p_2} + \ldots \right)$$

(2.13)

The average information per time interval is referred to the term Entropy.

$$H = \frac{I_{total}}{T} = -k \sum_{i=1}^{M} p_i \ln p_i$$

(2.14)

Where, $M$ is the total number of realizations of a process $x_t$. Applying the concept of maximum entropy to spectral analysis, the relationship between entropy and spectral density of a Gaussian process can be expressed as

$$H = \frac{1}{4f_N} \int_{-f_N}^{f_N} \log \left( S(f) \right) df$$

(2.15)

Where, $S(f)$ is the power spectral density and $f_N$ is the Nyquist frequency, which is the highest frequency that can be coded in a waveform and is equal to half the sampling rate. Following
the principle of maximum entropy (as discussed in Ulrych and Bishop [1975]), the well known expression for MEM spectral density for a linear process $x_t$ is

$$S_{MEM} = \frac{P_M}{f_N^2 + \sum_{i=1}^{M-1} \gamma_j \exp (-i2\pi fj\Delta t)^2}$$

(2.16)

Here, $P_M$ is a constant and $r_j$ are the prediction error coefficients determined from the data. Van den Bos [1971] establishes the relation between MEM spectral analysis and AR representation of a random process. Ulrych and Bishop [1975] demonstrated this by showing that the unknown auto covariance coefficients estimated by maximizing the entropy of the process and that by AR processes are same. This point out the fact that MEM spectral analysis is equivalent to the least square fitting of an AR model to random process. Therefore, the representation of a random process by an AR model is the one that exhibits the maximum entropy. In the computation of MEM spectrum using equation 2.16, the two main parameters one should know are firstly the prediction error filter coefficients (or equivalently the AR coefficients) and the length of prediction error filter $M$ (or order of AR process). A common method in use to estimate the AR coefficients is by means of solving Yule-Walker equations, which can be obtained simply by multiplying Eq. 2.16 by $x(t-k)$ and take the expectation values.

One of the most important aspects in the MEM spectral analysis is the selection of the length of prediction filter $M$ (or the order of AR process), which is the chief limitation of this method due to the lack of the quantitative methods in determining $M$. The value of $M$ also determines the resolution of the spectral peak. Therefore a small value of $M$ may result in a too smooth spectrum which cannot distinguish the underlying spectral content. Also a large value of $M$ can result in spurious peaks. Therefore, an appropriate choice of $M$ between a good resolution (high $M$) and no spurious peaks (low $M$) is required [Ghil and Taricco, 1997; Schlindwein and Evans, 1992]. To overcome this limitation, many model-order estimators have been proposed, such as the final prediction error (FPE) [Akaike, 1970] the criterion which chooses the order
that minimizes the prediction error, the Akaike information criterion (AIC) [Akaike, 1974],
the criterion AR transfer function (CAT) [Parzen, 1976] etc. Ulrych and Bishop [1975] have
performed a numerical evaluation of the FPE criteria using different estimates of the M value.
They point out that the distribution of minimum FPE have large variance when M is greater
than about half the length of the data (N/2). According to authors, the variance is less and
therefore, the results are consistent for a cutoff of M=N/3. Ndiitwani and Sutcliffe [2009]
have demonstrated the estimation of PEF by experimenting with artificially generated signals.
The test signals consisted of sinusoids with different frequencies and amplitudes mixed with
and without noise. They have shown that for a 90 s time series without noise the expected
spectral peaks are resolved with smaller PEF value of 10, whereas for the same time series
with noise added, different frequency peaks were resolved clearly only for a higher PEF value
of 20 and for both time series with and without noise, the FPE value of 40 started introducing
spurious peaks. They also noticed that an increased level of noise content and smaller values
of amplitude also demands higher PEF values in the identification of frequency peaks. Thus in
short, for a pure signal the shorter PEF length is preferable whereas for signals contaminated
with noise and those having smaller amplitude longer length is preferable.

2.6.2 Cross spectral Analysis

Cross spectral analysis facilitates one to study multiple time series and their relations with
one another as a function of frequency. The different cross spectral analysis tools used in the
thesis are

- Cross-Correlation

The cross-correlation function gives the measure of the similarity between two time-series
shifted in time relative to one another. In the relationship between two time series \( x_t \) and
\( y_t \), the time series \( y_t \) may be related to past lags of \( x_t \). Using the cross-correlation function
(CCF) one can estimate the lags at which two time series match. Applying a lag $T$, the cross-covariance between the pair of signals is given as

$$\sigma_{x,y}(T) = \frac{1}{N} \sum_{t=1}^{N} (x_{t-T} - \bar{x})(y_t - \bar{y})$$  \hspace{1cm} (2.17)

Where, $\bar{x}$ and $\bar{y}$ are means of the signals $x$ and $y$ having $N$ samples each. Now, the cross correlation can be defined as the covariance normalized by the standard deviation of $x$ and $y$. Mathematically correlation coefficient is expressed as,

$$r = \frac{\sigma_{x,y}(T)}{\sigma_x \sigma_y}$$ \hspace{1cm} (2.18)

Where, $\sigma_x = \left[ \frac{1}{N} \sum_{t=1}^{N} (x_{t-T} - \bar{x})^2 \right]^{\frac{1}{2}}$, $\sigma_y = \left[ \frac{1}{N} \sum_{t=1}^{N} (y_{t-T} - \bar{y})^2 \right]^{\frac{1}{2}}$

$\sigma_x$ and $\sigma_y$ are the standard deviations of $x$ and $y$ respectively. Therefore, the correlation coefficient is the average product of departures of two variables from their respective means divided by the product of the standard deviations of those variables.

When cross correlation gives the correlation between two signals at different lags, the autocorrelation of a signal gives the correlation with itself at different point in time i.e., if $x=y$ then cross correlation reduces to auto correlation.

- **Cross spectral density**

As PSD is the Fourier transform of the autocorrelation of a signal (Wiener-Khinchin theorem), $x_t$, the cross spectral density (CSD) is the Fourier transform of the cross-correlation of the signals. In other words it gives the estimate of the power shared by a given frequency for two different signals. Cross spectral analysis enables one to understand the relationship between the two time series such as the coherence and cross phase. CSD is described as
\[ P_{xy}(\omega) = \sum_{t=-\infty}^{\infty} \left[ \sigma_{x,y}(t) \exp(-i\omega t) \right] \]  

(2.19)

where, \( \sigma_{x,y}(t) = \sum_{l=-\infty}^{\infty} x(l)y(l-t) \) is the cross-correlation of the signals \( x_t \) and \( y_t \) having standard deviation nearly equal to 1. By substituting \( \sigma_{x,y} \) in Eq. (2.20),

\[ P_{xy}(\omega) = \sum_{t=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \left[ x(l)y(l-t) \exp(-i\omega t) \right] \]  

(2.20)

Writing \( \exp(-i\omega t) = \exp(-i\omega l) \exp(i\omega t) \),

where \( k = l - t \), then

\[ P_{xy}(\omega) = X(\omega)Y(-\omega) \]

where, \( X(\omega) = \sum_{l=-\infty}^{\infty} x(l) \exp(-i\omega l) \) and

\[ Y(\omega) = \sum_{l=-\infty}^{\infty} y(k) \exp(i\omega k) \]

For real signals, \( Y(-\omega) = Y^*(\omega) \), where * denotes the complex conjugate.

Therefore,

\[ P_{xy}(\omega) = X(\omega)Y^*(\omega) \]  

(2.21)

denoting that CSD is the product of the Fourier transform of one signal and the complex conjugate of the Fourier transform of other. Hence CSD can be estimated by two methods i.e., either by using cross-correlation given by Eq. 2.20 or by Fourier transform method given by Eq.(2.21). For \( x=y \), CSD reduces to PSD.

**Coherence**: Coherence is a measure of the degree of relationship, as a function of frequency, between two time series. The coherence or the mean squared coherence between two time series is defined as
$C_{xy}(f) = \frac{P_{xy}^2(f)}{P_{xx}(f)P_{yy}(f)}$ \hspace{1cm} (2.22)

Where, $P_{xy}$ is the CSD and $P_{xx}$ and $P_{yy}$ are the PSD of the time series $x$ and $y$ respectively.

- **Cross Phase**: The cross phase between two signals can be represented as

$$\theta_{xy}(f) = \tan^{-1}\left(\frac{Im(C_{xy}(f))}{Re(C_{xy}(f))}\right)$$ \hspace{1cm} (2.23)

### 2.7 Summary

This chapter presents a detailed description about different geomagnetic field models and how they can be used in estimating the residual fields at satellite. It also briefly discusses various signal processing tools used throughout the course of this thesis, for the investigation of residual magnetic field measurements.
Chapter 3

Characteristics of equatorial electrojet derived using Swarm mission satellites

3.1 Introduction

The E-region ionosphere is a dynamo layer, where the atmospheric neutral winds cause charge particles to move across the magnetic field resulting in electric fields and the currents. The primary eastward electric fields together with the horizontal geomagnetic field at the dip equator cause hall and Pederson currents to flow in a narrow altitudinal region bounded by the neutral atmosphere below and collision less plasma above, resulting in strong vertical electric fields. This vertical electric field produces large eastward hall currents and therefore greatly enhances the net eastward current. This intense eastward jet current flowing during daytime in the ionospheric E-region at 106 km at the dip equator is called equatorial electrojet (EEJ) [Chapman, 1951; Onwumechili, 1998].

The study of EEJ has been extensively carried out since several decades using various observational platforms and models [Forbes, 1981; Onwumechili, 1998]. Different observational
platforms used for EEJ studies include ground based observations, sounding rockets and satellites, each one having its own advantages and limitations. The ground based observations [Fambitakoye and Mayaud, 1976; Raghavarao and Anandarao, 1987; Rastogi, 2007] record the temporal variations of the magnetic field over a particular location, but it lack in spatial coverage as many of the areas around the globe is covered by forest and oceans. Satellites on the other hand, record the magnetic field variations revolving around the earth in different orbits at different altitudes. Among different satellites, the polar low earth orbiting (LEO) satellites [Alken and Maus, 2007; Cain and Sweeney, 1973; Jadhav et al., 2002; Lühr et al., 2004, 2008] have the advantage of true spatial coverage, as it covers the entire globe in a day. But, it lacks in recording the diurnal geomagnetic field variations caused by quiet time ionospheric currents, due to its rapid motion. Both ground and satellite measurements give the height integrated effect of ionospheric/magnetospheric currents, whereas rockets [Chandra et al., 2000; Onwumechili, 1992; Sampath and Sastry, 1979; Sastry, 1970] are the only means to get height profile of the ionospheric currents. However, the rocket cannot record the spatial and temporal variations. Apart from the observations, different theoretical and numerical models were also developed to address the physical features of EEJ [Richmond, 1973; Stening, 1985; Sugiura and Cain, 1966; Sugiura and Poros, 1969; Untiedt, 1967].

Polar LEO satellite observations are distinctly advantageous in EEJ studies as it provides the global observation of the current system, spanning the currents latitudinally and longitudinally on a given day. Using the total magnetic field measurements from very first LEO mission, POGO, it was shown that the signature of the EEJ currents is characterized by a negative depression in magnetic field over equatorial latitudes [Cain and Sweeney, 1973; McCreadie, 2005; Onwumechili and Agu, 1980, 1981]. POGO was followed by Magsat, a sun-synchronized satellite in the dawn-dusk orbit. It provides the first evidence of the existence of meridional currents associated with EEJ in the equatorial ionosphere [Maeda et al., 1982]. Jadhav et al. [2002] and Ivers et al. [2003] studied the characteristic of EEJ current system in detail by using the total magnetic field measurement using Ørsted satellite measurements. Jadhav et al. [2002] estimated the EEJ parameters like peak current density, total current and
width of the current system using Ørsted data. They found that the EEJ strength estimated at ground using satellite data correlate well with the EEJ observations from Indian and American ground observatories. Later, Lühr et al. [2004] deduced the characteristics of the EEJ currents using scalar magnetic field measurements from CHAMP thereby reaffirming the results from Ørsted. To derive a global picture of EEJ, Alken and Maus [2007] developed the climatological model of EEJ, using the scalar magnetic field measurements from Ørsted, CHAMP and SAC-C satellites. Using this empirical model, they estimated the local time, longitudinal and seasonal dependence of EEJ current. Lühr et al. [2008] made use of this model in estimating the influence of non migrating DE3 tidal mode on the intensity of EEJ. The reverse electrojet phenomenon, known as the Counter Electrojet (CEJ) is also reported in the scalar magnetic field measurements at Ørsted by Vichare and Rajaram [2011]. They delineated the characteristics of the global distribution of CEJ by investigating its longitudinal, LT and seasonal dependence.

The magnetic field data from all these earlier LEO missions have been analyzed by different methods by different researchers for e.g. Jadhav et al. [2002] fitted Onwumchilli’s empirical model of EEJ currents into the magnetic field observations, while Lühr et al. [2004] fitted a series of line currents. However the broad features of the EEJ obtained based on independent methods are consistent. In the present chapter, we aim to derive the global features of EEJ using the X-component of the magnetic field from the recently deployed polar LEO mission satellites Swarm. The chapter is organized as follows. Section 3.2 presents the data and identification of EEJ signatures. Section 3.3 describes the empirical model of EEJ and the method of analysis used in this study. The derived EEJ current parameters are presented in Section 3.4. The altitudinal variation of EEJ signatures and the characteristics of forward and return currents of EEJ are elaborated in section 3.5 and 3.6 respectively. Section 3.7 and 3.8 discusses the longitudinal and LT variation of the EEJ. Finally the results are discussed and summarized in section 3.9.
3.2 Data set and identification of EEJ signature

European space agency (ESA)’s multi-satellite mission Swarm, consist of three identical satellites namely Alpha (Swarm-A), Bravo (Swarm-B) and Charlie (Swarm-C). The satellites were launched together on November 2013 into a near polar orbit with inclination $> 87^\circ$. Later in January 2014, the spacecrafts were moved into different orbits and attained the final constellation in April 2014. Swarm-A and Swarm-C orbits side by side at an altitude of 460 km, whereas Swarm-B moves at a higher altitude of 520 km. With a higher inclination orbit, Swarm-B drifts longitudinally from Swarm-A and C by $20^\circ$ in every year. All the three satellites complete one orbit in 90 min duration and hence constitute nearly 15 day and night passes each in 24 h. Drifting slowly in local time (LT) by 1 h in every 11 days, satellites witnesses all LT sectors in nearly 4 months duration.

The present study utilizes the vector magnetic field measurements in NEC (North East Centre) frame from fluxgate magnetometer onboard satellites Swarm-B and Swarm-C for a period of one and half year from January 2014 to June 2015. The data set used is Level 1b magnetic product: MAGX_LR_1B with 1 Hz sampling. As we are interested in investigating the EEJ characteristics, only satellite passes during geomagnetic quiet periods with $\sum Kp \leq 10$ in the LT range 0900-1500 h are considered here. In order to separate the magnetic field variations due to ionospheric currents, the main field model, Potsdam Magnetic Model of Earth (POMME) 6.1 [Maus et al., 2010], is subtracted from magnetic field recorded by Swarm. POMME accounts for the internal (core and crustal) field, its secular variation and acceleration. It also accounts for the magnetic field contributions from static magnetospheric currents and time varying ring currents. The residual fields so obtained contain magnetic field contributions from various ionospheric currents. In order to identify clear EEJ signatures from the residuals, the contribution of other ionospheric currents such as solar quiet (Sq) and also the ambient magnetic field not properly removed by POMME 6.1 has to be removed. This is achieved by fitting a polynomial of degree 5 on the latitudinal profile of the residual fields excluding $\pm 14^\circ$ dip latitudes. The fitted polynomial is then subtracted from the data to obtain
the magnetic field variations due to equatorial ionospheric currents. Recently, a geomagnetic field model based on Swarm data, Swarm Initial Field Model (SIFM) is released. Note that the ambient field model used in the present study is POMME 6.1, which is 2006 epoch based model and therefore may not appropriately estimate the ambient magnetic field in years 2014-2015. However, the disparity associated with longer wavelength can be removed by subtracting a polynomial of degree 5 and hence can be considered suitable for EEJ studies. As EEJ current flows in the east-west direction in a narrow latitudinal region near dip equator, the residual magnetic field variations in X component within ±20° dip latitudes is only considered in this study. A total of 1115 daytime satellite passes from over 70 days were obtained from the considered quiet period and are further analyzed to identify the EEJ signatures.

A typical EEJ signature monitored by polar LEO satellite marks a minima in the magnetic field value near the dip equator followed by two maxima on either sides [Cain and Sweeney, 1973; Jadhav et al., 2002; Lühr et al., 2004]. Figure 3.1 depicts a typical EEJ signature observed by the Swarm-B satellite. Although this typical signature of EEJ is presented in a few previous research papers, we are presenting it again as it would help the readers to know the parameters used in the present study. The two maxima denoted by S1 and S2 mark the edge of the EEJ and are hereafter called as the shoulders. These shoulders can be assumed to represent the signatures of the EEJ return currents in the magnetic field measurements. In Figure 3.1, the width and the amplitude of EEJ signature are marked as $S_1S_2$ and $H_1H_2$ respectively. For each satellite pass, the latitudinal profile of EEJ is identified by a completely automated program. As the EEJ signature varies from pass to pass, program also takes care of the alternatives in the EEJ signature. The criteria used for selecting the EEJ signature are adopted from Jadhav et al. [2002] (Section 2 in their paper) and are described as follows. (1) The Presence of a well defined minimum within ±2° of the dip equator, (2) minimum followed by two well defined maxima, one on ether sides. (3) If only one well defined maximum is present, the other is considered to be at a symmetrically opposite point with respect to the location of minimum. (4) The maxima identified only as a change in slope, are also considered as a shoulder.
Following this criteria, nearly 820 satellite passes for each satellite were identified with EEJ signatures and are investigated further.

### 3.3 Methodology

The magnetic signatures of EEJ with a depression near dip equator and the shoulders on both the flanks observed by the satellite is considered to result from the eastward current flowing near the dip equator and the westward return currents on either sides flowing below
the satellite altitude in the E-region. An empirical model based on the continuous 
distribution of current density for EEJ given by Onwumchili [1997] is fitted to the electrojet signatures 
identified in the X component of the magnetic field recorded by the satellite. According to 
the model, the current density at a point (x, z) is given by

$$ j = j_0 a^2 (a^2 + \alpha x^2) (b^2 + \beta x^2) \over (a^2 + x^2) (b^2 + z^2) $$

With the centre of the current system as the origin, x is the latitudinal distance positive in 
the northward direction, y is positive eastward and z is the vertical distance from the current 
layer positive downwards. Here, a and b are the scale lengths and \( \alpha \) and \( \beta \) are dimensionless 
constants controlling the distribution of currents along x and z respectively. \( j_0 \) is the peak 
current density at x=0 and z=0. The current intensity is computed by integrating the current 
density, j through the altitudinal extent of the entire current shell. The variation of the current 
intensity with latitude is given as

$$ J = J_0 {a^2 + \alpha x^2 \over a^2 + x^2} $$

Where, \( J_0 \) is the peak current intensity in A/km. The northward component of the magnetic 
field X (in nT) caused by this east-west thin current sheet is given as

$$ X = {K a \over 2 (sg. z) P^2} \left[ (\nu + \alpha \nu + 2a) (u + b)^2 + (\nu + \alpha \nu + 2a) (u + a)^2 \right] $$

where,

$$ P^2 = (u + b)^2 + (\nu + a)^2 $$

\( K = 0.2\pi J_0 \) is the magnetic constant in nT,

$$ u = |x|, \quad v = |z|, \quad sg. z = \text{sign of } z = \frac{z}{v} $$
Considering the current is flowing at 106 km altitude and b=0, the magnetic field variation resulting from this current sheet at satellite locations \((x, z)\) within ±20° latitudes is estimated using Eq. (3.3). Here the three unknown values \(\alpha\), \(a\) and \(K\) which defines the shape, width and amplitude respectively of the electrojet signature is estimated by an iterative method as described by Jadhav et al. [2002]. In the present study, in order to get a more realistic estimate of EEJ, the values of \(\alpha\) and \(a\) are estimated separately for both the hemispheres, unlike Jadhav et al. [2002], who assumed it to be symmetric. With values of \(\alpha\), \(a\) and \(K\) identified separately for northern and southern hemispheres that fits the best in the actual observations, EEJ can now be estimated at any altitude. The procedure is completely automated and is performed for all satellite passes those exhibit discernible EEJ signatures.

We firstly validate the reliability of the method adopted here in identifying the EEJ parameters. This is done by estimating X variations at Swarm-C using the measurements from overhead Swarm-B satellite pass, and comparing with the actual observations from Swarm-C satellite. EEJ X at Swarm-C is computed using the model values identified by fitting the EEJ model to the Swarm-B observations. Swarm-B and Swarm-C which are orbiting at two different altitudes came close in longitude during the month of April 2014. In this period there were several passes for which Swarm-B and C were almost over identical longitudes (< 5°) with nearly identical universal time (UT) (difference <~ 3 min). Here, we have restricted the data to this period during when Swarm-B and Swarm-C were passing one above the other. We obtained 43 such satellites passes for which comparison is made.

Figure 3.2, shows the comparison between the amplitudes of EEJ estimated (EEJ \(X_{Calculated}\)) and observed (EEJ \(X_{Observed}\)) at Swarm-C. The scatter shows a linear variation with the fitted linear regression line having slope 1. A good cross correlation (CC) of 0.96 is found between the EEJ amplitudes estimated and observed at Swarm-C satellite. The excellent match between the EEJ amplitudes obtained from the direct observations and the model validates the technique adopted here.
3.4 EEJ current parameters

The different EEJ parameters studied here are (1) the peak current density \( J_0 \), expressed by

\[
J_0 = \frac{K}{0.2\pi}
\]  
(3.4)

(2) the total eastward current \( I_+ \), is given by

\[
I_+ = I_{+NH} + I_{+SH}
\]  
(3.5)
Where,

\[ I_{+}^{(SH)} = \frac{a_{SH} J_0}{2} \left[ (-\alpha_{SH})^{1/2} + (1 + \alpha_{SH}) \tan^{-1} \left( \frac{1}{-\alpha_{SH}} \right)^{1/2} \right] \]  \hspace{1cm} (3.6)

\[ I_{+}^{(NH)} = \frac{a_{NH} J_0}{2} \left[ (-\alpha_{NH})^{1/2} + (1 + \alpha_{NH}) \tan^{-1} \left( \frac{1}{-\alpha_{NH}} \right)^{1/2} \right] \]  \hspace{1cm} (3.7)

(3) the full width \( W_{Current} \) of the current sheet,

\[ W_{Current} = W_{Current(SH)} + W_{Current(NH)} \]  \hspace{1cm} (3.8)

Where,

\[ W_{Current(SH)} = \frac{a_{SH}}{\sqrt{-a_{SH}}} \]  \hspace{1cm} (3.9)

\[ W_{Current(NH)} = \frac{a_{NH}}{\sqrt{-a_{NH}}} \]  \hspace{1cm} (3.10)

and finally, (4) the location of the electrojet axis with respect to the dip equator, i.e., the dip latitude at which EEJ peaks. Here, \( \alpha_{NH} \) and \( a_{NH} \) denotes \( \alpha \) and \( a \) in northern hemisphere and similarly \( \alpha_{SH} \) and \( a_{SH} \) denotes that in southern hemisphere.

These four current parameters are estimated for all the considered passes of Swarm-B and are compared with the amplitude and width of EEJ estimated at ground using the model values. The statistics is portrayed in Figure 3.3. Figure 3.3a shows the linear relationship between the peak current density \( (J_0) \) and EEJ amplitude estimated at ground \( (EEJ-X_{Ground}) \) with a good CC of 0.90. The total eastward current \( (I_+) \) also showed a clear linear dependence with the EEJ amplitude at ground (Figure 3.3b). Here, the scatter is found to be less with an increased correlation of 0.96 compared to that of \( J_0 \) thereby indicating that \( I_+ \) better decides the EEJ signatures at ground compared to \( J_0 \). Figure 3.3c shows the dependence of the location of the electrojet axis \( (x_0) \) on the EEJ amplitude at ground. It is observed that the EEJ strength is smaller for the current axis located away from the dip equator i.e., weak EEJ appear to
deviate from the dip equator. In Figure 3.3d, the relationship between peak current intensity and the width of EEJ at current height is shown. There are a few previous reports which show the dependence of both these parameters. Lühr et al. [2004] although could not find a good CC between these two parameters, reported that higher current densities have larger widths. On the other hand, Jadhav et al. [2002] concluded that smaller current densities can have larger width. However, our Figure 3.3d do not show any systematic dependence of the width of EEJ on peak current intensity. Analysis of larger data set may throw some light on this relationship.

In general, the EEJ parameters estimated using Swarm measurements are consistent with that obtained using Ørsted [Jadhav et al., 2002] and CHAMP [Lühr et al., 2004] satellite data.
3.5 Altitudinal variation of EEJ signatures

Figure 3.4: EEJ signature estimated (solid line) at (a) Swarm-B, (b) Swarm-C, (c) current height and (d) ground, using Swarm-B measurements, together with actual observations (dotted line) from Swarm-B and Swarm-C

Altitudinal variation of EEJ parameters such as amplitude and width are investigated using Swarm-B and Swarm-C observations along with the fitted empirical model of EEJ. The observations are shown in Figure 3.4. Here, the satellite passes of Swarm-B and Swarm-C are selected for the period when both were orbiting one above the other at nearly identical longitudes (< 3°). Arranged in the decreasing order of altitude, panels from top to bottom in
Figure 3.4 show EEJ estimated (solid line) at locations of (a) Swarm-B, (b) Swarm-C, (c) at 105 km altitude, and (d) at ground by fitting the electrojet model to Swarm-B observations. The actual observations (dashed line) from Swarm-B and Swarm-C are also shown together with the fitted profiles in Figures 3.4a and b. The figure exhibits the EEJ signatures and its characteristic features such as amplitude and width, at different altitude. With opposite sense of magnetic field directions above and below the current layer at 106 km altitude, EEJ shows inverted signatures at satellites and at locations below the current altitude. Unlike at satellites, the EEJ signature below the current layer shows a maximum near dip equator and two minima on either side, with the locations of minima marked as the shoulders of EEJ.

It is obvious to find that amplitude of EEJ depends on the distance from the current system and is clearly demonstrated Figure 3.4. EEJ shows maximum amplitude at location just below the current layer (Figure 3.4c). With increasing distance from the current sheet, it is observed that the EEJ amplitude decreases, i.e., EEJ signatures at higher distance from the current layer are found to have smaller amplitude. At ground, which is 106 km below the current layer, EEJ amplitude decreases by $\sim0.4$ times the peak value (Figure 3.4d). whereas at Swarm-B (Figure 3.4a) and Swarm-C (Figure 3.4b), which are nearly 4 times at higher distance compared to ground, the EEJ amplitude is found to reduce by $\sim0.8$ times its peak value.

The width of EEJ signature when compared to that of amplitude is found to have inverse dependence on the distance from the current layer. The width of the EEJ signature varies directly proportional to the distance from current layer, i.e., as the distance from the current layer increases the width of the signature also increases. EEJ signature is found to be most narrow near the current layer. At ground and satellites, the width of EEJ signature is found to increase by $\sim2^\circ$ and $\sim4^\circ$ respectively.

Figure 3.5 shows the average variation of the (a) width and (b) amplitude of EEJ at different altitudes estimated using observations from Swarm-B. The blue bars in Figures 3.5a and 3.5b shows the average values estimated by considering all the selected passes of Swarm-B and the red bars shows that for the satellite passes when Swarm-B was moving over Swarm-C.
at nearly identical longitudes (<∼3°). The average profile shows maximum amplitude and minimum width near current altitude, with amplitude (width) decreasing (increasing) with increasing distance from the current layer. The average values also show that, EEJ amplitude reduces by ∼0.4 and ∼0.8 times the peak value at ground and at satellites respectively. Similarly the width at ground increases by ∼2° and that at satellites increases by ∼4°. Hence, the amplitude and width of EEJ shows inverse relationship with altitude.

3.6 Characteristics of the forward and return currents of EEJ

Figure 3.6 shows the latitudinal profile of the current density derived from Eq.3.2 for a Swarm-B satellite pass. Here, the minima on either sides of the dip equator marked as B and B1
are termed as the "shoulders" of EEJ. These shoulders indicate the westward currents peak locations, which can be the return currents of EEJ. Here, we use the current density profile to investigate the characteristic features of the forward (eastward) and return (westward) currents of the electrojet. Here we would like to bring to the reader’s notice the average current density profile presented by Lühr et al. [2004] in their Figure 3. They have demonstrated that the return current peak at $\pm 5^\circ$ dip latitudes and reduces to zero level at almost $4^\circ$ off the shoulder locations in both the hemispheres. Considering this we have now assumed that the return currents are present up to a latitudinal distance $4^\circ$ beyond the shoulder locations in both the hemispheres. Therefore, in order to estimate the forward and return currents from the current density profile, we fitted a line (black dotted line) passing through the points $4^\circ$ beyond the肩部位置。
shoulder locations in both the hemispheres which is marked as zero level and then estimates the area enclosed by line and the current profile. In Figure 3.6, the area shaded in magenta and blue represents the total (both the hemispheres) forward and total return currents respectively.

![Figure 3.6](image)

**Figure 3.6:** Area shaded in magenta and blue represents the total (both the hemispheres) forward and total return currents respectively.

The forward and return currents are estimated for all the selected satellite passes of Swarm-B as described above and its statistical features are shown in Figure 3.7. Figure 3.7a shows the variation of the return currents with peak current density ($J_0$). The return currents are found to vary proportional to the peak current density, implying that stronger jet currents will cause larger return current flows. In Figure 3.7b, the variation of the return currents with forward current is shown. In general the return currents showed a linear variation with the forward current, but with a larger scatter, which may indicate that the return currents can be either small or large for a particular value of forward current. The slope of the fitted linear
regression line (red line) is found to be $0.25 \pm 0.02$ with 95% confidence levels (green lines). However, in general, the value of slope is found to vary between a maximum of 0.7 and a minimum of 0.1. This may indicate that the value of return currents can vary between 0.1 to 0.7 times that of forward currents.

### 3.7 Longitudinal variation

The longitudinal variation of the running average of different EEJ parameters is detailed in this section. Here, the average values of EEJ parameters are computed for a longitudinal window of $30^\circ$, stepping forward by $15^\circ$, with three-points smoothing. The error bars shown here represent the standard error.

Firstly we present the longitudinal variation of the average values of the amplitude and width of EEJ estimated at ground and is shown in Figure 3.8. Earlier studies have shown that EEJ undergoes a strong variability in its amplitude and shows peaks at different longitudes. As indicated by the previous researchers these peaks in EEJ could be due to the tidal winds in the E-region ionosphere [England et al., 2006; Fang et al., 2009; Kil et al., 2011]. Different studies [Alken and Maus, 2007; Jadhav et al., 2002; Lühr et al., 2008, 2012] have proved the strong influence of non-migrating tides on EEJ. Diurnal Eastward wave number 3 (DE-3) non-migrating tides are found to have a major effect on EEJ resulting in a 4 peak structure in the EEJ amplitude during major part of the year. Here using Swarm-B observations averaged over different seasons, we obtain the four peak structures in the EEJ amplitude (3.8a). The peaks observed at $0^\circ$, $100^\circ$, $200^\circ$ and $270^\circ$E are well in agreement with the earlier observations using Ørsted [Jadhav et al., 2002] and CHAMP [Lühr et al., 2008] and by the climatologically model of EEJ [Alken and Maus, 2007]. The width of EEJ (Figure 3.9b) estimated at ground also showed similar four peak structure with matching peaks.

Figure 3.9 shows the longitudinal variation of the latitudinal extent of forward and return currents of EEJ. The latitudinal extent of forward current is considered to be the locations of
the boundaries of forward current marked as B and B1 in the current density profile in Figure 3.6. The average variations in both northern and southern hemispheres are shown in Figures 3.9b and 3.9c respectively. Similarly, Figures 3.9a and 3.9d show the average location of the return current peaks (location of A and A1 in Figure 3.6) in both the hemispheres. The forward current band is observed to have a latitudinal width of ±4° and the return current is found to peak between ±4° to ±6° dip latitudes. These observations are in accordance with Lühr et al. [2004]. But, in contradiction to the observations of Ivers et al. [2003] and Lühr et al. [2004], here we found that, the latitudinal extent of the current band (including both forward and return currents) undergoes a longitudinal variation, showing a systematic four peak structure. The location of these peaks matches well with the longitudinal variation of EEJ amplitude and width presented above. The variations in northern and southern hemispheres are found to
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3.8 Local Time variation

Figure 3.10 depicts the LT variation of the mean EEJ amplitude (Figure 3.10a) and the mean deviation of EEJ axis from the dip equator (Figure 3.10b). Here the hourly mean values are calculated using the observations from satellite passes over all longitudes. Figure 3.10a shows a clear variation in EEJ amplitude, peaking near 1100 LT and reduced during both morning and afternoon hours. The EEJ current axis also showed a deviation from the dip equator with LT. It is observed that EEJ axis slightly shifts away from the dip equator during morning and afternoon hours. The deviation in EEJ axis is found to be anti-correlated with EEJ amplitude,
Figure 3.10: LT variation of (a) the amplitude of EEJ at ground and (b) the average deviation of EEJ axis from dip equator

i.e., when EEJ axis is away from the dip, the amplitude of EEJ at ground is found to be small. This shows the dependence of EEJ amplitude on the location of EEJ axis.

3.9 Discussion

Magnetic field measurements from LEO satellites form an excellent data base for the study of equatorial electrojet and its global variability. Polar LEO satellites in its transit from pole to pole monitor the EEJ currents flowing at the equatorial latitudes. The magnetic field measurements by these satellites are used to study various parameters of EEJ [Alken and Maus, 2007; Ivers et al., 2003; Jadhav et al., 2002; Lühr et al., 2004, 2008]. On a single day, the satellite monitors EEJ flowing over different longitudes around the globe at nearly identical LTs, and hence it is possible to study the longitudinal variability of the current system. Till date different methodologies have been used to derive an understanding about the features of the electojet currents using various polar LEO satellite missions. Through present chapter, we intent to revisit the problem using an independent data set from a recent multi-satellite mission Swarm.

In this study, we have fitted an empirical model of electrojet into the Swarm magnetic field observations to obtain the EEJ current parameters, such as peak current density, total forward
current, the width of the current system etc. Unlike the previous studies which fitted empirical model of EEJ assuming symmetry of the EEJ signature in both the hemispheres, present work takes into account the hemispheric asymmetry. Here, we obtain the model parameters separately for both hemispheres. The methodology adopted in finding the current parameters are validated by estimating X variations at Swarm-C using the nearly simultaneous measurements from overhead (longitudinal separation $< 5^\circ$) Swarm-B satellite pass, and comparing with the actual observations from Swarm-C satellite. The current parameters obtained are found to be well correlated with EEJ characteristics such as amplitude and width estimated at ground. This confirms that the current parameters estimated in the present study can be used in investigating the features of EEJ.

The EEJ signatures have inverted signatures above and below the ionospheric current height. Further for the first time we have shown here the height variation of the amplitude and width of EEJ (Figures 3.5). It is demonstrated that with increasing distance from the current layer, EEJ amplitudes decreases and width increases. The EEJ amplitude at ground is found to reduce to $\frac{3}{4}$ of its peak value near current height (105 km), whereas at satellite altitude (400 km), the EEJ amplitude is found to reduce to $\frac{1}{3}$ of the peak value. At the same time, the width increases by $2^\circ$ and $4^\circ$ at ground and satellites respectively.

The present study also brings out the interesting features of the forward and return currents of EEJ. The return currents estimated are found to vary proportional to the peak current density (Figure 3.7). It can be noted that the current sheet with larger peak current densities has stronger return currents. The return currents are also found to vary linearly with forward current, but with the scatter increasing with forward current values. The slope of the fitted linear regression is found to be $0.25 \pm 0.02$ with 95% confidence level. However, the ratio between the forward and return currents is in general, found to vary between 0.1–0.7.

Another important characteristic feature of the current investigated is its latitudinal extent (Figures 3.9b and 3.9c). The forward current band is found to have a latitudinal width of $\pm 4^\circ$ and also shows strong longitudinal variability with four peak structure. The average locations
of the return current peaks vary between $\pm 4^\circ$ to $\pm 6^\circ$ dip latitude, and are also found to have longitudinal variation similar to forward currents in both the hemispheres (Figures 3.9a and 3.9d). The width of the current band is observed to peak at $30^\circ$, $90^\circ$, $200^\circ$, and $280^\circ$E longitudes and is consistent with the longitudinal profile of EEJ current amplitudes estimated using previous LEO missions [Alken and Maus, 2007; Jadhav et al., 2002; Lühr et al., 2008].

The longitudinal variation of the amplitude and width of the EEJ signature also shows four peak structures (Figures 3.8a and 3.8b). The peaks are found to match well with that of variation of the latitudinal width of forward and return current. These variations as pointed out by the previous researchers are caused by strong influence of non migrating DE3 tidal mode on EEJ [Alken and Maus, 2007; Jadhav et al., 2002; Lühr et al., 2012].

Although polar LEO satellite cannot witness the day-to-day temporal variation of EEJ, the average variation of Electrojet features with LT can be investigated with the considered data set of one and half year during when satellite witnesses all LTs nearly 5 times. The amplitude of EEJ estimated at ground showed a clear LT dependence, with amplitude peaking at $\sim 11:00$ LT (Figure 3.10a). It is observed that during noon hours, the EEJ axis lies close to the dip equator, whereas during morning and evening hours EEJ axis deviates from the dip equator. So it can be inferred that the weak EEJ appear to deviate slightly from the dip equator. These observations are also in accordance with the previous observations [Farmbitakoye and Mayaud, 1976; Jadhav et al., 2002].

The characteristic features of EEJ parameters discussed in the present chapter are broadly in accordance with those obtained from previous LEO missions. With this background, we aim to carry out further investigations analyzing the different current systems associated with EEJ (such as meridional currents, thick shell of EEJ current system, etc.) in detail.
3.10 Summary

In this chapter the characteristic features of electrojet current are studied using observations from Swarm mission satellites. We derived various current parameters such as peak current density, total forward current and the width of the current system by fitting an empirical model of EEJ to Swarm observations. The magnetic field signatures of EEJ at different altitudes are then estimated using model parameters. The main results derived from this study are summarized below.

1. The electrojet signatures observed at Swarm-C are found to be consistent with that predicted using Swarm-B measurements when both the satellites were moving simultaneously over identical longitudes, with an altitudinal separation of 50 km.

2. The amplitude and width of EEJ signatures are found to vary with altitude, i.e., a maximum amplitude and minimum width is observed for the EEJ signature estimated close to the current layer. For EEJ signatures estimated away from the current layer, the amplitude and width showed decreasing and increasing values respectively.

3. The total forward and return currents are estimated and the fitted linear regression line suggests that the ratio between total return to forward current is $0.25 \pm 0.02$ with 9% confidence level.

4. The amplitude and width of EEJ estimated at ground showed strong longitudinal variation exhibiting a four peak structure.

5. The latitudinal extents of the forward and return currents are also found to have longitudinal variation similar to that of the amplitude and width of EEJ.

6. The EEJ amplitude at ground showed a clear LT dependence, with a maximum at $\sim 11:00$ LT.

7. For stronger EEJs, the electrojet axis are found to lie close to the dip equator.
Chapter 4

Storm time magnetic field variations observed by Swarm

4.1 Introduction

In the previous chapter, we have studied the quiet time ionospheric current systems using magnetic measurements obtained from Swarm satellite mission. In this chapter, we attempt to study the geomagnetic storm time magnetic field variations, and associated current systems mainly flowing in the magnetosphere.

Geomagnetic storms are produced by enhanced solar wind-magnetosphere energy coupling through the mechanism of magnetic reconnection [Dungey, 1961; Gonzalez et al., 1994; Sugiuura and Poros, 1971], which cause large disturbances in the Earth’s environment. A typical geomagnetic storm signature is characterized by a depression in the horizontal (H) component of the geomagnetic field at low to middle latitudes. This depression is mainly caused by the ring current encircling the Earth in a westward direction in the equatorial plane and can be monitored by the Dst or SymH index Daglis et al. [1999]; KAMIDE et al. [1998]; Wang et al. [2003]. The Dst index has time sampling interval of one hour, while SymH index is...
sampled at each minute. These indices are computed using the magnetic field measurements at longitudinally separated low latitude ground stations.

The ring current is not the only contributor to the magnetic field perturbations during geomagnetic storms. The field aligned and ionospheric closure currents produce an approximately 20% positive offset in the estimated Dst index for the case of closure through an eastward electrojet [Siscoe and Crooker, 1974]. The weakening of the background magnetic field by the ring current self-field results in 7%-34% larger currents [Carovillano and Siscoe, 1973]. The effects of the substorm current wedge can leak into the Dst index, producing positive contributions of up to a few tens of nT [Friedrich et al., 1999]. A 25%-30% negative contribution to Dst is possible from enhanced magnetotail currents during magnetic storms and substorms [McPherron, 1997; Turner et al., 2000]. A review of these contributing current systems is presented by Greenspan and Hamilton [2000]. Thus there are various currents other than symmetric ring currents (SRC), such as partial ring current (PRC), region 1 (R1) and region 2 (R2) field aligned currents (FACs), magnetopause currents, magnetotail currents etc.

So far, in the literature these current systems are studied using ground based and magnetospheric satellite-based magnetic field measurements, in addition to various other types of datasets. Attempts have been made by previous researchers Balan et al. [2011]; Lühr and Liu [2006]; Manoj et al. [2013]; Sivla and Okeke [2011] in investigating magnetospheric process such as geomagnetic storm and its effect on thermosphere/ionosphere system using polar LEO observations. These studies are mainly based on the electron density measurements and wind drag information derived from LEO observations. However magnetic field measurements from polar LEO satellites have been less explored in studying these magnetospheric phenomena. Recently, Dunlop et al. [2015] found matching signatures of FACs simultaneously near the ionosphere at Swarm orbit (∼500 km) and in the magnetosphere (Cluster satellites) at medium (∼2.5 $R_E$ altitude) orbits using a particular Swarm and Cluster conjunction. They reported a clear evidence of both small-scale and large-scale FACs and clear matching structure of the large-scale currents at both Cluster and Swarm. In this chapter we present some
new results obtained from our analysis performed for three geomagnetic storms happened
after the launch of Swarm mission.

4.2 Data set and method of analysis

Present Chapter analyses magnetic field measurements from Swarm -A satellite during three
geomagnetic storms. Being a polar orbiting mission, Swarm satellites cover entire latitudinal
range in about 45 minutes during its half traverse in the orbit. Here, we look for the signature
or the contribution of the ring current and other disturbed time magnetospheric currents in
the Swarm magnetic field measurements. For simplicity, we have used the total magnetic
field data measurements from Swarm -A satellite. The POMME 6.1 model of geomagnetic
field is subtracted from the satellite observations. Through this geomagnetic field model,
we have removed only main and crustal field component and did not remove any external
contribution or induced current component. In order to remove quiet time ionospheric current
contribution such as EEJ, Sq etc from the Swarm magnetic field measurements, we selected
nearby geomagnetic quiet day ($\sum Kp<10$), and subtracted the quiet time passes having similar
longitude ($\pm 1{\degree}$) and nearly same local time (LT) ($\pm 0.5$ hr). This ensures the removal of
quiet time currents. The residual fields obtained this way are analyzed further. The residual
field variations within $\pm 40{\degree}$ geomagnetic latitude along each satellite pass is considered here.
Since the satellite traverses within $\pm 40{\degree}$ in just 20 minutes, while storm time variations take
place on the time scale of days, we have plotted the residual fields along different satellite
passes comprising alternate day and night time passes, with universal time (UT).
4.3 Results

4.3.1 Geomagnetic storm on 17-18 March 2015

The most intense geomagnetic storm of solar cycle 24 till date, took place during 17-18 March 2015. The SymH index reached below $\sim$-200 nT. The Swarm-A satellite traversed in the early morning ($\sim$7 LT) and evening local times ($\sim$19 LT) during the period of this storm. The top panel of Figure 4.1 shows the residual total magnetic field measurements at each satellite pass during 17-18 March 2015. The latitudinal profiles between $\pm 40^\circ$ are shown here. The red and black colour indicate near dawn and dusk satellite passes respectively. The residual magnetic field (actual observation - internal geomagnetic field) on 10 March 2015, which was a geomagnetic quiet day with $\sum Kp$=8 are also shown in the same panel with blue colour. The quiet time passes in nearby longitude (within $\pm 10^\circ$) and local time are selected. The difference between disturbed and quiet time satellite magnetic fields are shown in the middle panel, along with the SymH (magenta) and AsyH (cyan) indices. Note that the scales for the satellite results and SymH are shown on the left side Y-axis, while that for AsyH index is shown on the right side. The bottom panel shows the solar wind pressure (green) and the $z$ component of the interplanetary magnetic field (IMF) (black), with the scales for the the interplanetary magnetic field shown on left and that of solar wind pressure on the right side. The vertical dashed lines indicate the times of equatorial crossings of the satellite orbits.

This storm comprised of storm sudden commencement (SSC), initial, main and recovery phases. The sudden impulse of $\sim$50 nT magnitude occurred at $\sim$5 UT on 17 March. The SymH index dropped to $\sim$100 nT at $\sim$9 UT and then started recovering, but soon later again started deceasing. SymH reached $\sim$200 nT at $\sim$23 UT, thus the main phase of the storm showed two-step decrease with total main phase interval of $\sim$17 hr. Then the recovery took place during almost entire day on 18th March. Interestingly, the satellite data shows the trend similar to SymH, including the double step of the main phase. The difference between disturbed and quiet times can be considered as the contribution purely due to storm
Figure 4.1: Geomagnetic storm during 17-18 March, 2015. Top panel: Residual total magnetic field during daytime (red) and night time (black). Blue curves show the residual fields during quiet day, 10 March 2015. Middle panel: Difference between disturbed and quiet time passes, along with SymH (magenta) and AsyH (cyan) indices. Bottom panel: IMF-Bz (black) and solar wind pressure (green).

Time dynamics, which is minimum before the SSC (Middle panel in Figure 4.1). Moreover, one can notice that there is discernible difference between the amplitudes of the magnetic field variations during early morning (near dawn) and night (near dusk) passes, with stronger amplitudes during night time passes. The difference between day and night passes becomes large especially during the main phase of the storm. Interestingly, the AsyH index also shows enhanced values during that time and hence the satellite observations are capable of recording the asymmetry between near dawn and dusk hours. Generally, the AsyH index appears to be high during enhanced solar wind dynamic pressure with southward IMF.
Figure 4.2: Geomagnetic storm on 17-18 March 2015: Comparison between the satellite observations (solid) and model computations (dashed) during daytime (red) and nighttime (black) at the equatorial crossings. Vertical dotted lines show the times of equatorial crossings.

The magnetic field recordings at the satellite contain the contributions due to SRC as well as other current systems such as PRC, magnetopause Chapman-Ferraro currents, magneto-tail currents, FACs, currents due to penetrated electric fields etc. Since satellite observes the net effect of superimposed currents, it is not possible to separate the contributions due to various currents. Nevertheless, we compared these observations with the output from an empirical model by Tsyganenko [Tsyganenko and Sitnov, 2007] that provides the contribution from above mentioned current systems. Figure 4.2 shows the comparison between satellite observations (solid) and model results (dashed). For the purpose of comparison, we have considered the results only at the equatorial crossings. Day and night values are shown by red and black curves respectively. The total field component is computed by taking the square root of the addition of the squares of three components, which are positive values. Whereas the difference (disturbed day - quiet day) give negative values. Therefore, for the better comparison between observations and model, we have shown the negative values of the total field.
CHAPTER 4. *Storm time magnetic field variations*

Positive variation of about 70 nT is observed at the \( \sim 5 \) UT, which coincides with the time of SSC. Also its amplitude matches well with that of SSC noted by the SymH index. But this was not evident in the model predictions. It seems that the model underestimates the Chapman-Ferraro magnetopause currents. Interestingly, the model predictions during nighttimes (near dusk) are stronger than that during daytimes (near dawn), and hence the model predictions match with the observations. The finer variations in the main as well as recovery phases during nighttimes are duplicated by the model predictions excellently. Daytime observations also show matching trends with the model predictions, except the daytime satellite pass at \( \sim 15 \) UT, which shows variation of very small amplitude. This shows that, in general the currents such as ring current, PRC, magnetotail currents, FACs are capable to produce the observed day-night asymmetry and also the finer variations. The minimum amplitude attained by nighttime satellite passes is \( \sim -300 \) nT, while that by daytime satellite pass is \( \sim -200 \) nT. The SymH index shows the minimum variation of \( \sim -200 \) nT, and thus the amplitude of the symmetric part of the azimuthally distributed contribution obtained from satellite measurements matches very well with that obtained by ground-based measurements (i.e. SymH index).

4.3.2 Geomagnetic storm on 25 December 2013

A weak geomagnetic storm took place on 25 December 2013 with \(-50 \text{ nT} < \text{SymH} < -20 \text{ nT}\), preceded by SSC at 5 UT. The main phase duration is \( \sim 8 \) hr. The traverses of Swarm-A satellite covered near noon and mid-night LTs. The satellite observations (residual fields) match very well with the time profile of the SymH index (middle panel of Figure 4.3). The satellite passes during 5-6 UT show positive variations, which coincide with the SSC and initial phase. The day-night difference is stronger between 12-19 UT covering the later part of main phase and early recovery phase, which coincides with the enhanced values of AsyH index. Unlike previous geomagnetic storm of 17-18 March 2015, dynamic pressure of solar wind was not significantly high, but the IMF Bz was southward.
Figure 4.3: Geomagnetic storm on December 25, 2013. Format is same as Figure 4.1. Quiet day on 24 December 2013 with $\sum Kp = 3$ is used.

The comparison of satellite observations with model estimates shows very good match (Figure 4.4). Observations show positive increase between 5-6 UT, coinciding with the positive variation in SymH index. However this increase is not evident in the model predictions. The magnetic field drops to $\sim 70$ nT for the night time pass and to $\sim 45$ nT for the daytime pass. The minimum SymH goes to $\sim 45$ nT and hence symmetric part observed at day and night is consistent with the SymH index, which is computed using ground based observations. Model estimates also show simultaneous decrease. But, model values are stronger for day time passes than night time passes. So, the model predictions are not consistent with the observations.
Geomagnetic storm of moderate category took place on 8th December 2013 with -100 < SymH < -50 nT. During this period, the Swarm-A satellite was passing through near noon-midnight meridian. This storm started without clear SSC, rather with some disturbed signature (Figure 4.5). There was sudden increase in the solar wind pressure but accompanied with southward turning of the IMF Bz, which resulted in complex geomagnetic response. Since this storm shows two steps within the main phase and hence it is similar to the first one to some extent. The satellite residual fields also reveal similar trend with two distinct main phase lobes (middle panel of Figure 4.5). The comparison between satellite observations and model shows a match to fairly good extent (Figure 4.6). The minimum values at ∼5 UT and ∼8-9 UT are observed in observation as well as in the model estimates, which correspond to the two minima recorded by the SymH index. The amplitude of maximum variation obtained from satellite and model matches well with that obtained from SymH index (∼-60 nT). It can be noticed that the day-night difference is not systematic through the entire storm profile. Satellite observations show night time values are stronger than daytime in general, but at ∼7 UT and beyond 14 UT the trend reverses. Model estimates show systematically stronger values during day time. Thus model predictions obtained here are similar to those noticed in the
previous case of the weak storm. In the late recovery phase (beyond 16 UT), the asymmetry in
day and night satellite passes becomes stronger, which is also reflected in the AsyH index, but
not in the model predictions. Thus, it is clear that model estimates considering magnetopause,
ring, PRC, magnetotail and R1, R2 currents are not able to produce the observed asymmetry.

## 4.4 Discussion and Summary

In this chapter, we have investigated the magnetic field variations recorded by Swam satellite
during geomagnetic storms. The results of three storm events of solar cycle 24 representing
major, moderate and weak storms are presented here. The most intense storm of current solar
The internal contributions in the total magnetic field recordings at Swarm satellite are removed by subtracting POMME 6.1 geomagnetic field estimates. Note that only internal and crustal component of POMME model is considered here. Therefore, the remaining magnetic field variations during geomagnetic storms contain the contribution due to quiet time ionospheric current and various disturbed time magnetospheric and ionospheric currents, and their induced parts. The quiet time ionospheric contribution is removed by subtracting the residual fields at nearby longitude (within ±10°) and local time (within 0.5 hr) obtained on a quiet day. This process also ensures the removal of any local anomalies present, which are not properly considered by the POMME model. The remaining magnetic field variations, which are called as residual fields and considered to have contribution only due to disturbed magnetospheric-ionospheric system are analyzed further.

The polar LEO satellite spans the latitudinal range between +40 and -40° in just 20 minutes, while storm time variations take place on the time scale of days. Therefore, we displayed the latitudinal profiles of residual fields along different satellite passes with UT, comprising alternate day and night time passes. It showed very similar time variation as that of SymH index during all three storms. This demonstrates that the LEO satellite-based magnetic field variations...
measurements are consistent with the ground-based ones.

Further, we compared the satellite observations with the model estimates predicted using Tsyganenko model. The amplitude of maximum variation during storm-time obtained from satellite and model matches well with that obtained from SymH index, during all three storms.

Also, the day-night asymmetry in the amplitude of the variation is observed during all the storms, which found to be coincident with large values of AsyH index. So, asymmetry recorded by the LEO satellite is consistent with ground-based estimates. However, this asymmetry is not clearly evident in the model predictions, especially during moderate and weak storms. The model is found to reproduce the observed asymmetry better during major storm. Moreover, the satellite observations clearly show stronger amplitudes during night than that during daytime. But the model estimates for weak and moderate storms exhibit stronger variations during daytimes, and hence are not consistent with the observations. During major storm, the match between model and observations is very good, as far as day-night difference and shorter period variations are concern. Although the amplitudes based on observations and model differ. This may suggest that the model estimates considering magnetopause, ring, PRC, magnetotail, R1, R2 currents are not able to produce the observed asymmetry during moderate and weak storms, while during major storms, model predictions are better, although model underestimates the variations.
Chapter 5

Low-latitude Pi2 oscillations observed by CHAMP satellite

5.1 Introduction

The impulsive damped geomagnetic field oscillations in the frequency range 6.6-25 mHz are termed as Pi2 pulsations. These short-lived oscillations are believed to be excited by sources in the night side magnetosphere. Substorms are identified as one of the common energy sources for Pi2s observed in different regions. During substorm, Pi2s are manifested at ground right from auroral to equatorial latitudes, with different longitudinal extent ranging from midnight sector at high latitudes to several hours of local time including daytime at low latitudes [Keiling and Takahashi, 2011]. Review articles by Olson [1999], Yumoto et al. [2001], and Keiling and Takahashi [2011] discuss different source mechanisms responsible for the generation of Pi2s observed in different latitudes. It is presently understood that high to middle latitude Pi2s are associated with the field aligned currents which are launched in the plasma sheet in association with the disruption of the cross-tail current during substorm onset [Nishimura et al., 2012]. The transverse portion of the disturbances produced at the time
of field dipolarization travels via Alfvén modes into the polar ionosphere which in turn is manifested as Pi2 oscillations at these latitudes. On the other hand, the compressional portion of the MHD wave travels earthward across the magnetic field and couples energy to different wave modes [Olson, 1999]. In the inner magnetosphere, these compressional waves excite cavity-like oscillations and are considered as a possible mechanism for low-latitude Pi2s in the night side.

During substorm onset and expansion phase, Pi2s are often observed in low latitudes over a wide range of longitude and are therefore considered as useful substorm indicators [Sakurai and Saito, 1976; Yumoto, 1986]. Daytime Pi2s are found to be a common phenomenon at low [Sutcliffe and Yumoto, 1989, 1991] and equatorial ground stations [Sastry et al., 1983; Stuart and Barsczus, 1980; Yanagihara and Shimizu, 1966]. In a statistical study by Nosé et al. [2006], they have shown that in low latitudes, large amplitude nighttime Pi2s are often accompanied by daytime ones with similar waveforms. Pi2s observed in day and night ground stations were observed to have nearly identical period and similar phase. However, amplitudes of these oscillations were higher at auroral breakup meridian and decreased with the longitudinal separation from the breakup region. Daytime Pi2s identified near the dip equator are reported to have enhanced amplitudes in comparison to low-latitude ones. Shinohara et al. [1997] attributed it to the instantaneous penetration of electric field variations from the polar ionosphere to dayside equatorial ionosphere, which amplifies the equatorial currents in the enhanced ionospheric conductivity regions.

Using satellite observations, it is possible to observe Pi2 pulsations at different radial distances from the Earth’s surface. In a statistical study of Pi2 properties in the inner magnetosphere (L < 4) using Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (CCE) satellite and ground observations, Takahashi et al. [1995] found that Pi2 oscillations are dominated by compressional and radial components at satellite and are found to have high coherence with H component at low-latitude midnight ground station Kakioka when the satellite was on the nightside. But no convincing evidence of Pi2s was present in CCE
CHAPTER 5. Pi2 at LEO satellite

observations when the satellite was in the dayside. Nighttime Pi2s are also detected in the topside ionosphere using various LEO satellites. One of the earliest of the nighttime Pi2 reports at ionospheric altitude is by Takahashi et al. [1999] using UARS observations. The oscillations are found to be identical and in phase with night side ground station. Later with the observations using Ørsted [Han et al., 2004] and CHAMP [Sutcliffe and Lühr, 2003, 2010] similar Pi2 signatures were identified at ground and satellite, which confirms the existence of Pi2 signatures in the topside ionosphere during nighttime.

Simultaneous occurrence of low-latitude Pi2 oscillations in the night and terminator sides is investigated by Kim et al. [2010] using electric and magnetic field measurements from Time History of Events and Macroscale Interactions during Substorms (THEMIS)-E and THEMIS-D satellites located in dawn and dusk sectors, respectively. In this case study, highly coherent oscillations were observed in the poloidal components at satellite in the dawn sector and H at midnight ground station, but at the same time there was no evidence of Pi2s in the dusk sector. The authors suggest that the plasmaspheric resonance energy, which is thought as a possible cause for Pi2s observed in the inner magnetosphere, escapes azimuthally and its longitudinal attenuation is larger on the duskside than on the dawnside. Morning time Pi2s are reported in ETS-VI satellite (L = 6.3) observations in the compressional and radial components which showed identical period and waveform with northsouth component X at ground [Nosé et al., 2003]. The observations are in agreement with cavity oscillations.

Although low-latitude Pi2s are identified at ground in different local time (LT) sectors, its daytime existence in space remains an open debate. Han et al. [2004] for the first time reported the identification of low-latitude daytime Pi2s in the topside ionosphere using Ørsted data. They reported 2 day events which showed similar oscillations in satellite compressional and ground H components, having opposite phase and smaller amplitudes at satellite. The authors suggest the source mechanism for the daytime Pi2 to be the currents in the equatorial and low-latitude ionosphere generated by the penetrated electric field impressed in the polar ionosphere during substorm. But other than these 2 day events presented, Han et al. [2004]
could not identify similar observations of daytime Pi2s. Later Sutcliffe and Lühr [2010] using CHAMP data reported that no Pi2 signatures can be detected in topside ionosphere during daytime. They supported their observation with the help of a model adopted from Kikuchi and Araki [1979]. According to the model, the electric field imprinted in the polar ionosphere is distributed globally in the Earth-ionosphere wave guide, where the ionospheric electric fields will be mapped upward along geomagnetic field lines, while the magnetic field due to the ionospheric current is confined between the ionosphere and Earth. Hence, toroidal currents flowing on the dayside between ionosphere and ground generate magnetic fields that are confined to the Earth-ionosphere cavity. As a consequence, no Pi2-related magnetic signals can be detected in the topside ionosphere.

Thus, there are two contradicting results about daytime Pi2s above the ionosphere using Ørsted and CHAMP. In this study, we focus on the observational aspect of low-latitude daytime Pi2 oscillations at topside ionosphere using CHAMP along with underneath ground and examine whether daytime Pi2s identified at ground are manifested simultaneously in the topside ionosphere or not.

The chapter is organized as follows. In section 5.2 we discuss the method of Pi2 detection and data set used. Section 5.3 presents typical examples of Pi2s of different frequencies observed during daytime and nighttime separately. Section 5.4 discusses the non-Pi2 contribution at satellite. Sections 5.5 and 5.6 include discussion and summary, respectively.

### 5.2 Methodology and Data

First, the identification of Pi2 events is done using high-resolution and high-precision data from induction coil magnetometer located at ground station, Shillong (SHL; 25.92°N, 91.88°E), India. The data are sampled at 64 Hz with an accuracy of 0.2 pT. Preliminary identification of Pi2 events is done by the visual inspection of the dynamic spectrum and the high-pass-filtered (>2 mHz) time series of H component at SHL. Spectral plots and the corresponding
Figure 5.1: Criteria used for the identification of substorm-associated Pi2 at Shillong (SHL) during nighttime, occurred on 10 February 2007. (a) AL index, (b) Wp index, (c) dynamic spectrum for SHL H, and (d) time series of SHL H component (high pass filtered $>2$ mHz). Pi2 onset at 15:48 UT is marked by the vertical red dashed line.

time series which showed a sudden impulse in the frequency range 6.6-25 mHz are marked as possible Pi2 oscillations. To confirm Pi2 and its association with substorm activity, we further looked into the AL and Wp indices. Wp (Wave and planetary) is a substorm index developed by Nosé et al. [2012] which reflects the Pi2 power at low latitude. It is considered as a useful indicator of substorm onset. AL and Wp indices together provide the evidence of substorm activity and associated Pi2 oscillations at low latitude. Wp index being sensitive to the onset of even smaller substorms in comparison to AL [Nosé et al., 2009], we have chosen $Wp\ (\geq 0.5)$ as the primary criterion for selecting Pi2 events. AL and Wp values are obtained from World Data Center (WDC), Kyoto, web page. Figure 5.1 describes the identification of Pi2 event associated with substorm activity. The event presented occurred on 10 February
2007 with Pi2 onset at 15:48 UT. During this event, SHL was in the night sector with LT \( \sim 22 \) h. Figures 5.1a and b show the AL and Wp indices respectively for 10 h interval containing Pi2 onset. A sudden depression in AL index by \( \sim -300 \) nT and a simultaneous increase in Wp index (\( \sim 0.8 \) nT) mark the onset of substorm which coincides with Pi2 onset. Figures 5.1c and d show the dynamic spectra and time series respectively of the high pass filtered H oscillation at SHL, where a sudden burst having frequency \( \sim 10 \) mHz is evident immediately after 15:48 UT. The red dotted line, which marks the onset of Pi2, shows the simultaneous decrease (increase) in AL (Wp), confirming the presence of substorm associated Pi2s. Other than this event, two more distinct Pi2 impulses at around 19 and 20 UT were clearly seen in the dynamic spectra as well as in the time series. These events are accompanied with simultaneous increase (decrease) in Wp (AL) indices, though Wp is slightly less than 0.5.

Figure 5.2 describes a typical daytime (near noon) Pi2 event identified at SHL on 23 August 2009. The dynamic spectrum and time series of filtered H component at SHL (Figures 5.2c and 5.2d) showed an impulsive oscillation with frequency \( \sim 14 \) mHz at 05:14 UT. SHL being in the local daytime, these oscillations are compared with the H variations at a low-latitude station, San Juan (SJG) located near midnight (LT \( \sim 1 \) h). The dynamic spectrum (Figure 5.2e) and high pass filtered H oscillations at SJG (Figure 5.2f) also showed clear Pi2 impulse with onset exactly matching with that at SHL. The onset is marked with red dotted line. The Pi2 impulse observed in SHL as well as SJG H components at 05:14 UT accompanied by a depression in AL by \( \sim -400 \) nT and an increase in Wp by \( \sim 1.5 \) nT (Figures 5.2a and 5.2b) further confirm the existence of substorm-associated Pi2 oscillations. Here one can also note the presence of a Pi2 impulse at \( \sim 04:48 \) UT in the dynamic spectra (Figures 5.2c and 5.2e) and time series (Figures 5.2d and 5.2f) of both day and night ground stations with Wp nearing 0.5. Other than these Pi2 oscillations, there are additional undulations present at both ground stations (Figures 5.2d and 5.2f), casting their signatures in the dynamic spectra as well (Figures 5.2c and 5.2e). The amplitudes of these undulations are higher at dayside station.

Once Pi2s are detected in the ICM data from Shillong observatory as described above, we
Figure 5.2: Criteria used for identifying substorm-associated Pi2 at SHL during daytime, on 23 August 2009. (a-d) Same format as in Figure 1. (e) Dynamic spectrum and (f) the time series of H component at midnight station, San Juan (SJG) (high pass filtered >2 mHz). Vertical red dashed line marks Pi2 onset at 05:14 UT.

Further look for the location of CHAMP satellite. The present study is limited to the events, for which (1) CHAMP passes were between ±60° magnetic latitude; (2) data from underneath low-latitude ground station within ~ ±30° of CHAMP longitude are available for the comparison of satellite observations with ground; (3) local time (LT) at CHAMP is either day (07:00-17:00) or night (20:00-04:00); (4) the presence of Pi2 at dayside ground station is ensured before examining daytime Pi2 events at CHAMP; and (5) coherence between satellite and ground oscillations is greater than 0.5 at Pi2 frequency. With the first four conditions we could select a total of 51 Pi2 events with 27 nighttime and 24 daytime events. Consideration of the fifth criteria reduced the number of daytime Pi2 events identified at CHAMP to 12,
while the number of nighttime events remained unchanged.

The vector magnetic field measurements in NEC (North East Centre) coordinate with 1 s sampling interval from fluxgate magnetometer on board CHAMP are used for the study. CHAMP (Challenging Mini satellite Payload) was launched in July 2000 into a near-circular polar orbit with an initial inclination of \( \sim 87^\circ \) and an altitude of \( \sim 454 \) km. The orbital period of CHAMP is around 92 min and therefore makes around 15 day and night passes in 24 h. First, we calculate the residual field at CHAMP by subtracting the main field model POMME 3.1 (Potsdam Magnetic Model of Earth) [Maus and Lühr, 2005] from the observed data. The residual field obtained is then rotated into field-aligned coordinates to get the variations in terms of transverse and longitudinal components. To achieve this, we have adopted the approach discussed by Rajaram et al. [1992]. The field-aligned coordinates are defined by the unit vectors, \( \hat{b}, \hat{\phi} = \hat{b} \times \hat{r}/|\hat{b} \times \hat{r}| \) and \( \hat{n} = \hat{\phi} \times \hat{b} \) where, \( \hat{b} = \vec{B}_0/|\vec{B}| \) is the unit vector along the direction of the background magnetic field \( \vec{B}_0 \) at CHAMP. The unit vector \( \hat{r} \) is along the radius vector to the satellite location. The magnetic field perturbations along the unit vectors \( \hat{b}, \hat{\phi}, \) and \( \hat{n} \) give three orthogonal magnetic field components, namely, compressional (positive northward), toroidal (perpendicular to the field line and azimuthally eastward), and poloidal (perpendicular to the field line and radially inward), respectively. In this study we restrict our analysis to the compressional component observed by the satellite. Horizontal (H) component of the geomagnetic field from low-latitude ground observatories listed in Table 5.1 is used in this study. Ground data used from Indian longitudinal sector are induction coil data with 64 Hz sampling recorded at Shillong (SHL) and that from other sectors are fluxgate magnetometer data with 1 Hz sampling. The induction coil data are down sampled to 1 Hz to keep the uniformity in the data set.
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Table 5.1: List of Ground Stations Used

<table>
<thead>
<tr>
<th>Ground Stations</th>
<th>Station Code</th>
<th>Geographic</th>
<th></th>
<th>Geomagnetic</th>
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<td></td>
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<td>Longitude (deg)</td>
<td>Latitude (deg)</td>
<td>Longitude (deg)</td>
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<td>91.88E</td>
<td>16.14N</td>
<td>165.11E</td>
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<td>140.19E</td>
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<td>150.77W</td>
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<td>TFS</td>
<td>42.08N</td>
<td>44.70E</td>
<td>36.81N</td>
<td>123.99E</td>
</tr>
<tr>
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<td>SJG</td>
<td>18.11N</td>
<td>66.15W</td>
<td>27.92N</td>
<td>6.53E</td>
</tr>
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<td>89.63W</td>
<td>40.05N</td>
<td>20.21W</td>
</tr>
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<td>158.0W</td>
<td>21.58N</td>
<td>89.71W</td>
</tr>
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<td>07.95S</td>
<td>14.38W</td>
<td>02.52S</td>
<td>57.06E</td>
</tr>
</tbody>
</table>

5.3 Observations

Based on the dominant frequency of Pi2 oscillation (defined as characteristic frequency), we classify the identified Pi2s into three different frequency zones viz., 6-10 mHz, 10-15 mHz, and 15-25 mHz. Pi2s observed during nighttime and daytime are presented separately. The LT range of nighttime and daytime has been selected to exclude the terminators, as Pi2 events during terminators can have different properties. Power spectral densities (PSDs) are estimated for satellite compressional and ground H components (band passed between 2 and 25 mHz) using maximum entropy method. PSDs are normalized with respect to the variance of the H oscillations at nightside ground station. A lower cutoff frequency of 2 mHz of the band-pass filter which is well before the lower limit of Pi2 range is used to avoid any modulation of the frequencies of interest.
Figure 5.3: Nighttime Pi2 oscillations (frequency between 6 and 10 mHz) observed on 17 May 2007 when CHAMP and SHL were in nightside. (a) Locations of ground station SHL and CHAMP satellite orbit, with vertical dotted line representing midnight meridian. (b) PSD of CHAMP compressional (Sat B //) and SHL H components. The 99% confidence levels are also shown. (c) Time series of compressional and H components filtered in the frequency range 6.6-25 mHz. Magnetic latitude and the magnetic local time (MLT) values of CHAMP are given at the top and bottom of Figure 5.3c, respectively. The scale for the satellite component is shown on the left side and that for ground H is shown on the right side for both Figures 5.3b and 5.3c.
5.3.1 Nighttime Pi2s

Pi2 Frequency Between 6 and 10 mHz

Figure 5.3 describes a nighttime Pi2 event having characteristic frequency between 6 and 10 mHz, occurred on 17 May 2007 with Pi2 onset shortly after 21:45 UT. The event lasted for \(~15\) min between 21:45 and 22:00 UT. During the event CHAMP and SHL were in the post-midnight sector at \(~2\) h and \(4\) h LT, respectively. In this time interval CHAMP was mostly in the Northern Hemisphere moving from approximately 9°S to 51°N. The locations of CHAMP orbit and ground station SHL are shown in Figure 5.3a. The midnight meridian is marked with vertical dotted line. Figure 5.3b shows the PSD for CHAMP compressional (blue solid line) and SHL H (black dotted line) components. Identical Pi2 frequency peaks at 9 mHz are observed in both satellite and ground, with higher power at satellite than that at the ground. The 99% confidence levels plotted for satellite compressional (magenta solid line) and ground H (cyan solid line) components confirm that the peaks are well above the confidence level. Figure 5.3c shows the time series filtered in the conventional Pi2 band (6.6-25 mHz) for satellite compressional (blue solid line) and SHL H (black dotted line) components. Identical in-phase oscillations are evident in both compressional and H components with the higher amplitude at CHAMP than at the ground. The coherence between satellite and ground oscillations is \(~1\) at Pi2 frequency (9 mHz).

Pi2 Frequency Between 10 and 15 mHz

Nighttime Pi2 event having characteristic frequency between 10 and 15 mHz is presented in Figure 5.4. The event considered occurred on 13 February 2007 between 15:26 and 15:38 UT with Pi2 onset immediately after 15:26 UT. During the event CHAMP and SHL were in the premidnight sector with LT \(~22\) h. Dominant Pi2 frequency peak at \(~11\) mHz (Figure 5.3b) is evident in both compressional and H components (coherence at 11 mHz is \(~1\)), which are
Figure 5.4: Nighttime event occurred on 13 February 2007 at CHAMP and SHL with Pi2 frequency between 10 and 15 mHz. Format is the same as in Figure 5.3.
Figure 5.5: Nighttime Pi2 event observed on 2 March 2008 at CHAMP and KAK with frequency $>15$ mHz. Format is the same as in Figure 5.3.
well above the 99% confidence level. The filtered time series (Figure 5.4c) show coherent in-phase oscillations at satellite and ground with comparable amplitudes.

**Pi2 Frequency Between 15 and 25 mHz**

Figure 5.5 shows a nighttime Pi2 event with its characteristic frequency >15 mHz observed on 2 March 2008. The mean LT at CHAMP and KAK were 22.8 h and 0.4 h, respectively. A clear Pi2 impulse of ~2-3 min duration is evident at ~15:05 UT. Compressional and H components showed identical frequency peak at 15.5 mHz but with slightly higher power at ground than satellite (Figure 5.5b). High coherence of ~0.9 at Pi2 frequency confirms the simultaneous presence of Pi2 at satellite and ground. Pi2 oscillations at satellite and ground appeared to be matching and in phase with slightly higher amplitude at ground (Figure 5.5c). Here it can be noted that the ground station is close to the midnight meridian, while satellite was in the premidnight (~23 LT) sector, which might result in the higher Pi2 amplitudes at ground, unlike other nighttime observations presented above.

**Summary of Nighttime Observations**

Apart from the events presented above, we have identified 24 more nighttime cases with different Pi2 frequencies. All 27 nighttime events are filtered in the conventional Pi2 band (6.6-25 mHz), and their wave characteristics are displayed in Figure 5.6 (shaded area). All nighttime events falling in three different frequency groups (shown by different symbols) showed high coherence (>0.6) (Figure 5.6a) between satellite compressional and ground H components. The cross-phase angle between satellite and underneath ground oscillations is found to be less than 30° (Figure 5.6b) for all the nighttime events. Figure 6c shows the percentage of events having satellite to ground amplitude ratio less than 1, where nighttime events are shown by black bars. These percentage values are found to be 25, 8, and 43 in the frequency bands 6-10 mHz, 10-15 mHz, and 15-25 mHz, respectively (average ~25%), indicating that ~75%
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Figure 5.6: Statistical results of the characteristics of Pi2 oscillations in the frequency bands 5-10 mHz (crosses), 10-15 mHz (circles), and 15-25 mHz (filled triangles). LT dependence of (a) coherence and (b) cross-phase angle between satellite and underneath ground station. (c) Bar plot showing the percentage of events with satellite to ground amplitude ratio less than 1 for day (red bar) and night (black bar) LT. Events with coherence $>0.5$ are used in Figures 5.6b and 5.6c.
of nighttime events have higher amplitude at satellite. The coherent in-phase oscillations observed in the compressional component at satellite and H at the ground are in accordance with previous satellite-based studies suggesting cavity-mode oscillations during nighttime [Cuturrufo et al., 2015; Han et al., 2004; Sutcliffe and Lühr, 2003, 2010; Takahashi et al., 1995]. If Pi2 pulsations are generated by the cavity-mode resonance, then those Pi2 signatures should appear in the poloidal component as well [Sutcliffe and Lühr, 2010; Takahashi et al., 1995]. Therefore, in order to confirm the existence of cavity-mode oscillation, we examined the poloidal component at satellite. Around 90\% of the nighttime events showed matching oscillations of the same periodicity in the poloidal component with that of the satellite compressional and ground H components, thereby confirming the cavity-mode resonance as viable generation mechanism for nighttime Pi2 oscillations. We also examined the signature in the toroidal component and found that Pi2 events were absent in the toroidal components for over 60\% of nighttime events.

5.3.2 Daytime Pi2s

In this section we present daytime Pi2 events observed at CHAMP with simultaneous observations from low-latitude ground stations from both day and night sectors.

Pi2 Frequency Between 6 and 10mHz

Figure 5.7 shows a noon time Pi2 event having characteristic frequency less than 10 mHz. The event occurred on 3 June 2007, with the Pi2 onset after 18:22 UT. The mean LT at CHAMP, BSL, and SHL were 12.2 h, 12.4 h, and 0.5 h, respectively (Figure 5.7ca). PSD (Figure 5.7b) shows identical frequency peak at 8 mHz in the midnight ground station SHL (black dotted line) and daytime ground station BSL (red dotted line). Pi2 power is found to be much higher at night ground station compared to day ground station. Although identical peak at 8 mHz is evident in dayside CHAMP observations, contribution from lower frequencies is
also observed (blue solid line), which is absent on ground. The wave power of Pi2 frequency at CHAMP is higher than that of underneath ground station BSL. The Pi2 frequency peaks observed at all three locations are well above the confidence level, with very high coherence values (∼0.9 between two ground stations and ∼0.7 between satellite and dayside ground station). Figure 5.7c depicts the identical in-phase oscillations in H component at SHL and BSL with higher amplitude at nightside station than that at day. A good cross correlation (CC) of 0.8 at nearly zero time lag is observed between two ground stations. Compressional oscillation at CHAMP shows a moderate match with that of H at day ground with a maximum CC value of -0.6. Main Pi2 impulse during 18:24-18:27 UT shows opposite phase at satellite and ground with satellite amplitude higher than dayside ground. However, there are additional oscillations with higher amplitude at CHAMP (18:22-18:24 UT), which are not present in the day and night ground observations.

Figure 5.8 shows a morning time event with Pi2 frequency ≤ 10 mHz, occurred on 14 September 2009 at 16:25 UT. At the time of the event CHAMP and HON were in early morning sector with mean LT ∼8 h and 6 h respectively and KAK was in postmidnight sector at ∼2 h. Identical frequency peak (Figure 5.8b) at ∼10 mHz is evident in both ground stations, with the daytime Pi2 power much smaller than the nighttime one. Satellite observations also showed exactly identical frequency peak at 10 mHz (coherence ∼0.9), with slightly higher power at satellite than daytime ground. Filtered time series in conventional Pi2 frequency band, presented in Figure 5.8c, showed identical in-phase oscillations at both ground stations (CC ∼1 at zero lag). Oscillations at satellite are also found to be matching with dayside ground showing a good CC of 0.8 at -30 s lag (which corresponds to nearly 100° shift for 10 mHz). Thus, the fluctuations at CHAMP appear to be phase shifted (Figure 5.8c). Pi2 amplitudes at both CHAMP and HON are observed to be nearly half that of the night station KAK.
Figure 5.7: Daytime Pi2 event (frequency <10 mHz) occurred on 3 June 2007 when CHAMP and BSL were in the dayside and SHL was located in the nightside. (a) Locations of SHL, BSL, and CHAMP satellite orbit; midnight meridian is shown by vertical dotted line. (b) PSD of compressional component at CHAMP (Sat B//) and H components at SHL and BSL, along with 99% confidence levels. (c) Time series of compressional and H components filtered in the frequency range 6.6-25 mHz.
Figure 5.8: Morning time Pi2 event having frequency < 10 mHz observed on 14 September 2009 when CHAMP and HON were located on dayside and KAK was located on nightside. Format is the same as in Figure 5.7
Pi2 Frequency Between 10 and 15 mHz

In Figure 5.9, we present a daytime Pi2, having characteristic frequency between 10 and 15 mHz. The event occurred on 23 August 2009, with the Pi2 onset at \( \sim 05:14 \) UT. The LT at CHAMP, TFS, and SJG were 8.7, 8.1, and 0.7 h, respectively. Both ground stations in the day (TFS) and night (SJG) sectors showed identical frequency peaks at 13.7 mHz, with slightly higher power at SJG than at TFS. Compressional component at satellite showed a shifted frequency peak at \( \sim 14.6 \) mHz (shift is less than 1 mHz). Coherence between satellite and ground at 13.5-15.5 mHz frequency range is found to be near 0.8. Other than this common Pi2 peak near 14 mHz, compressional component at satellite showed a dominant power in the lower frequency band of Pi2, which was not present in night and found to be less dominant in dayside ground station. Figures 5.9c and 5.9d show band-pass-filtered time series in the frequency range 6.6-25 mHz (full Pi2 frequency range) and 11-25 mHz (excluding lower frequencies of Pi2 band), respectively. Though there are identical near-inphase oscillations at two ground stations, the match with the satellite compressional component is poor, when filtered in the conventional band (Figure 5.9c). The correlation between the oscillations at CHAMP and ground is found to be poor, with maximum CC value of 0.35 at -35 s lag. The dominant power from the lower range of Pi2 band seems to have stronger influence in the oscillations at satellite, leading to poor match with ground Pi2 oscillations. So in order to avoid this non-Pi2 contribution, we filtered the data in a frequency band ranging 11-25 mHz (Figure 5.9d). A significant increase in CC (-0.7 at time lag nearly 0 s) between satellite and ground is observed with this new band-pass-filtered time series. Thus, the compressional component at satellite oscillates antiphase with ground H components. The amplitude of the daytime Pi2 oscillations is observed to be higher at ground compared to CHAMP.

In Figure 5.10, we present one more case of daytime Pi2, having characteristic frequency between 10 and 15 mHz. The event took place on 5 February 2008, immediately after 14:39 UT. The mean LT at CHAMP, ASC, and KAK were 12.8 h, 13.6 h, and 23.9 h, respectively. Identical Pi2 frequency peak at 12.6 mHz is present in both day (ASC) and night (KAK) ground
Figure 5.9: Daytime Pi2 event having frequency between 10 and 15 mHz observed on 23 August 2009, when CHAMP and TFS were in the dayside and SJG was in the nightside. (b and c) Same format as in Figures 5.7b and 5.7c. (d) Time series of compressional and H components filtered in the frequency band of 1125 mHz.
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Figure 5.10: Pi2 event with frequency between 10 and 15 mHz occurred on 5 February 2008 when CHAMP and ASC were in the dayside and KAK was in the nightside. The format is the same as in Figure 5.9. (d) Narrowband filter applied in the frequency range 1025 mHz.
stations, whereas compressional component at satellite showed a slightly shifted (by less than 1 mHz) peak at \( \sim 11.7 \text{mHz} \) (coherence \( \sim 0.6 \)). Apart from this Pi2 peak (at \( \sim 12 \text{ mHz} \)), compressional component showed a dominant peak at 7 mHz, which was absent in both ground stations. Similar to the previous event when filtered in the conventional Pi2 range, a poor match between satellite and ground is observed (Figure 5.10c). The compressional oscillations appear to be modified by the lower frequency component present at CHAMP. To get clear Pi2 oscillations at satellite, this lower frequency component is avoided by filtering in the band 10-25 mHz, which resulted in highly matching oscillations in both satellite and ground (Figure 5.10d). In the conventional Pi2 band the oscillations at satellite and ground showed a poor CC \( \sim -0.3 \) at (-10 s lag) which improved to \( \sim -0.8 \) (at -10 s lag) on applying a band-pass filter between 10 and 25 mHz. Therefore, removing the lower frequency contribution within the Pi2 band at satellite brings out the matching signature of Pi2 with that on ground. This treatment helps us in clearly identifying the presence of daytime Pi2 oscillations, which otherwise lead to the belief that Pi2 oscillations do not exist at satellite altitude. Compressional component oscillates nearly antiphase with ground H components, with compressional amplitude smaller than H oscillations at ASC. Also, the amplitude of the Pi2 oscillations is observed to be higher in the night sector compared to that in the day sector (both satellite and ground).

**Pi2 Frequency Between 15 and 25 mHz**

Figure 5.11 (same format as of Figure 5.9) shows a typical daytime Pi2 event with characteristic frequency greater than 15 mHz. The Pi2 event occurred on 30 April 2007 in the interval 15:55-16:05 UT, when CHAMP and ASC were in the dayside with mean LT \( \sim 14.8 \) h and KAK was in the postmidnight sector at \( \sim 1 \) h. PSD (Figure 5.11b) shows a dominant peak at 19.5 mHz in the KAK H component, thereby implying that the Pi2 frequency of the considered event resides in the higher side of Pi2 band. H oscillations in the dayside ground station ASC also showed identical frequency peaks, confirming the presence of Pi2 in the dayside
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Matching frequency peak is also observed in the compressional oscillations at CHAMP. In addition to the Pi2 frequency peak at 19.5 mHz, compressional component also showed dominant peak in the lower frequency range of Pi2 (at ∼8 mHz), together with other peaks at 11.8 and 15.5 mHz. Pi2 power is observed to be higher at KAK (nightside) compared to ASC (dayside), and dayside ground is higher than that at satellite. A good coherence of ∼0.9 is observed between day and night grounds as well as between satellite and ground oscillations at Pi2 frequency around 19-20 mHz. Time series filtered in the frequency ranges 6.6-25 mHz and 16-25 mHz are shown in Figures 5.11c and d, respectively. It is clearly seen from Figure 5.11c that although day and night ground stations show matching impulsive in-phase oscillations, waveform at satellite is altered. The cross correlation between satellite and ground is found to be 0.35 at a lag of 25 s. In other words we can say that the presence of additional frequencies in the compressional component (which are absent in day and night ground stations) modifies the Pi2 signatures at satellite. In order to avoid these frequencies, we applied a filter in the narrow frequency band 16-25 mHz range, which shows clear Pi2 oscillations at CHAMP matching with ground. The CC between satellite and ground is found to be improved significantly to ∼0.8 at nearly zero lag on applying this narrowband filter. Dayside Pi2 oscillations observed at satellite are lower in amplitude and opposite in phase compared to ground (ASC) (Figure 5.11d).

Figure 5.12 shows another daytime Pi2 event having characteristic frequency >15 mHz occurred on 22 May 2008. The PSD (Figure 5.12b) at day (ASC) and night (KAK) ground stations showed identical Pi2 frequency peak at around 15.5 mHz, and a good coherence ∼0.9 is observed at this frequency. Satellite observations also showed matching Pi2 peak with ground (coherence ∼0.6 at Pi2 peak); however, a dominant power unique to satellite is obvious in the lower frequency side. Figure 5.12c shows matching oscillations at both the ground stations (CC ∼0.9 at zero lag), but the match with the satellite is poor (CC ∼0.3). As the dominant Pi2 frequency is at ∼15.5 mHz, we applied a band-pass filter in the frequency range 13-25 mHz in order to avoid the lower frequency part that contaminates the Pi2 oscillations at CHAMP. Figure 5.12d presents highly correlated (CC ∼0.95 at nearly zero lag)
oscillations at satellite and ground. Pi2 oscillations are found to be antiphase above and below the ionosphere, with the amplitude of oscillations at satellite smaller than that of underneath ground.

Figure 5.11: Daytime Pi2 event having frequency >15 mHz observed on 30 April 2007 when CHAMP and ASC were in the dayside and KAK was in the nightside. Figure 11 is in the same format as in Figure 5.9. (d) Time series filtered in the frequency range 16-25 mHz.
Figure 5.12: Pi2 event with frequency >15 mHz observed on 22 May 2008 when CHAMP and ASC were in the dayside and KAK was located in the nightside. Format is the same as in Figure 5.9. (d) Filtered time series in the frequency range 13-25 mHz.
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Summary of Daytime Observations

Other than the six events presented above, we have identified 18 more daytime Pi2 events that occurred at day and night low-latitude ground stations simultaneously with coherence > 0.8.

Besides the two events presented for Pi2 frequency < 10 mHz, there were two more daytime events from the same frequency group, which showed Pi2 oscillations at both the dayside satellite and the ground. But at the same time, there were six other events for which the simultaneous oscillations were absent at satellite. In those six cases, a strong power in the lower frequency side of Pi2 band was present, which appeared to modify the Pi2 frequency at CHAMP. As a result, we could not identify an isolated well-defined Pi2 frequency peak at satellite, even though it was present in both day and night ground stations. In these cases, the coherence and CC between satellite and ground were found to be poor (<0.5). The Pi2 events which showed simultaneous oscillations at satellite might have suffered less alternation at CHAMP compared to the other six events. This may be because of either the high intensity of Pi2 event that might have marked its signature despite the presence of lower frequency contribution (Figure 5.7) or the less dominance of non-Pi2 power at satellite during morning time (Figure 5.8).

In case of Pi2s with frequency between 10 and 15 mHz, other than the two presented events (both near noon), there were three more daytime Pi2 events observed in CHAMP. But there were six events which were not unambiguously identified at CHAMP. A total of three cases of daytime Pi2s with frequency > 15 mHz were detected at the topside of the ionosphere. In general, we found smaller CC values (-0.3 to -0.35) between satellite and ground oscillations when filtered in the conventional Pi2 band. Application of a band-pass filter that excludes the lower frequencies present at satellite resulted in a significant increase in CC (-0.7 to -0.8) with nearly 180° phase shift between satellite and ground. Generally, the amplitude of the Pi2 oscillations on ground is found to be greater than at the satellite resulting in satellite to ground ratio less than 1.
Thus, it is evident from the present investigation that during all daytime events, CHAMP observes a significantly strong power of non-Pi2 origin consistently in the lower frequency range of Pi2 band. These strong lower frequency oscillations can greatly modify the characteristics of temporal oscillations of Pi2s at satellite which have relatively smaller amplitudes. As a result, monitoring Pi2 signatures at CHAMP during daytime will largely depend on its characteristic frequency. The wave characteristics of all Pi2 events summarized in Figure 5.6a clearly demonstrate this aspect of the daytime Pi2s. Pi2s falling in lower frequency range <10 mHz are found to be more prone to contamination as they are significantly overlapped by lower non-Pi2 frequencies. Figure 5.6a shows that out of total 10 daytime Pi2 events identified in this range (shown by crosses in Figure 5.6a, only four events (40\%) showed coherent oscillations at satellite (>0.5). In the intermediate frequency range (10-15 mHz) shown by circles, 5 out of 11 cases (45\%) showed simultaneous oscillations at satellite. The Pi2 events are observed to be sufficiently intense for those cases for which simultaneous oscillations were detected at satellite. Pi2s falling in the higher frequency end (>15 mHz) (shown by filled triangles) are found to be least affected. In this frequency regime we came across only three dayside events and markedly all the three (100\%) events were identified concurrently at satellite. Thus, the coherence between satellite and ground oscillations during daytime is found to vary with Pi2 frequency. In general, the coherence is smaller during daytime compared to that during nighttimes. Other characteristics of Pi2 signatures such as cross-phase angle and amplitude ratio between satellite and ground (Figures 5.6b and c) are computed only for the events with coherence >0.5. These events are further narrow band filtered to eliminate the non-Pi2 contribution at the satellite. The cross-phase angles are found to be higher during daytime (>90\°) when compared to night. The percentage of events having satellite to ground amplitude ratio less than 1 is found to be 100\% for Pi2s with frequencies >15 mHz. The percentages are 50 and 60 for the frequencies <10 mHz and 10-15 mHz bands, respectively. This indicates that on average 70\% of daytime Pi2 events showed smaller amplitudes at satellite compared to ground. Apart from compressional component, we have also examined the poloidal and toroidal components at satellite. In all the daytime events we could not identify
coherent Pi2 signatures in these components.

5.4 Non-Pi2 contribution at polar LEO satellite

In order to examine the presence of lower frequencies that are present at the satellite, we investigated the frequency spectra of total magnetic field measurements at CHAMP during international geomagnetic quiet days ($\sum Kp \leq 5$) of the years 2007-2009 and estimated the power in different frequency bands: 5-10 mHz, 10-15 mHz, and 15-25 mHz. The maximum power in each frequency band is identified for all day (09:00-17:00) and night (21:00-05:00) satellite passes separately. The averaged PSD estimated from over 1905 ($127 \times 15$ passes) satellite passes for daytime and nighttime each in the three frequency bands is shown in Figure 5.13. During daytime, the largest power is observed between 5 and 10 mHz, which decreases significantly in 10-15 mHz and 15-25 mHz bands (Figure 5.13a). During nighttime, the power in 5-10 mHz band is significantly less compared to that during daytime. Nighttime powers in 5-10 mHz and 10-15 mHz frequency bands are comparable (Figure 5.13b). Power in 15-25 mHz band is found to be very small during both daytime and nighttime. These observations indicate the dominance of larger wavelengths in the quiet time magnetic field measurements at CHAMP during daytime, which reduces significantly during nighttime. As the polar orbiting satellite traverses, it monitors various ionospheric currents present at different latitudes [Jadhav et al., 2002] and hence the spatial frequencies due to equatorial, low- to middle-latitude ionospheric current systems (such as equatorial electrojet (EEJ), Sq, and return flows of EEJ currents) can be present in the magnetic field measurements during daytime. The observations also show that although less, a significant power is present in 10-15 mHz band that is consistently present in both daytime and nighttime, which do not have obvious explanation. Thus, one can realize that significant power in 5-10 mHz and 10-15 mHz frequency bands present on quiet days during daytime could be because of various encompassing ionospheric current systems monitored by CHAMP due to its orbital motion. As a result, the Pi2 oscillations (which are relatively smaller in amplitude) in the satellite observations may get masqueraded
by the spatial frequencies (larger amplitudes) present in the satellite data, especially during daytime.

Figure 5.13: Bar plot showing average power spectral density (PSD) of residual total field for all quiet days with $\sum Kp \leq 5$ of the years 2007-2009 in three frequency bands 5-10 mHz, 10-15 mHz, and 15-25 mHz for (a) day (09:00-17:00 h) and (b) night (21:00-05:00 h) local time sectors.

5.5 Discussion

Pi2s which are associated with substorm occurrence in the nightside of the magnetosphere are often observed in daytime ground stations simultaneously with their night counterparts [Sutcliffe and Yumoto, 1991]. But their identification in space is mainly limited to nighttime till date. As mentioned in section 5.1, there are contradicting reports about the identification of daytime Pi2s in LEO satellites and therefore it is puzzling whether to believe or not the existence of daytime Pi2s at topside ionosphere. The main focus of this work is to examine whether daytime Pi2s identified at ground stations exist simultaneously at topside ionosphere. If yes, how are these waves manifested in CHAMP observations? Does its detection at satellite depend on the frequency of Pi2 oscillation? Bearing these questions in mind, we grouped the
Pi2s on the basis of its characteristic frequencies into three subgroups (6-10 mHz, 10-15 mHz, and 15-25 mHz).

Although polar LEO satellites provide an opportunity to look into Pi2 oscillations at topside ionosphere, it can impose certain limitations in monitoring these waves. One of the important limitations which may affect these oscillations is the Doppler effect that arises due to the motion of satellite. As Pi2 oscillations at low to middle latitudes are considered to be primarily compressional, we consider the source speed as Alfven speed ($v_{Alfven}$), which is the lower limit of the speed with which compressional waves travel and the receiver speed as speed of CHAMP satellite ($v_{Sat}$), which is computed to be 7.7 km/s. Frequency observed by satellite ($f_{Sat}$) due to its motion is given by equation (1), where $f_0$ is the actual frequency of the waves.

In the inner magnetosphere during daytime the typical Alfven speed is $\sim$200 km/s, which gives $f_{Sat} \approx f_0$, as $\frac{v_{Sat}}{v_{Alfven}}$ is much less than unity. The percentage change in the observed frequency is computed to be less than 4% of the actual frequency. Hence, one can conclude that the Doppler effect due to motion of the satellite is very small for the compressional component of Pi2 oscillations observed by CHAMP.

\[
f_{Sat} = f_0 \left[ 1 + \frac{v_{Sat}}{v_{Alfven}} \right]
\]  

(5.1)

All the daytime Pi2 events identified in the present study are first examined at day and night ground stations for highly coherent (coherence $>0.8$) and in-phase oscillations with matching waveforms, confirming the global occurrence of the Pi2. The amplitude of the Pi2s at daytime ground station is found to be much smaller than nighttime ones. Although daytime Pi2s are identified at ground, their identification at satellite is not straightforward. The identification of daytime Pi2s at satellite depends strongly on the characteristic frequency of Pi2. It is relatively difficult to identify the coherent frequencies in the lower end of the frequency range of Pi2, while the Pi2s occurring at the higher end of the range are mostly coherent with underneath ground observations. This is because of the existence of background (non-Pi2) lower frequencies present at satellite during daytime. The general characteristics of daytime
Pi2s observed in the present study such as smaller-amplitude and out-of-phase oscillations at CHAMP compared to underneath ground observations are in accordance with the findings by Han et al. [2004]. Daytime observations of low-latitude Pi2s on ground were explained by invoking instantaneous penetration of electric field variations from polar to dayside equatorial to low-latitude ionosphere, where electric currents associated with this penetrated electric field would produce Pi2 oscillations in the magnetic field on the ground [Kikuchi and Araki, 1979; Shinohara et al., 1997; Yumoto et al., 2001]. Similar explanation for the daytime Pi2 observed in Õrsted data was quoted by Han et al. [2004]. They attributed the lower amplitude at satellite to longer distance of Õrsted (>500 km) from the ionospheric current height (∼110 km) and also to the induced currents in the Earth surface. However, Sutcliffe and Lühr [2010] found no coherent Pi2 oscillations in CHAMP, which they explained with the same penetration model of Kikuchi and Araki [1979], but with the assumption that the model is homogeneous in the east-west direction. Under this assumption, the magnetic field due to ionospheric current is confined between the ionosphere and the ground Kikuchi and Araki [1979] and therefore magnetic field oscillations of Pi2s cannot be observed above the ionosphere. They also mentioned the effect of Earth-induced current (similar to Han et al. [2004]) in nullifying the Pi2 signature above the ionosphere. However, the above mentioned assumption is not valid in the actual scenario of the ionospheric currents, and hence, it is possible to get magnetic field variations above the ionosphere with opposite direction to that on ground. Thus, our daytime Pi2 observations can also be explained by the existing understanding. However, the cited penetration model of Kikuchi and Araki [1979] is considered to be questionable Yumoto et al. [1997].

The important question is why the measurements from the same satellite are revealing two different conclusions (present work and Sutcliffe and Lühr [2010]). Also, why could Han et al. [2004] identify only two cases of daytime Pi2s in the Orsted data, whereas majority of the Pi2 events showed poor correlation between Õrsted and ground observations? Present analysis focusing on different bins within Pi2 frequency band can provide answer to these questions. Normally, Pi2 oscillations are more likely to occur in the lower side of the conventional Pi2
CHAPTER 5. Pi2 at LEO satellite

band as evident from ground observations [LI and YUMOTO, 2000]. Our analysis shows that these oscillations are more prone to contamination at satellite height during daytime, and only very intense events will be observed simultaneously at satellite and ground. This is why Sutcliffe and Lühr [2010] could not identify daytime Pi2 in CHAMP data and Han et al. [2004] were able to observe limited number of daytime events at satellite.

Another issue raised by Sutcliffe and Lühr [2010] is about the non uniformity in the observation of out-of- phase oscillations between Ørsted and ground, as they noticed four daytime cases in the reports of Han et al. [2004], with CC>0.6 but with in-phase oscillations. It should be noted that these events occurred when the satellite was either in the morning or evening sector and mostly confined to the latitudinal range 20°-60°. It is possible that during these events, the ionospheric conductivity was smaller and the penetrated electric fields may not have significant role to play. Therefore, the in-phase oscillations at satellite and ground could be thought of as result of cavity oscillations whose dominance was significant compared to penetrated fields.

According to the present understanding, the Pi2s observed at any location on ground or space mainly comprises of contributions from a substorm current wedge oscillations, inner magnetospheric cavity-like oscillations, a surface wave at the plasmapause, a bouncing mode of impulsive field-aligned currents at auroral latitudes, and penetration of Pi2 electric field from auroral latitude to the dayside equatorial ionosphere [Olson, 1999; Yumoto et al., 2001]. For low- to middle-latitude Pi2s, essentially two components, viz., cavity-mode oscillations and an instantaneous transmission of electric field from high- to low-latitude ionosphere, are responsible. For nightside low-latitude Pi2, the earlier one is dominant, while for Pi2s at the terminator to dayside, both the sources contribute. The effect of the penetration of Pi2 electric field mainly depends on the ionospheric conductivity, so its dominance varies with local time; e.g., near dawn or dusk terminators ionospheric conductivity is relatively weak and hence cavity-mode oscillations are mainly responsible for Pi2 observation, whereas near local noon,
ionospheric currents associated with penetrated electric field would play significant role resulting in out-of-phase oscillations between ground and satellite and satellite-to-ground amplitude ratios smaller than unity. At the same time, one cannot rule out the existence of cavity oscillation at dayside, which can give in-phase oscillations above and below the ionosphere.

5.6 Summary

The present study clearly demonstrates that it is possible to observe daytime Pi2s above the ionosphere. Our findings based on the compressional component at CHAMP and H component at underneath ground station are summarized as follows:

1. During nighttime coherent in-phase oscillations having similar waveform are observed in CHAMP and ground irrespective of whether characteristic Pi2 frequency resides in the lower or higher end of Pi2 band.

2. Mostly, the amplitude of nighttime Pi2s is found to be comparable or slightly greater at satellite than on the ground.

3. Around 90% of the nighttime events showed Pi2 signatures in the poloidal component as well, thereby confirming the cavity-mode resonance as viable generation mechanism for nighttime Pi2 oscillations.

4. Although daytime Pi2s are observed on ground, their identification at satellite is not straightforward.

5. Detection of daytime Pi2s at satellite depends on its characteristic frequency.

6. During daytime, Pi2s with higher frequencies (>15 mHz) can be considered more suitable for the detection in the topside ionosphere using polar LEO satellites, provided that suitable band pass filter avoiding background frequencies at satellite is applied.
7. The satellite to ground amplitude ratio is found to be dependent on the characteristic Pi2 frequency. In general, the satellite to ground amplitude ratio is found to be less than 1 during daytime.

8. During noon time, Pi2 oscillations at satellite are out of phase with respect to those observed on the ground.

9. The inability of earlier studies to detect Pi2s in polar LEO satellites could be due to significant modulation of Pi2s by the background non-Pi2 frequencies present in daytime satellite passes.

10. It is proposed that a combination of fast cavity-mode oscillations and an instantaneous transmission of Pi2 electric field from high- to low-latitude ionosphere is the responsible mechanism for the daytime Pi2 oscillations. The relative dominance of these two processes is determined by prevailing ionospheric conductivity. Higher ionospheric conductivity would result in the dominant effect of penetration electric fields from high to low latitude, whereas cavity-mode oscillation would prevail during low-conductivity state of the ionosphere.
Chapter 6

Spatial frequencies associated with the latitudinal structures of ionospheric currents seen by CHAMP

6.1 Introduction

The magnetic field measurements from polar Low Earth Orbiting (LEO) satellites are widely used to study various ionospheric and magnetospheric processes such as ionospheric E-region currents, F-region currents, equatorial plasma bubbles (EPBs), spread-F, geomagnetic pulsations etc. [Jadhav et al., 2001, 2002; Lühr et al., 2015, 2004; Ndiitwani and Sutcliffe, 2009; Park et al., 2013, 2009a; Pedatella et al., 2011; Stolle et al., 2006; Vellante et al., 2004]. Due to the motion of the polar LEO satellite, it can also observe the spatial structures of these processes [Iyemori et al., 2015; Lühr et al., 2014; Nakanishi et al., 2014; Park et al., 2009a; Stolle et al., 2006]. This can result in the observation of certain frequencies in the magnetic field recorded by LEO satellites. Therefore, the magnetic field variations observed by the LEO satellite can have varied frequencies, which can be of temporal (e.g. geomagnetic pulsations)
or spatial (e.g. latitudinal structures of ionospheric phenomena observed by the satellite due to its motion) origin.

The spatial structures of various quiet time ionospheric phenomena with different periodicities have been noticed by previous researchers in the magnetic field measurements at LEO satellites. While studying night time F-region currents using CHAMP total magnetic field measurements, Lühr et al. [2002] observed a close association of these currents with small spatial scale (100 Km) intensity fluctuations, which they attributed to F-region irregularities like spread F phenomenon. Later, using vector magnetic field measurement from CHAMP, Stolle et al. [2006] studied the magnetic deflections associated with post sunset equatorial spread F (ESF) in detail. They could observe the finest spatial scales of ESF to around few tens of meters, resulting in a periodicity <30 s in the parallel magnetic field component at CHAMP. Similar observations of magnetic fluctuations associated with equatorial plasma bubbles (EPBs) were deduced by Park et al. [2009a] in the CHAMP data. Park et al. [2009b] reported the occurrence of spatial structures having periodicities <30 s in the zonal and meridional components at CHAMP during night hours, which they attributed to mid latitude magnetic fluctuations (MMFs). The characteristics of observed MMFs were found to be consistent with medium scale travelling ionospheric disturbances (MSTID) and are attributed to spatial structures of field aligned currents (FACs). In a comprehensive survey of electromagnetic signatures related to EPBs, Lühr et al. [2014] observed magnetic field fluctuations in the transverse components having periodicities <1 s in the post sunset hours, which were interpreted as Alfvénic signatures (carried by FACs) accompanying plasma density depletions of scales lengths 150 m - 4 km. Nakanishi et al. [2014] reported the presence of global and frequent appearance of small amplitude fluctuations with 10-30 s period in the zonal and meridional components of the magnetic field measurements at CHAMP. Similar observation was also confirmed by Iyemori et al. [2015] using SWARM mission satellites. These oscillations from mid-to-low latitudes showed strong LT and seasonal dependence; and were attributed to the spatial structures of FACs generated by the ionospheric dynamo driven by the atmospheric gravity waves propagating from the lower atmosphere to ionosphere. Thus
in the low-to-mid latitudes, the magnetic field fluctuations in various components having periodicities <30 s (frequency >33 mHz) associated with the spatial structures of ionospheric irregularities and FACs monitored by the polar LEO satellites are well noticed and accounted in the literature.

The ultra low frequency (ULF) oscillations of Earth’s magnetic field called as geomagnetic pulsations are recorded as temporal oscillations in the magnetic field measurements. The geomagnetic pulsations, which are the manifestation of magnetohydrodynamic (MHD) waves, are produced by various processes in the Earth’s magnetosphere and solar wind. Therefore, the study of pulsations is of great significance as it can serve as a diagnostic tool for the identification of space weather events. Furthermore, the observations of these ULF oscillations using LEO satellites stand advantageous as it provides an opportunity to study the geomagnetic pulsations from the topside of the ionosphere and hence to investigate the effects of the ionosphere on the propagation of geomagnetic pulsations.

The continuous pulsations (Pcs) in Pc1-4 bands (frequencies >15 mHz) are analyzed using LEO satellite magnetic field measurements Cuturrufo et al. [2015]; Heilig et al. [2010, 2007]; Jadhav et al. [2001]; Ndiitwani and Sutcliffe [2009]; Park et al. [2013]; Pilipenko et al. [2008]; Sutcliffe et al. [2013]; Vellante et al. [2004]; Yagova et al. [2015]. However, the observation of geomagnetic pulsations with frequencies <15 mHz (comprise Pc5 and part of Pc4 bands) are mostly confined to magnetospheric satellites and ground, and are not well reported at polar LEO. Similarly, the impulsive geomagnetic pulsations with frequency range between 6.6-25 mHz, termed as Pi2s are well studied using LEO observations during night times [Cuturrufo et al., 2015; Han et al., 2004; Sutcliffe and Lühr, 2010; Takahashi et al., 1999; Thomas et al., 2015], nevertheless the daytime observation of Pi2s at polar LEO revealed different conclusions about its detection at topside ionosphere and hence remained puzzling Han et al. [2004]; Sutcliffe and Lühr [2010]. In a recent article, Thomas et al. [2015] showed that daytime compressional Pi2s at CHAMP can be severely contaminated by the background low frequencies
(<15 mHz) those are particularly present in satellite observations. They attributed those background frequencies to the spatial structures of E-region ionospheric currents monitored by the satellite. They also demonstrated that upon eliminating these frequencies, clear daytime Pi2s can be observed at CHAMP.

While studying Pc3 pulsations, Heilig et al. [2007] noticed the presence of lower frequency (<10 mHz) in the compressional component at CHAMP (their Figure 5). Although not examined in detail, they attributed its origin to the inadequate removal of the crustal anomalies by the ambient magnetic field model. Thus, the background lower frequencies observed by Heilig et al. [2007] and Thomas et al. [2015] were believed to be of non-temporal origin. In a comparative study of ULF oscillations in Pc3-5 bands (1-100 mHz) using CHAMP and two magnetospheric satellite missions (Cluster and Geotail), Balasis et al. [2012] reported that the Pc4-5 waves could not be detected at CHAMP, whereas magnetospheric satellites could detect the pulsations from all the three bands of Pc3-5. They attributed these observations to the fast motion of CHAMP satellite through field lines at lower altitudes. Le et al. [2011] have reported Pc2-3 waves seen by ST-5 satellite, moving in dawn-dusk orbit with 105.6° inclination, which they identified to be the Doppler shifted Pc4-5 oscillations resulted due to the rapid motion of spacecraft across the resonant field lines azimuthally at low latitudes. Also Thomas et al. [2015] suggested that the Pi2s in the compressional component from the higher frequency range (>15 mHz) are more suitable for the detection in the topside ionosphere using polar LEO satellites. Thus in general, the observation of temporal oscillations (Pis or Pcs), at polar LEO satellites are mainly limited to higher frequencies (>15 mHz). In this context, the observation of background lower frequencies (<15 mHz) as reported by Heilig et al. [2007] and Thomas et al. [2015] at LEO satellites may provide some insight into the possible reasons for the non-detection of geomagnetic pulsations with lower frequencies at polar LEO.

Although these lower frequencies are noticed at CHAMP by Heilig et al. [2007] and Thomas et al. [2015], they related their origin to different mechanisms. Thomas et al. [2015] ascribed
these frequencies to the spatial structures of the ionospheric current systems monitored by the polar LEO satellite in its transit from pole to pole, whereas Heilig et al. [2007] attributed them to the crustal anomalies present in the satellite measurements. Hence, there are different opinions about the origin of these frequencies. Also as described above, the magnetic field variations of spatial origin related to various ionospheric phenomenon are only reported for frequencies $>33$ mHz, by previous researchers. Therefore the spatial structures having frequencies $<30$ mHz are less explored. In these perspectives, detailed investigation of these frequencies is important. Firstly, we establish the existence of the frequency peaks in the total magnetic field variations (compressional) at the satellite, during geomagnetic quiet conditions. Here, we detail for the first time the origin of these frequencies by investigating their characteristics.

This chapter is organized as follows: Section 6.2 presents the data set and the method of identifying frequency peaks. Section 6.3 shows the characteristics of the observed frequencies such as its LT, longitudinal and seasonal dependence. Section 6.4 examines the solar wind (SW) conditions prevailed during the period of the present study, to estimate the level of contribution of geomagnetic pulsations in the identified frequency peaks. Section 6.5 demonstrates the effect of these frequencies on the temporal oscillations of Pc4-5 waves. The results are discussed in section 6.6 and finally section 6.7 concludes the findings.

### 6.2 Data and method of analysis

Magnetic field measurements obtained from the CHAMP satellite during international quiet days of two years (2008-2009) are utilized in this study. The solar minimum period considered for the present analysis ensures the low level of geomagnetic activity. The German satellite CHAMP was launched in July 2000 into a near circular polar orbit and lasted for 10 years in orbit till September 2010. In this duration, the CHAMP descended in altitude from initial 456 to 250 km. With an orbital period of $\sim92$ min, CHAMP orbits around Earth 15 times a day.
Its orbit drifted slowly in LT descending 1 h in 11 days and hence monitored all LT sectors in approximately 4 month duration. The considered two years of measurements therefore, give good global coverage of the magnetic field observations over all LT sectors.

The magnetic field data used in the present study are obtained from the fluxgate magnetometer on-board CHAMP with 1s sampling rate. As magnetic field measured at CHAMP has contributions from various geomagnetic sources of internal and external origin, we have subtracted the geomagnetic field model (Potsdam Magnetic Model of Earth) POMME 6.1 [Maus et al., 2010] from the magnetic field recorded by CHAMP. POMME model accounts for the main geomagnetic field and its secular variation and acceleration. It also accounts for the crustal contributions. It can be noted that the signatures of crustal anomalies can result in certain frequencies in CHAMP data [Sutcliffe and Lühr, 2003]. Apart from the internal field, POMME also provides contributions from static magnetospheric currents and the induction effect caused by the time varying ring current. Therefore, the residual field obtained after subtracting POMME has contributions from various quiet time ionospheric currents such as equatorial electrojet (EEJ), solar quiet (Sq), FAC etc. It can also have contributions due to disturbed time ionospheric and magnetospheric processes. Since the period of present work is geomagnetically quiet, the disturbed time contributions can be minimal. For this study, we have utilized 120 days comprising first five international quiet days of each month of the years 2008-2009, which provided total $\sim$3600 ($30 \times 120$) half satellite orbits consisting of a day and a night pass each. Only CHAMP passes within $\pm 50^\circ$ magnetic latitude are considered for the study to avoid complex and intense high latitude contribution. In order to remove the broad trend, a high pass filter with cut off frequency of 1.5 mHz is applied to the residual total magnetic fields. Here, it should be noted that the residuals in the total magnetic field is the same as that in the compressional component.

The PSD of the high pass filtered total magnetic field is estimated for each pass, using Maximum Entropy Method (MEM). MEM spectrum is computed for a data window of $\sim$1600 points with an Auto Regression order (length of prediction filter) 300. A typical profile of the
residual total magnetic field observed by CHAMP (red curve) during daytime between $\pm 50^\circ$ magnetic latitudes is shown in Figure 6.1a. Figure 6.1b shows the normalized (by variance) PSD of the observed residual total magnetic field (red curve) along with 99% confidence level. Considering the MEM spectrum to be Chi-square distributed with two degrees of freedom, the confidence level equals to 99th percentile value for Chi-square times the normalized red noise spectrum [Gilman et al., 1963]. The frequency peaks identified between 3-21 mHz are considered in the study. Prominent frequency peaks (at $\sim 4.5$, 7, 9, 13, 17 and 21 mHz) are marked by red arrows. Although, a few satellite passes showed frequency peaks $>21$ mHz,
they were not found consistent and hence not considered in the present study.

Since we have removed the background ambient magnetic field from CHAMP observations, the residual field depicted in Figure 1a represents the magnetic field variations due to external sources like quiet time ionospheric currents. The negative depression near dip equator and the positive lobes on its either side clearly mark EEJ and the associated return current signatures respectively in the total magnetic field variations [Jadhav et al., 2002; Lühr et al., 2004]. Also, the profile displayed in Figure 6.1a shows slight dip between ∼25°-35° magnetic latitude in both the hemispheres, which could be due to superimposed effect of Sq and EEJ return currents.

Since polar LEO satellite traverses over the entire latitudinal range in short time (∼45 min), it predominantly records the latitudinal (spatial) variations rather than the temporal variations of the ionospheric currents. As a result the spatial structures of varied wavelengths associated with the latitudinal profile of ionospheric currents can be present in the magnetic field measurements at the satellite. The orbital period being ∼92 min, CHAMP covers ∼4° of latitude in one minute. The frequency of 3 mHz, corresponds to time period of ∼5.5 min. In this duration the satellite covers ∼22° of latitudinal extent, which is referred hereafter as latitudinal wavelength. Thus the present study examines the spatial structures having latitudinal wavelengths <22°.

A typical signature of EEJ has amplitude over 20 nT and latitudinal width between ∼8°-12°, which would be covered by CHAMP in ∼2-3 min. Therefore, the latitudinal profile of EEJ with the periodicity of ∼2-3 min would result in a frequency of 8-6 mHz. Although, it should be noted that the width and amplitude of EEJ has strong day-to-day and longitudinal variability [Jadhav et al., 2002]. The day to day variability in the EEJ current pattern is strongly associated with the variability in the thermospheric neutral tidal winds. Since the typical EEJ signature being encompassed of a negative depression and two positive lobes of variable amplitudes, it can give rise to multiple frequency peaks of variable power. In order to demonstrate this point, we have plotted the EEJ profile obtained by fitting empirical model given by
Onwumechili [1998] to the CHAMP observations (Blue curve in Figure 6.1a). The PSD of the fitted EEJ profile is shown in Figure 6.1c, which shows prominent frequency peaks at \( \sim 4.5 \) mHz, 7 mHz and 9 mHz (marked with blue arrows), demonstrating the existence of different frequencies corresponding to the displayed EEJ profile in Figure 6.1a. Interestingly, the frequency peaks of the fitted EEJ profile (Figure 6.1c) coincide well with the first three frequency peaks of the observed residual field (Figure 6.1b), with the identical powers. Nevertheless, it should be noted that the number of frequency peaks and their centre frequencies varies with the shape and size of the EEJ profile. Normally only two peaks are observed in the fitted EEJ profile, which match with the first two frequencies of the observed profile. This may indicate that first two to three peaks \((< 10 \text{ mHz})\) in the observed residual field are associated with the latitudinal structure of EEJ, as powers of the coinciding frequencies are nearly the same. It is possible that similar wavelengths can be associated with the latitudinal structures of other current systems, but EEJ being the strongest among the currents flowing in the equator to mid latitude region, the powers of frequencies associated with other ionospheric currents can be of smaller magnitudes. The observed higher frequency peaks may be associated with the smaller scale latitudinal wavelengths of other currents systems such as ionospheric dynamo currents driven by gravity waves, Sq etc.

<table>
<thead>
<tr>
<th>Bin</th>
<th>Frequency range (mHz)</th>
<th>Latitudinal wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin1</td>
<td>3 6</td>
<td>11 - 22</td>
</tr>
<tr>
<td>Bin2</td>
<td>6 9</td>
<td>7 - 11</td>
</tr>
<tr>
<td>Bin3</td>
<td>9 12</td>
<td>5 - 7</td>
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<tr>
<td>Bin4</td>
<td>12 15</td>
<td>4 - 5</td>
</tr>
<tr>
<td>Bin5</td>
<td>15 18</td>
<td>3.6 - 4</td>
</tr>
<tr>
<td>Bin6</td>
<td>18 21</td>
<td>3 - 3.6</td>
</tr>
</tbody>
</table>

Frequency peaks and the related power are identified for all the selected 3600 passes using an
automated program. The program identifies the frequency peaks >3 mHz which are above 99% confidence level. The frequencies identified are then classified into six bins between 3-21 mHz, each of width 3 mHz. As discussed before, the observed frequencies can be attributed to the spatial structures of various daytime ionospheric currents, observed by spacecraft at LEO. Different frequency bins and equivalent approximate latitudinal wavelengths are shown in Table 6.1. If no well defined frequency peak is identified in a bin, then it is marked as 'absent'. The frequency peaks beyond 21 mHz are not considered in the study because their power is very small and the occurrence is rare. In the present study, significant frequency peaks (>99% confidence level) between 3-21 mHz were evident consistently in almost all the satellite passes.

6.3 Characteristics of observed frequencies

In this section, we delineate the characteristics of the observed frequencies by studying the LT, longitudinal and seasonal variation of the PSD (not normalised) in each frequency bin. Here, it should be noted that the LT considered in this study is the magnetic local time at equatorial crossing for a given satellite pass.

6.3.1 Local time variation

Figures 6.2 and 6.3 show the LT variation of the running average of PSD peaks from six frequency bins. In order to avoid the regional effects, we have confined the study to two longitudinal sectors viz., Indian (Geographic Longitude: 70°-90°E) (Figure 6.2) and American (Geographic Longitude: 260°-290°E) (Figure 6.3). In two years of time, CHAMP spans all LTs nearly 6 times. The average values are computed by taking a running average of PSD for a data window of 2 h, shifted by 0.5 h in successive steps (solid curve in Figures 6.2 and 6.3). The error bars (vertical lines) represent the standard error. Here, one can notice that
CHAPTER 6. Spatial frequencies at CHAMP

Figure 6.2: LT dependence of frequency peaks from (a) Bin1, (b) Bin2, (c) Bin3, (d) Bin4, (e) Bin5 and (f) Bin6, with error bars, over Indian sector.

Figure 6.3: Same as Figure 6.2, but for American sector.
in both the longitudinal sectors, a clear LT dependence is seen in the frequency bins 1 and 2 which corresponds to a latitudinal wavelength of 7°-22° (Figures 6.2(a, b) and 6.3(a, b)), with a maximum power near noon that reduces to much smaller values at night. Also, a secondary peak is evident at ∼15 h in Bin 1, in the Indian sector. In American sector, the secondary peak is not well defined and appeared early in LT at ∼14 h. In bins 3-4 (latitudinal wavelength 4°-7°), although less significant, an enhancement towards noon is even evident, over Indian (Figures 6.2(c, d)) and American (Figures 6.3(c, d)) sectors. Whereas, bins 5-6, (Figures 6.2(e, f), 6.3(e, f)) did not show any systematic LT dependence in both the longitudinal sectors and also a considerably less power is apparent in these bins compared to that in bins 1-4. The maximum PSD values from bins 5-6 are less than the minimum values of power from bins 1-4. The average power is observed to decrease from bin 1-6 in both sectors.

6.3.2 Longitudinal variation

Figure 6.4 shows the longitudinal variation of the average PSD in each frequency bin. Here, the LT is fixed to 10-13 h when the ionospheric conductivity and hence the daytime ionospheric currents are stronger. The average values are estimated by taking the running average of PSD for a longitudinal window of 30°, stepping forward by 10°, with three-points smoothing. The average variation of the PSD in the frequency bins 1, 2 and 3 (Figures 6.4a, 6.4b and 6.4c) show four maxima i.e., around 0°, 90°, 200° and 280°E longitudes. Frequency peaks from Bin4 show a three peak patterns with maxima located near 90°, 190° and 270°E longitudes. Here the peak at 0° seems to be absent. The longitudinal variation in Bin 5 and Bin 6 appears almost flat. Nevertheless, few isolated peaks are observed in these frequency bins, but their amplitudes are very small and they are not found to be consistent with those in Bins 1-4. Therefore, we conclude that no systematic zonal pattern is present for the higher frequency bins that correspond to smaller latitudinal wavelengths of 3°-4°. At the same time, the latitudinal wavelengths between 4°-22° show well defined four peaks in power, located at ∼0°, 90°, 200° and 280°E longitudes.
Figure 6.4: Longitudinal variation of frequency peaks from (a) Bin1, (b) Bin2, (c) Bin3, (d) Bin4, (e) Bin5 and (f) Bin6, with error bars, during 10-13 LT.

6.3.3 Seasonal variation

In order to study the seasonal dependence of the PSD during 10-13 LT, we have used February, March and April months to represent vernal equinox; May, June and July months for June solstice; and November, December and January months for December solstice. During 2008-09, near September equinox, the CHAMP was almost always outside the 10-13 LT range and hence we could not study the variation for the autumnal equinox, thereby confining equinoxial studies to Spring months only. It can be noticed from Figure 6.5 that the average PSD value from Bin 1 is maximum during equinox in both sectors (Red bars in Figure 6.5a and b). Also clear equinoxial maximum is evident for Bin 2 in the American sector, while in the Indian sector, equinoxial value is slightly higher than December solstice, confirming equinoxial high (dark blue bars). Bin 3 and Bin 4 show maxima at June and December solstices respectively,
6.4 Geomagnetic activity and solar wind parameters

Since the observed frequencies (3-21 mHz) in the present analysis overlap with the Pc4-5 (2-22 mHz) and Pi2 (6-25 mHz) pulsations, it is of primary importance to check the contributions of the temporal oscillations in the frequencies reported here. It has been known since long time that the continuous geomagnetic pulsation activity in Pc3-5 (∼2-100 mHz) frequency band is well correlated with solar wind (SW) parameters [Saito, 1964]. Dayside
Pc3-4 pulsations observed mainly at low-middle latitudes were reported to have their origin in the upstream solar wind. The amplitude, period and the occurrence rate of these pulsations are reported to have good correlation with solar wind velocity [Singer et al., 1977; Wolfe et al., 1985], interplanetary magnetic field (IMF) strength [Bolshakova and TROITSKAIA, 1968; Troitskaya et al., 1971], and cone angle [Greenstadt and Olson, 1976; Wolfe, 1980] respectively. The cone angle, which is the angle between the sun-Earth line and the direction of IMF, is a key factor governing the occurrence of daytime Pc3-4 pulsations. A low cone angle (<30°) is considered to be the favourable condition for the generation of dayside Pc3-4 pulsations [Greenstadt and Olson, 1976; Russell et al., 1983; Yumoto et al., 1985]. Pi2 pulsations are primarily associated with substorm activity [Olson, 1999], and hence the level of geomagnetic activity mainly decides the occurrence of Pi2s.

Figure 6.6: Histograms of (a) \( \sum Kp \) index and (b-h) the average AL index, SW and IMF parameters during the considered geomagnetic quiet days of the years 2008-2009.
Therefore, in order to check the contribution of the geomagnetic pulsations in the observed frequencies, we examine the geomagnetic activity and the solar wind conditions prevailed during the considered period of study.

The histograms of $\sum K_p$ and AL indices, together with SW and IMF parameters during considered 120 quiet days are shown in Figure 6.6. The $\sum K_p$ is found to be $\leq 5$ for $\sim 95\%$ of the days denoting the fairly good quiet geomagnetic conditions (Figure 6.6a). The average values of the AL, SW and IMF parameters are estimated during each satellite pass ($\sim 25\text{ min}$). AL index which is mainly $> -50\text{ nT}$ during $\sim 90\%$ of the satellite passes (Figure 6.6b), confirms that there is no substorm occurrence during the period considered in the present analysis. The average proton density ($N_p$) is found to be in general low with $\sim 95\%$ cases having $N_p \leq 10$ (Figure 6.6c). The average SW velocity was mostly between 250-400 km/sec and on a few occasions ($< 15\%$) SW velocity was between 400-500 km/s (Figure 6.6d). The cone angle (Figure 6.6e) is found to be $> 30^\circ$ for more than 85% of satellite passes. Total IMF (Figures 6.6f) and IMF Bx (Figures 6.6g) are observed to have smaller values. It is also to be noted that the IMF Bz (Figures 6.6h) was mostly near zero level or northward. Thus the SW parameters depicted here ensure low solar activity existed during the considered days of study.

If the frequencies observed in the present study are caused by temporal pulsations having its origin external to the magnetosphere, then one would expect a clear dependence of the power of the observed frequencies on SW and IMF conditions [Heilig et al., 2007; Liu et al., 2010; Mathie and Mann, 2000; Singer et al., 1977] Figures 6.7 and 6.8 investigates the dependence of the average power in each frequency bin with SW velocity and cone angle respectively. The average variation of the powers in each frequency bin with SW velocity is computed by taking a running average of PSD for a data window of 20 km/s. The error bars (vertical lines) represent the standard error. Similarly, the cone angle dependence of the average power in each frequency bin is computed for a data window of $10^\circ$ stepping it forward by $5^\circ$.

It is interesting to note that the average power did not show any explicit dependence on either the SW velocity (Figure 6.7) or the cone angle (Figure 6.8). Normally, for pulsations of
upstream origin, the power of oscillations has negative correlation with cone angle and that for external sources other than upstream origin, the pulsations activity in Pc4-5 range, has positive correlation with SW velocity [Greenstadt et al., 1979; Liu et al., 2010; Mathie and Mann, 2000; Singer et al., 1977]. Therefore, the observations depicted in Figures 6.7 and 6.8 clearly indicate that the frequencies observed in the present analysis are not of SW origin. However, in Bins 5 and 6, a weak trend opposite to that expected for Pc4-5 pulsations of SW origin is observed.

Heilig et al. [2010] have reported that the Pc3-4 activity completely ceases during the periods of extremely low Np. Therefore, we have analyzed the period when Np was \( \sim 0.9 \ \text{cm}^{-3} \). The other SW parameters prevailing during this selected period were: \( K_p = 2 \), SW velocity=\( \sim 470 \ \text{km/s} \), cone angle=\( \sim 80^\circ \) and IMF Bz \( \sim 1 \ \text{nT} \). The PSD of the total magnetic field during the
CHAPTER 6. Spatial frequencies at CHAMP

Figure 6.8: Variation of the average power of frequency peaks with cone angle for (a) frequency Bins 1-3 and (b) Bins 4-6. Error bars indicate the standard errors.

considered CHAMP pass is shown in Figure 6.9. Here, it is observed that even with this low Np level (Np < 1), multiple frequency peaks from different frequency bins are still evident in the CHAMP observations with significantly high powers. These observations indicate that, frequencies observed in the total magnetic field measurements at CHAMP during its quiet time passes between \( \pm 50^\circ \) magnetic latitude, are not mainly dominated by pulsations. However, the contribution of the ULF compressional activity on the observed frequencies to a much lesser extent cannot be ruled out completely.
Figure 6.9: Log plot of PSD of the total magnetic field recorded at a daytime CHAMP pass between ±50° magnetic latitude during 0225-0250 UT on 04 March 2008 with N_p < 1 cm⁻³. Red arrows mark the frequency peaks identified and magenta curve denote the 99% confidence level.

6.5 Modification of Pc4-5 oscillations at CHAMP

Recently, Thomas et al. [2015] reported that the Pi2 oscillations are highly contaminated during day hours by the background lower frequencies (<15 mHz) present at CHAMP. In this section we present a case study showing the possible interference of these background frequencies on the signatures of Pc4-5 pulsations observed by the CHAMP satellite. The occurrence of continuous Pc5 activity during the quiet period of 1-8 August 2008 prior to a CIR-induced storm on 9 August 2008 was reported by Urban et al. [2011]. Total magnetic field measurements from a satellite pass during this period of Pc5 activity is presented here to depict the manifestation of Pc4-5 signatures at CHAMP.

Figure 6.10 shows the Pc4-5 event observed at ground station BOU (Boulder: Geographic Coordinates: 40.1°N, 254.8°E) and the simultaneous observations from over head CHAMP during daytime, on 01 August 2008 between 1515-1536 UT. Figure 6.10a shows the PSD of
Figure 6.10: Pc4-5 event on 01 August 2008 between 15:15-1535 UT. (a) PSD of the CHAMP compressional (blue solid curve) and BOU H component (black dotted). Time series of satellite compressional and BOU H component filtered (b) in Pc5 band (1.5-6.5 mHz), (c) in Pc4 band (7-22 mHz), (d) narrow band passed (9-22 mHz) and (e) narrow band passed (14-22 mHz). Magnetic latitude of CHAMP is given at the top of Figures 6.10b and d. The universal time (UT) and magnetic local time (MLT) values are given at the bottom of Figure 6.10c and e. The scale for the satellite component is shown on the left side and that for ground H is shown on the right side.

the satellite compressional and BOU H components (high pass filtered above 0.5 mHz). In the Pc5 range (∼1-7 mHz), where a distinct frequency is evident at ∼5 mHz in ground H, the satellite showed significantly shifted frequency peak at ∼3 mHz. Also, the power is found to be nearly two orders higher at satellite compared to ground. The band pass filtered time series in the Pc5 range appeared to be distinctly different at CHAMP and ground (Figure 6.10b) with
cross correlation (CC) < 0.2. The signatures at satellite are found to be dominated by the EEJ profile at ~1527-1531 UT with amplitude 10 times higher than the ground Pc5. Therefore, the Pc5 pulsations at CHAMP are severely modified by the dominant latitudinal profile of EEJ currents.

In the Pc4 band (7-22 mHz), ground H component showed frequencies at ~11 and 17 mHz, whereas satellite compressional component showed frequency peaks at ~7, 12 and 17 mHz. Thus, additional frequency at 7 mHz is noticed at satellite, which was not present in the ground observations. The frequency peak at ~11 mHz at ground seems to be shifted to ~12 mHz at satellite, whereas the frequency peak at 17 mHz is evident at both ground and satellite. The time series band pass filtered in Pc4 range (Figure 6.10c) showed poor match (CC ~ 0.2) between the oscillations at satellite and ground. In order to eliminate the contribution from 7 mHz frequency peak at satellite, we applied a narrow band pass filter within Pc4 band in frequency regime 9-22 mHz (Figure 6.10d). Though improved (CC ~ 0.4), the oscillations at satellite and ground still appeared to be different, even after removing the additional frequency contribution. But on applying a further narrow band pass filter between 14-22 mHz (Figure 6.10e), which removes the frequencies < 14 mHz from the satellite observations, a good match (CC ~ 0.8 at 15 s lag) between satellite and ground is observed. This indicates that the observations of geomagnetic pulsations having frequencies < 15 mHz at LEO satellite are highly contaminated. This imposes limitations on the detection of Pc4-5 oscillations at CHAMP satellite during daytime.

6.6 Discussion

The present analysis notices the existence of frequencies < 20 mHz in all CHAMP passes during quiet geomagnetic conditions in the total (compressional) magnetic field component. These frequencies observed by LEO satellite can be of temporal or of spatial origin. The temporal fluctuations (also known as geomagnetic pulsations) having frequency > 15 mHz
are well studied using polar LEO satellite data, however lower frequency pulsations mainly
constituting Pc4-5 and Pi2 bands (<15 mHz) faced problems in its detection at polar LEO
satellites [Balasis et al., 2012; Thomas et al., 2015]. A few researchers have noticed the
presence of background frequencies <15 mHz in the compressional component at CHAMP
satellite [Heilig et al., 2007; Thomas et al., 2015] which they thought to be non-temporal oscil-
lations, but attributed to different origins such as latitudinal (spatial) structures of ionospheric
currents and crustal anomalies. Hence the source of these frequencies is not well understood
yet. Similar to Thomas et al. [2015] who noticed contamination of Pi2s, in this chapter we
have shown that these lower background frequencies (power ∼102-103 nT2/Hz) can severely
alter the pulsations of Pc4-5 band (typical power ∼10 nT2/Hz). Therefore, study of these
lower frequencies present at LEO satellites is of great importance. The present work aims to
delineate the characteristics of the frequencies <20 mHz identified in the CHAMP magnetic
field variations, which can assist in determining the origin of these low frequencies.

We examined whether the observed frequencies are of temporal origin. As many ULF Pc3-5
pulsations are caused due to changes in the solar wind parameters, we checked the solar wind
conditions and geomagnetic activity during the days considered in the present study. Low
∑Kp and AL values together with low level of Np, SW velocity and nearly zero IMF Bz
values ensure the low solar activity. In addition, we examined the dependence of power of the
observed frequencies on the magnitude of SW velocity and also on the cone angle. It is found
that the average power in each frequency bin is independent of SW velocity (Figure 6.7) and
cone angle (Figure 6.8), suggesting the observed frequencies in the present study are not Pc
4-5 oscillations caused by the solar wind or IMF parameters. We also ensured the presence of
the observed lower frequencies in the CHAMP data, even during the period of negligible Np
(<1), and hence confirm that these are not Pc4 oscillations of upstream origin [Heilig et al.,
2010]. The other geomagnetic pulsations such as substorm associated Pi2 can also fall in the
band of frequencies reported here. But the lower |AL| values discard the existence of Pi2
oscillations as well.
Thus it is established here that the observed frequencies in the present study are dominantly not of temporal origin of SW/IMF dependent pulsation type. The other possibility is that the reported frequencies can be due to the spatial structures of the quiet time ionospheric phenomena [Thomas et al., 2015]. In that case, the observed frequencies are expected to have characteristics similar to those of ionospheric current systems. Therefore, the present chapter examines the characteristics of these frequencies such as LT, longitudinal and seasonal dependence.

A clear LT dependence with maximum power during noon and minimum at night is evident in Bin1, 2, 3, and 4 (Figures 6.2, 6.3 (a-d)). The power is observed to be nearly 2-3 orders higher during noon compared to night (Bin1-3). This day-night difference in the power may suggest that the daytime phenomena (ionospheric E-region dynamo driven currents such as EEJ, Sq etc.) are playing significant role in the occurrence of these frequencies. No such LT dependence was is observed in frequency Bin5 and 6. The secondary peak observed near 15 LT in Figure 6.2 and 6.3 could be associated with counter electrojet (CEJ). The prominence of the secondary peak is more in the Indian sector compared to the American sector. This is in accordance with Vichare and Rajaram [2011] who noticed that CEJs are more prone to occur over the Indian region than American longitudes.

Further, the longitudinal variation near local noon hours (10-13 LT) shows four peak structure for the frequencies from Bin 1, 2, 3 with maxima at 0°, 90°, 200° and 280°E longitudes (Figure 6.4). This average longitudinal pattern matches well with the earlier reports of longitudinal variation of EEJ based on LEO satellite missions [Alken and Maus, 2007; Jadhav et al., 2002; Lühr et al., 2008], which was attributed to the non-migrating tidal activity, in particular to DE3 tidal mode [Lühr et al., 2008]. The significant longitudinal variation of Sq observed by Pedatella et al. [2011] using CHAMP observations revealed its seasonal dependence. During northern summer, they found a wave number 1 longitudinal structure, whereas during rest of the year, the wave number 3 structure is found to be prominent. Note that the longitudinal pattern displayed in our study includes both the hemispheres as well as all the seasons. However,
the longitudinal positions of the peaks in Bin 4 are in broad agreement with those reported by Pedatella et al. [2011] for Sq currents.

The seasonal variations of the spectral powers over Indian and American sectors show an equinoctial maximum for Bin 1,2 (Figure 6.5). These observations are in broad agreement with the previous reports about the seasonal variations of EEJ using various LEO missions [Alken and Maus, 2007; Jadhav et al., 2002; Lühr et al., 2008] and ground based observations [Campbell, 1997]. It should be noted that the latitudinal profile of the residual magnetic field presented in Figure 6.1a clearly marks the signature of EEJ along with other variations. The first two to three frequency peaks of the observed residual field (Figure 6.1b) match very well with those of the modeled EEJ (Figure 6.1c). Thus, the present work demonstrates that the reported frequencies $<10 \text{ mHz}$ (Bin 1-2) mainly correspond to the latitudinal profile of the EEJ. The LT, longitudinal and seasonal characteristics of Bin 1-2 also suggest its association with EEJ currents, thereby confirming the contribution of EEJ in the reported frequencies $<10 \text{ mHz}$. It is also possible that, other current systems can have similar frequencies corresponding to the Bins 1-2. However, EEJ being the strongest among various currents flowing in the equator to mid latitude region, the frequencies will be dominated by the EEJ currents.

The seasonal variations of the spectral powers show solstice maximum for Bin 3,4 in both Indian and American sectors. The solstice maximum for Bin 3,4 is consistent with the seasonal variation of Sq at mid-to-low latitudes [Campbell, 1997; Vichare et al., 2012]. Moreover, the asymmetry in the Sq current system is normally enhanced during solstice months [Yamashita and Iyemori, 2002]. Ionospheric dynamo driven by non-migrating tidal modes as well as gravity waves can produce the Sq magnetic field variations of frequencies corresponding to Bin 3-4 (wavelength: 4-7°). The LT and longitudinal variation of power in Bin 3-4 also broadly supports the contribution of Sq in these frequency bins.

Thus, the characteristics of the frequencies from Bin1-4 ($<15 \text{ mHz}$) seem to indicate that the dayside ionospheric E-region currents are responsible for their occurrence. Based on single event, [Heilig et al., 2007] had suggested that these lower frequencies ($<10 \text{ mHz}$) could be
due to crustal anomalies which are not properly removed by POMME model. This possibility is not applicable to the frequencies reported here, as the observed frequencies have significant LT and seasonal dependence. However, the contribution of the spread F associated magnetic fluctuations having spatial scales $\sim 100$ km noticed by Lühr et al. [2002] during pre midnight hours cannot be neglected.

Therefore, the explanation for the observed lower frequencies ($<15$ mHz) can be as follows. As polar LEO satellite traverses over different quiet time ionospheric current systems, it monitors the spatial distribution of these currents over different latitudes. The spatial structures associated with different current systems can cause certain frequencies in the geomagnetic field variations recorded by CHAMP (as described in Section 6.2). As the shape and size of the spatial structures of the ionospheric currents undergo strong day to day variability due to the influence of neutral winds, the frequency of the spectral peak associated with them also vary. The frequencies consistently observed in the present study can be therefore thought of as the latitudinal structures of various ionospheric currents monitored by CHAMP during its transit. For frequencies $<15$ mHz, which correspond to a latitudinal wavelength of $4^\circ$-$22^\circ$ (Table 6.1), the present study demonstrates the characteristics of the E-region ionospheric currents and therefore supports the proposed scenario. Whereas for frequencies $>15$ mHz (latitudinal wavelength $<4^\circ$) a clear dependence on LT, longitude and season could not be identified, and hence may not be associated with the ionospheric dynamo. Therefore, our work indicates that the spatial structures of daytime ionospheric currents can produce frequencies $<15$ mHz (wavelengths $>4^\circ$) in the LEO satellite observations. These frequencies can be observed only by the polar LEO satellite, due to its motion from pole to pole and hence inherent to LEO satellite observations.

Therefore, present study strongly recommends that the consideration of these intense and intrinsic frequencies is very vital while studying relatively smaller amplitude geomagnetic pulsations (Pi2, Pc4-5) using polar LEO measurements, which otherwise may lead to the misinterpretation. Considering the tremendous data available through previous and ongoing
LEO satellite missions, it is of paramount importance to take a notice of this aspect while studying pulsations using LEO satellites.

6.7 Summary

The major findings of this chapter are as follows.

1. Dominant frequencies \( \leq 20 \text{ mHz} \) are observed in the compressional component of the magnetic field in almost all CHAMP passes during quiet geomagnetic conditions.

2. The spectral powers of the observed frequencies show no dependence on solar wind velocity and cone angle and therefore are not related to the geomagnetic pulsations.

3. Frequency peaks \( \leq 15 \text{ mHz} \) showed strong LT, longitudinal and seasonal dependence.

4. Present study establishes that the observed frequencies \( \leq 15 \text{ mHz} \) are caused by the latitudinal structure of the different E-region ionospheric currents, which are monitored by CHAMP during its rapid motion over the current systems.

5. These frequencies are unique to polar LEO satellites and are found to alter the observations of geomagnetic pulsations (Pc4-5 and Pi2) at polar LEO significantly.
Chapter 7

Conclusions

The electrodynamic processes taking place in the Earth’s upper atmosphere caused by the energy input from the Sun is known as solar terrestrial interactions. These solar terrestrial processes manifest themselves as transient variations in the Earth’s magnetic field, which are either regular daily quiet variations or the rapid variations caused by the dynamic processes in the Sun. As these transient variations are the reflections of physical processes taking place in the Earth’s upper atmosphere, the investigation of geomagnetic fields can give useful insights to the complex process taking place in the space above us. The present thesis aims to understand some of these processes in depth by probing the magnetic field measurements from near Earth space. This thesis carries out studies on geomagnetic quiet time ionospheric and disturbed time magnetospheric phenomenon and also the coupling between the two through the study of Pi2 pulsations. Magnetic field measurements from various LEO satellite missions are utilized in this thesis to understand these processes by monitoring them from the topside ionosphere.

As this thesis is exclusively based on the magnetic field measurements from polar LEO satellites, the first step is to get the useful information concerning the solar terrestrial interactions from these measurements. As polar LEO satellites monitor the Earth from locations a few
hundred kilometers above the Earth’s surface, the magnetometers on board satellites record
the net magnetic field contribution from both internal and external sources. Therefore, in
order to study the transient geomagnetic field variations of external origin, the ambient mag-
netic field has to be effectively removed from the satellite measurements. Unlike ground, the
satellite being a moving entity its location constantly changes with time. Also, as ambient
magnetic field is different at different location, it is essential to get the accurate estimate of
the field at each satellite location. This is achieved using an appropriate geomagnetic field
model, which gives a reasonable prediction of the Earth’s ambient magnetic field for a given
location and at a given time. This thesis utilizes different versions of POMME main field
model depending on the epoch of study. The ambient fields so estimated are then subtracted
from the satellite observations. The difference between two gives the field variations which
are of external origin. These residual field variations can then be further investigated to study
various solar terrestrial processes.

The residual fields obtained at satellite are used to study

• Quiet time ionospheric currents near equator (EEJ)

• Disturbed time magnetospheric currents during geomagnetic storm

• Detection of substorm associated Pi2s at the topside ionosphere during daytime

• Background frequencies present at LEO satellites due to daytime ionospheric currents

• Role of background frequencies in the detection of Pi2s at the topside ionosphere

Main conclusions drawn from the thesis are listed below.

1. Study of quiet time magnetic field varitaions using Swarm mission satellites reveals
   similar characteristics of EEJ as obtained by previous studies based on Oersted and
   CHAMP satellite data. Our study suggests that the ratio between total return to forward
current is $0.25 \pm 0.02$ with 9% confidence level. The latitudinal extents of the forward
and return currents are also found to have longitudinal variation similar to that of the amplitude and width of EEJ showing four peak structures

2. Three geomagnetic storms of solar cycle 24 representing major, moderate and weak class of geomagnetic storm using Swarm A satellite magnetic field data are analysed. The study shows that the amplitude of maximum variation during storm-time obtained from satellite and model matches well with that obtained from SymH index, during all three storms. Also it is observed that the Tyganenko model estimates considering magnetopause, ring, PRC, R1, R2 and magnetotail currents are not able to produce the observed asymmetry during moderate and weak storms, while during major storms, model predictions are better.

3. During nighttime, coherent in-phase Pi2 oscillations are observed in the compressional component at satellite and horizontal component at underneath ground station for all the considered events, irrespective of the Pi2 frequency. But for daytime Pi2s we observed that its identification at CHAMP depends strongly on the frequency of Pi2 oscillation. The daytime Pi2 with frequency <15 mHz are found to be modified by a background frequency uniquely present in CHAMP observations. Whereas, Pi2s having frequency >15 mHz are less affected by these background frequencies, A clear signature of daytime Pi2s at CHAMP is detected upon eliminating the contribution from non-Pi2 frequencies at satellite from the lower end of Pi2 band.

4. Daytime Pi2s identified in the topside ionosphere showed coherent but mostly opposite phase oscillations with underneath ground station, and satellite-to-ground amplitude ratio is, in general, found to be less than 1.

5. Present thesis concludes that a combination of fast cavity-mode oscillations and an instantaneous transmission of Pi2 electric field from high- to low-latitude ionosphere is responsible for the observation of daytime Pi2s.
6. In order to identify the source of the background frequencies, we investigated the frequencies present in the CHAMP data during quiet geomagnetic conditions. The consistent occurrence of frequency-peaks $\leq 20$ mHz is observed in the compressional component of the magnetic field in almost all CHAMP passes. We found that the frequencies $< 15$ mHz present in CHAMP data are mainly due to the latitudinal structures of the ionospheric currents that are monitored only by the polar LEO satellites. These frequencies are found to alter the observations of geomagnetic pulsations (Pc4-5 and Pi2) significantly.

7. Therefore, the work performed in the present thesis emphasis that the consideration of these background frequencies is of paramount importance while studying geomagnetic pulsations (Pi2, Pc4-5) using polar LEO measurements, which otherwise may lead to the misinterpretation.

• Future work

The study of quiet time current system can be extended to study Sq, meridional currents etc. Vector field measurements from the Swarm satellite constellation can be used to study the three dimensional structure of quiet time ionospheric current systems.

The work carried out in this thesis about the pulsations deals only with the compressional component of the Pi2 pulsations. Therefore, the other components such as poloidal and toroidal can be explored in future studies.
Appendix A

Flow Chart
do while not end of file

Read sat location (lat, long, alt) and magnetic field components (X,Y,Z)

colat=90-lat
rsat=alt+R

X=cos(colat), Nmax=Nmax_int

Obtain Legendre polynomial $P_{n,m}(X)$ for internal field contribution

Calculate internal field in GEO coordinate system

Convert sat lat and long in GEO to GM coordinates to get mlat and mlong

mcolat=90-mlat
Calculate Sun's Declination (slat) and Right ascension (slong) in GEI coordinates

Convert slat and slong GM coordinates to get mslat and mslong

Calculate magnetic local time $MLT = mlong - mslong$

$X = \cos(mcolat)$  
$N_{max} = N_{max\_ext}$

Obtain Legendre polynomial $P_{n,m}(X)$ for external field contribution

$q = q_{sm}$, $s = s_{sm}$

Calculate external field due to ring current and magnetopause currents in SM coordinate system

$q = q_{gsm}$, $s = s_{gsm}$
Appendix

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Calculate external field due to tail currents in GSM coordinate system

\[ q = q_t \]

Obtain \( E_{st} \) and \( I_{st} \) values from \( D_{st} \) index

\[ D_{st} = D_{st} + I_{st} \]
\[ E_{st} = 0.79 \times D_{st} \]
\[ I_{st} = 0.21 \times D_{st} \]

Calculate external field due to time varying ring current and its induced part

\[ B_{zz} = q_t (1,0)^t (E_{st} - 2 \times I_{st}^t ((R/r_{sat})^3))^t P_{1,0}(x) \]
\[ B_{yr} = 0 \]
\[ B_{xr} = q_t (1,0)^t (E_{st} + I_{st}^t ((R/r_{sat})^3))^t P_{0,1}(x) \]

Transform the calculated external magnetic field contribution in GSM and SM coordinates to GEO

Net external field (GEO) = tail + magnetopause + ring current field

Net field = internal + external field contributions

Residual field = Observed (Satellite) - calculated (POMME) magnetic field

Separate the output into different passes from pole to pole

Print output on a file

Close satellite file
Soubroutine 1
To read POMME coefficients

Open POMME File

\[ \text{do } n = 1 \text{ to } N_{\text{max}} \]

Y

\[ \text{do } m = 0 \text{ to } n \]

Y

Read coefficients g, h, gd, hd, gdd, hdd, qgsm, sgsm, qsm, ssm, qt

N

Close POMME Coefficient File

End
subroutine 2

input: X, Nmax

Compute associated legendre polynomial for n=1:Nmax and m=0:n

\[ P_n^m(X) = \frac{(-1)^m}{2^n n!} (1-x^2)^{n/2} \frac{d^{m+n}}{dx^{m+n}} (1-x^2)^n \]

Apply schmidt semi-normalisation on calculated \( P_n^m(X) \)

End
Subroutine 3
To calculate internal field

Input: Nmax mf, Nmax SV, g, h, gd, hd, gdd, hdd, Pr,n,m(X)

Bzi=0, Byi=0, Bxi=0

do n=1 to Nmax mf

Y

ratio = \left( \frac{R}{rsat} \right)^n \times 2

Bz = Bzi - ratio\times(n+1)\times Bz
By = Byi - ratio\times By
Bxi = Bxi + ratio\times Bx

N

do m=0 to n

Y

if n < Nmax SV

N

Y

Bz = Bz + (g_{sv}(n,m)\times\cos(m\times long) + h_{sv}(n,m)\times\sin(m\times long)) \times Pr,n,m(X)
By = By + (h_{sv}(n,m)\times\cos(m\times long) - g_{sv}(n,m)\times\sin(m\times long)) \times m\times Pr,n,m(X)
Bx = Bx + (g_{sv}(n,m)\times\cos(m\times long) + h_{sv}(n,m)\times\sin(m\times long)) \times Pr,n+1,m(X)

End
Subroutine 4
To calculate external field

Input: Nmax_ext, q, s, P_{n,m}(X)

Bz=0, Bye=0, Bxe=0

do n=1 to Nmax_ext

Y

ratio = \left( \frac{rsat}{R} \right)^{n-1}

Bz = Bz + ratio^n Bz
By = Bye - ratio^0 Bye
Bxe = Bxe + ratio^0 Bxe

N

do m=0 to n

Y

Bz = Bz + (qgsin(n,m)cos(m^*MLT) + qgsin(n,m)sin(m^*MLT))P_{n,m}(X)
By = By - (qgsin(n,m)cos(m^*MLT) - qgsin(n,m)sin(m^*MLT))P_{n+1,m}(X)
Bxe = Bxe + (qgsin(n,m)cos(m^*MLT) + qgsin(n,m)sin(m^*MLT))P_{n+1,m}(X)

N

B_{se} = \frac{B_{se}}{\sqrt{(1 - X^2)}}

End
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*Indian Journal of Radio and Space Physics*, 16:54–75.


SYNOPSIS OF THE THESIS TO BE SUBMITTED
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IN THE FACULTY OF
SCIENCE

TITLE OF THE THESIS : INVESTIGATION OF MAGNETIC FIELD MEASUREMENTS
RECORDED BY LOW EARTH ORBITING SATELLITES

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Various ionospheric and magnetospheric phenomena have been studied extensively for decades using the magnetic field measurements from different observational platforms such as ground stations, sounding rockets and satellites, each one having its own advantages and limitations. The ground based observations record the temporal variations of the magnetic field over a particular location, but it lack in spatial coverage as many of the areas around the globe is covered by forest and oceans. Satellites on the other hand, record the magnetic field variations revolving around the earth in different orbits at different altitudes. As different satellite missions have different objectives, they record temporal or spatial variations depending on its orbit and altitude. Among different satellites, the polar low earth orbiting (LEO) satellites have the advantage of true spatial coverage, as it covers the entire globe latitudinally and longitudinally in a day. But, it lacks in recording the diurnal geomagnetic field variations caused by quiet time ionospheric currents, due to its rapid motion. Both ground and satellite measurements give the height integrated effect of ionospheric/magnetospheric currents, whereas rockets are the only means to get height profile of the ionospheric currents. However, the rocket cannot record the spatial and temporal variations.

A polar LEO satellite cruises in high inclination (\(> 85^\circ\)) orbit with altitude \(< 2000 \text{ Km}\), covering the entire globe within 24 hours. The orbital period being \(\sim 90 - 100 \text{ min}\), a LEO satellite orbits 15 times a day constituting \(\sim 15 \text{ day and night passes each, with nearly same local time (LT) at the equatorial crossings. One of the earlier LEO missions is POGO including OGO-2, 4 and 6 satellites, which was latter followed by Magsat, Oersted, CHAMP, SAC-C and Swarm satellites. The magnetic field recorded at LEO being comprised of contributions from various sources such as internal and external field, a geomagnetic field model is used to obtain the residual fields at LEO, which depicts the variations pertaining to various ionospheric and magnetospheric processes. As a polar LEO satellite traverses from pole to pole in a short while (\(\sim 45 \text{ min}\)), it predominantly witnesses the spatial variations of different ionospheric phenomena. Thus the residual magnetic fields obtained at satellite can be utilized
to study the latitudinal profiles of various quiet time ionospheric processes such as E-region (Jadhav et. al., 2002; Luhr et. al., 2004), F-region dynamo currents (Luhr et. al., 2002; 2006; 2015a), FACs (Luhr et. al., 2015b) and the magnetic signatures associated with F-region irregularities like equatorial plasma bubbles (Stole et.al., 2006; Park et. al., 2009). LEO satellites also monitors various disturbed times magnetospheric phenomenon such as geomagnetic storm, substorm etc. (Hamilton 2013). In addition, it also records the geomagnetic pulsations (Jadhav et. al., 2001; Vellante et. al., 2004; Sutcliffe and Luhr 2010), which are the ultra low frequency (ULF) oscillations of Earth’s magnetic field caused by various processes in the magnetosphere and solar wind and are recorded as temporal oscillations.

The Earth’s ionosphere is the ionized part of the upper atmosphere extending from 60 – 2000 Km. As ionosphere is constituted of nearly equal number of positive ions and electrons, the medium as a whole is treated as electrically neutral and is also called as partially ionized plasma. The ionospheric dynamics is mainly controlled by the atmospheric winds and tidal oscillations, which cause the charge particles to move across the magnetic field resulting in dynamo action, thereby causing currents to flow. It is known that the daily variations in the Earth’s magnetic field is caused by these dynamo driven currents flowing in the upper atmosphere during quiet geomagnetic conditions (Stewart 1882). At the dip equator, the nearly horizontal geometry of the Earth’s magnetic field result in various electrodynamic processes unique to this region. The intense jet current flow along dip equator in the ionospheric E-region called equatorial electrojet (EEJ) is one such feature which results from the enhanced ionospheric conductivity in a narrow zone above the magnetic dip equator during daytime. As the geographical location of India is such that EEJ current flow in the space above, the studies of these current systems are of particular interest to us.

The Earth’s atmosphere extending to thousands of kilometers into space above the ionosphere, where the behavior of charged particles is strongly affected by the magnetic fields of Earth and the Sun is the magnetosphere. Magnetosphere of the earth is a natural consequence of
Synopsis

the interaction of high stream of charged particles, such as the solar wind, with the intrinsic magnetic field of the earth. The Earth’s upper atmosphere comprising the ionosphere and magnetosphere is a highly dynamic system which respond to the changes in the solar wind and IMF conditions. The interaction of solar wind and IMF with Earth’s magnetic field will result in the loading of the enormous amount of energy and momentum from sun to the magnetosphere which result in various geomagnetic activities such as storms and substorms. These geomagnetic activities caused by the coupling between the solar wind and the Earth’s magnetosphere can give rise to the generation of various magnetohydrodynamic (MHD) wave modes. These MHD waves are manifested at ground as ULF oscillations of Earth’s magnetic field called as geomagnetic pulsations. The pulsations have frequencies ranging from approximately 1 mHz to 1Hz and appear as quasi-sinusoidal oscillations in the magnetometer data recorded at the Earth’s surface, in the ionosphere and in the magnetosphere. These waves as seen on the ground are in general grouped into two classes: 1) Pulsation continuous (Pc), which are quasi-sinusoidal oscillations each with well defined spectral peak and 2) Pulsations irregular (Pi), which have wave forms that are more irregular.

This thesis utilizes the vector magnetic field measurements from two major LEO missions, CHAMP (Challenging mini Satellite Payload) and Swarm satellites to study the ionospheric and magnetospheric dynamics. The CHAMP satellite was launched on July 2000 into a near circular polar orbit (inclination \(\sim 87^\circ\)) at an initial altitude of \(\sim 450\) km. It was in orbit for 10 years till 2010 during when the satellite descended in altitude to 250 Km. Swarm is a recent satellite mission with three satellite constellations placed in two different polar orbits; two of them flying side by side at an altitude of \(\sim 450\) km and a third at an altitude of \(\sim 530\) km. The main objective of the thesis is to investigate the geomagnetic field variations during quiet and disturbed conditions using vector magnetic field measurements from CHAMP and Swarm satellites.
The thesis concentrates on the following problems.

1. The study of the global features of EEJ current parameters derived from Swarm satellites during quiet geomagnetic conditions.

2. The study of the magnetic field variations recorded by Swarm satellites during geomagnetic storms.

3. Investigation of impulsive ULF oscillations in the frequency range 6.6-25 mHz termed as Pi2 pulsations associated with substorm phenomenon.

4. To examine the occurrence of daytime Pi2 in the topside ionosphere and understand its source mechanism.

5. Investigation of inherent spatial frequencies present in the total magnetic field measurements at LEO satellites during quiet geomagnetic conditions and its possible interference with temporal oscillations of similar frequencies.

The thesis contain seven chapters and the content of each chapters are briefed below.

Chapter 1

The first chapter of the thesis gives a basic introduction to the Earth’s magnetic field, and its various components. It proceeds with an overview of the Earth’s upper atmospheric regions namely ionosphere and magnetosphere and the electrodynamic processes taking place in it. Various geomagnetic activities like solar quiet variations and associated E-region dynamo currents (EEJ, Sq etc.) are discussed. A brief introduction to the disturbed time phenomenon like geomagnetic storm, substorm and different magnetospheric currents are also given. Further, a detailed discussion is made on the ULF geomagnetic pulsations (1mHz - 1Hz), in particular the substorm associated Pi2 pulsations (6.6-25 mHz) together with the
different magnetohydrodynamic (MHD) waves modes produced in the different regions of the Earth’s magnetosphere. Different geomagnetic indices representing various ionospheric and magnetospheric phenomena are also described. Since the present thesis is exclusively based on polar LEO measurements, the LEO satellites are discussed in detail, including its orbit specifications, advantages, limitations etc. In the end, the scope of thesis in addressing various electrodynamic processes in the ionosphere and magnetosphere are discussed.

Chapter 2

The Earth’s magnetic field contain contributions from various sources like internal field (core and crustal field), external field due to ionospheric and magnetospheric (Magnetopause currents, Tail currents and Dst dependent Ring Currents) currents, and their induced part on the ground. A geomagnetic field model is a spherical harmonic representation of the Earth’s magnetic field, which gives a reasonable approximation of the magnetic field with sources internal or/and external to the Earth’s surface. As the magnetic field measurements recorded by a polar LEO satellite contain contributions from sources internal and external to the Earth’s surface, a geomagnetic field model is used to get the residual field at satellite by subtracting the modeled values from the satellite observations. The residual field so obtained contain contributions from various ionospheric and magnetospheric processes and therefore can be further investigated to understand various electrodynamic processes. This chapter describes the spherical harmonic representation of the Earth’s magnetic field and also introduces different geomagnetic field models. The present thesis utilizes POtsdam Magnetic Model of Earth (POMME) (Maus et. al., 2005), which is based on the long data set of magnetic field measurements from CHAMP and Oersted satellites. POMME accounts for the main geomagnetic field, its secular variation and acceleration and contributions from static magnetospheric currents and the induction effect caused by the time varying ring current. In order to obtain the residual fields at LEO, a FORTRAN code is developed utilizing POMME model and is described in detail.
This chapter also discusses the spectral analysis tools extensively used in the thesis such as maximum entropy method for the power spectral density estimation together with the coherence and cross phase analysis. It also discusses the computation of time lagged correlation coefficient between two time series.

Chapter 3

Chapter 3 investigates EEJ current system using polar LEO multi satellite mission, Swarm. The year and half long vector magnetic field data from Swarm satellites (Alpha, Bravo and Charlie) are used to obtain the global features of EEJ. As the satellite orbit drifted slowly in LT descending 1 h in 11 days, the considered data set gives good global coverage of the magnetic field observations over all LT sectors. An empirical model of EEJ by Onwumechili (1997) is used to estimate the EEJ current parameters and is discussed in detail. In this study, the latitudinal profile of EEJ is identified for each daytime satellite pass during geomagnetic quiet period (Kp \( \leq 2 \)) of the years 2014 – 2015. By fitting the electrojet model in the satellite observations, different parameters of EEJ current flowing at 106 Km altitude are estimated. The magnetic field variations caused by this current at ground are then calculated. The method of analysis is validated using the correlation analysis of the magnetic field variations estimated at ground using two different satellites in the swarm constellation (Bravo and Charlie) orbiting at different altitudes. The zonal and LT variation of different EEJ parameters like the total current and peak current density together with the amplitude and width of EEJ estimated at ground are analyzed and are discussed.

Chapter 4

In the previous chapter, we studied the characteristics of the quiet time ionospheric currents using Swarm satellites, while Chapter 4 focuses on the investigation of magnetospheric
currents mainly flowing during geomagnetic storms. For this purpose, we have utilized the total magnetic field variations recorded by Swarm satellite Alpha, during three geomagnetic storms (8 Dec 2013, 25 Dec 2013 and 17 March 2015). The magnetic fields due to core and crustal origin are removed from the actual observations, so that the remaining field contains ionospheric and magnetospheric contributions. For each satellite pass, nearby quiet day \( \sum Kp \leq 5 \) pass with around same LT (within ±0.5 h) and longitude (within ±10°) was chosen. These quiet time passes are believed to contain the contributions from the quite time ionospheric and magnetospheric currents. Therefore one can assume that the removal of these quiet time passes from the disturbed ones will depict the magnetic field variations caused by the geomagnetic storms, and are termed as disturbed fields. The disturbed fields obtained from various daytime and nighttime satellite passes are found be consistent with SymH variations during the complete profile of geomagnetic storm including sudden commencement, initial phase, main phase and recovery phase. Therefore, the satellite observations can be used as a proxy for disturbed time index, such as Dst. The magnetic field variations during disturbed times consist of the contributions due to various magnetospheric and ionospheric currents such as symmetric ring current, partial ring current, tail current, magnetopause currents, currents associated with prompt penetration etc. Therefore, we have used Tsyganenko model to estimate the contributions from different sources and are compared with satellite observations at dip equator. This kind of analysis is done for the first time and reveals excellent match of the observations with the superposed effect of above mentioned currents. The results are discussed in detail.

Chapter 5

This chapter focuses on the study of the low-latitude Pi2 (6.6-25 mHz) pulsations using vector magnetic field measurements from CHAMP satellite and underneath ground observations. Pi2s are a common phenomenon at ground which occurs in conjunction with substorm activity. Although a night time phenomena, Pi2s are often observed in the low latitude daytime
ground stations. Pi2s are also detected in LEO observations during night times. However, its
daytime observations at LEO revealed different conclusions about its existence in the topside
ionosphere and remained controversial. The present study examines the simultaneous occur-
rence of daytime Pi2s in the LEO and underneath ground observations, which are initially
identified using high-resolution data from Indian station Shillong (SHL; 25.92°N, 91.88°E).
It is shown that the identification of daytime Pi2s at CHAMP (compressional component) de-
pends on the frequency of Pi2 oscillation, i.e., Pi2s with higher frequencies (> 15 mHz) are
more suitable for the detection in the topside ionosphere using polar LEO satellites. The pres-
ence of a dominant non-Pi2 power in the lower frequencies (< 15 mHz) of Pi2 band, is consis-
tently observed in the CHAMP observations during daytime. These background frequencies
which are unique to satellite are found to modify the Pi2 oscillations having frequencies < 15
mHz at CHAMP, whereas Pi2s having frequencies > 15 mHz are less affected by these back-
ground frequencies. This study clearly demonstrates that the signatures of daytime Pi2s are
possible to observe at CHAMP, provided that contribution from background frequencies at
satellite is eliminated. The night time Pi2s identified at CHAMP are in accordance with the
previous reports (Takahashi et al., 1995; Sutcliffe and Luhr, 2010; Han et al., 2004; Cuturrufo
et al., 2014) suggesting cavity as a viable mechanism. However, the characteristics of daytime
Pi2s observed at satellite and ground are found to be different from that of night time ones in-
dicating an additional mechanism responsible for the occurrence of Pi2s in the day side. The
results indicate that apart from fast cavity-mode oscillations, an instantaneous transmission of
Pi2 electric field from high to low-latitude ionosphere (Shinohara et. al., 1997) also plays a
major role in the occurrence of daytime Pi2s.

Chapter 6

Chapter 6 discusses the origin of the background frequencies reported in the previous chap-
ter, which are consistently observed in the CHAMP compressional magnetic field. The study
utilizes the residual total magnetic field measurements (same as the variation in compressional
component) recorded by CHAMP, during first five international quiet days of each months of the years 2008 – 09. The present study shows the existence of frequency peaks $\leq 20$ mHz in the total magnetic field at CHAMP for almost all passes between $\pm 50^\circ$ magnetic latitude. The quiet geomagnetic conditions and the negligible dependence of the observed frequencies on solar wind parameters suggest that, these frequencies are not related to the geomagnetic pulsations. This study shows a strong LT, longitudinal and seasonal dependence for frequencies $< 15$ mHz. These observed features were found to match with those of the equator-to-middle latitude ionospheric currents derived by earlier studies using LEO observations (Jadhav et. al. 2002; Yamashita and Iyemori 2002; Alken and Maus 2007; Luhr et.al., 2008; Vichare and Rajaram 2011; Vichare et al., 2012). Moreover, the frequencies observed $< 10$ mHz are found to match exactly with that of the latitudinal profile of the EEJ obtained by fitting the empirical model given by Onwumechili (1997) to the actual observations. As CHAMP, in its transit from pole to pole, spans latitudes between $\pm 50^\circ$ in a short time ($\sim 25$ min), it monitors various ionospheric currents like EEJ, its return currents, Sq currents, FACs etc., flowing over these latitudes. Since the satellite moves over these current systems rapidly at a fixed LT, it mainly records the spatial variations of these currents. As a result the spatial structures of varied wavelengths associated with different current system can be present in the magnetic field measurements at satellite. The observed frequencies $< 15$ mHz are therefore attributed to the spatial structures of quiet time ionospheric currents, which can be observed only by polar LEO satellites. These inherent frequencies present in CHAMP observations are found to alter the geomagnetic pulsations in Pc4-5 and Pi2 band significantly. The present paper strongly recommends the consideration of these intense and intrinsic frequencies while studying relatively smaller amplitude geomagnetic pulsations (Pi2, Pc4-5) using LEO measurements, which otherwise may lead to the misinterpretation. The results are discussed in detail.
Chapter 7  This chapter summarizes the results presented in chapters three to six and discuss
the scope of future work.

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