Low Latitude - Sferics, Tweeks and Whistlers: Present Understanding and Future Prospective

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Space weather: Interdisciplinary field gained lot of interest

Refers to the time variable conditions in the space environment that may effect space-borne or ground based technological systems

According to US National Space Weather Programme,

Conditions on the Sun and in the solar wind, magnetoshere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground based technological systems and can endanger human life or health.
Why do we care about Space Weather?

- Analogous to violent terrestrial weather such as during a hurricane
- can disrupt satellite communications, destroy spacecraft, and expose astronauts and occupants of high-flying aircraft to high amounts of radiation
- Storms can result in power outage, pipeline and railroad disruptions
- Interesting science to understand the mass and electromagnetic output and variability of the Sun
SUN

- Electromagnetic radiation
- Particle radiation

Solar Flare
- Sudden Ionospheric Disturbance
- Solar Cosmic Rays

CME
- Magnetic cloud
- Disturbed Solar Wind

Solar Wind

Impact on Earth’s Magnetopause / Magnetospheric compression & tremendous energy input

- Flare effect on Magnetic records
- Disturbed Magnetosphere
- Rapidly changing Ionospheric Current

Coupling

Intense ring current

Geomagnetic storms recorded at Magnetic Observatories
Sources of geomagnetic storms

- CMEs
- Magnetic Clouds
- Corotating high speed plasma streams

*This composite image illustrates the different phenomena that can result in geomagnetic activity on Earth.*
A magnetosphere has many parts, such as the bow shock, magnetosheath, magnetotail, plasmasheet, lobes, plasmasphere, radiation belts and many electric currents. It is composed of charged particles and magnetic flux. These particles are responsible for many wonderful natural phenomena such as the aurora and natural radio emissions such as lion roars and whistler waves.
Coronal mass ejections or CMEs carry enormous amounts of the Sun’s magnetic field with them. Often loop-like or bubble-like in appearance, when a CME plows into the solar wind, it can create a shock wave that accelerates particles to high energies. Behind that shock wave, the CME expands into a huge cloud that travels through the interplanetary medium and engulfs planets in its path. Out of these few CMEs are aimed at Earth, and carry strong southward magnetic fields of long duration. These southward field merge with the earth’s northward fields at the day-side boundary of the magnetosphere as allow transfer of solar wind energy, momentum and mass to the magnetosphere.
Example of Dst index

- Dst index for April 2000
- Major storms (Dst < -100 nT)
- Minor storms (Dst < -50 nT)

- Quiet Period
  - (no storm)

- Main Phase

- Recovery Phase
Space Weather

Energetic Electrons → Damage to spacecraft electronics
Solar Flare Protons → Radiation effects on avionics
Ionospheric currents → HF Radio wave disturbance
Geomagnetically induced currents in power systems
Induced effects in submarine cables
Telluric currents in pipelines
GPS Signal Scintillation
Magnetic interference in exploration surveys
Space Weather: Ionosphere/Magnetosphere studies using ELF/VLF Electro-magnetic Waves
L-Shell

- Given as $L = R/R_o$ where $R_o =$ radius of Earth, $R =$ distance along the equator from the Center of Earth.
- Indicates the height at which magnetic field lines crosses the magnetic equator.
- Describes a particular set of planetary magnetic field lines.
- We will often specifies the geospace locations in terms of L-shell.
- Field lines are horizontal at the magnetic equator & vertical at the magnetic poles.
Low – Mid - High Latitude

- Low latitude: 0-30°, \( L < 2 \)
- Middle latitude: 30-60°, \( 2 < L < 5 \)
- High latitude: 60-90°, \( L > 5 \)
Extremely Low & Very Low Frequency waves

**ELF/VLF Band of Spectrum**

**ELF:** 30 Hz – 3000 Hz

**VLF:** 3 kHz – 30 kHz

**ELF-VLF:** 30 Hz – 30 kHz
Sources of ELF / VLF waves

ELF/VLF waves has various Natural and Artificial origin:

- **Natural sources of ELF/VLF waves:**
  - Includes Lightning discharge from thunder storms, volcanic eruptions, dust storm and tornadoes, Earthquake, etc.

- **Man Made Sources of ELF and VLF Radio Waves:**
  - HF heating
  - Fixed frequency VLF transmitters
  - Nuclear explosions

However, on a global basis, by far the most significant source of wave at ELF/VLF is that generated by lightning discharges from thunderstorms.
**VLF Study**

**Broad band**
- Covers entire VLF Spectrum
  - 300Hz - 47.5kHz
- Example:
  - Sferics
  - Tweeks
  - Whistlers
  - ELF/VLF Emissions

**Narrow band**
- Fixed Frequency transmitter signals (Amplitude & Phase)
- Example:
  - Solar Flayer
  - Geomagnetic storm
  - Earthquake
  - Sprites, Elves, Blue jets
Low latitude
Whistlers
Some part of radiated energy in the VLF range penetrates the lower boundary of ionosphere and guided through the magnetosphere along the geomagnetic field lines. This is called magneto-ionic mode propagation.

These waves are received on earth surface without any appreciable attenuation and called whistler waves.

The sound of a whistler is a musical descending tone that lasts for a second or more which gives its name.
Whistler mode

The terminology 'whistler mode' is widely used because lightning generated whistlers waves propagate in this mode.

Whistler mode waves include waves having right hand polarization, and whose upper frequency cutoff is either the local electron plasma frequency or gyrofrequency, which ever is less (Stix, 1992).
The occurrence of whistler in low latitude is poorly understood, and it remains the focus of intense research activity.
..., to \( t_0 = 0.340 \text{ s} \)

Whistlers

Frequency (x \( 10^{10} \) Hz)

Time (s)

WB200311211211.dat

22nd Spectrogram

WB200507191307.dat

26th Spectrogram

WB200507191309.dat

15th Spectrogram

\( t_{0B} = 0.689 \text{ s} \)

\( t_{0A} = 0.657 \text{ s} \)

WB200311211211.dat

WB200507191307.dat

WB200507191309.dat

\( t_{0A} = 0.657 \text{ s} \)

\( t_{0B} = 0.689 \text{ s} \)
Probing Potentiality of the Magnetospheric Parameters:

Early 1950’s when it was understood that these radiations from lightning had traveled several earth radii out in space, so it carries subtle information about the medium through which they travel.

Thus analyzing the received wave-features, it is possible to derive information about the magnetospheric medium properties such as
- Electron and proton density,
- Electric and magnetic field distribution in the medium
- Flow of plasma between magnetosphere and ionosphere
- Irregularity patches in the ionosphere

➢ The most important contribution – discovery of PLASMAPAUSE by whistler waves observation (Carpenter D.L., 1964).

- Equatorial electron density drops by a factor of 10 to 100
Their dynamic spectra reveal a long sweeping arc that illustrates how the high frequencies arrive first, followed by lower ones.

The group velocity for whistler $v_g \propto \omega^{1/2}$

There dispersion is because of the great distances traveled by them through magnetosphere, which is strongly dispersive media.
Waves in magnetosphere follows complex trajectory.

- One type of field aligned irregularities serve as guiding structure for these waves known as “Duct”.
- Waves traveling in ducts maintain direction along magnetic field lines.
- In Non-Ducted propagation, waves are influenced by smoothly varying ionization in the ionosphere.
DUCTED Whistlers

The key step involved in generation and propagation mechanism of whistlers is the ducting of electromagnetic waves radiated by lightning discharge in electron density ducts aligned along geomagnetic field lines and its propagation over the path.

A Duct may either be density enhancement ("Crest") or density depletion ("Trough").

The Existence of duct is still only a theory but experimental evidence agree well.

All whistlers observed on the ground have propagates in ducts ????
For effective ducting wave normal angle should be less than $4^0$.

Waves with wave-normal angles greater than $4^0$ do not reach the earth surface and hence cannot be observed by the ground based equipments.

Equipments on board rockets and satellites usually observe them.
Types of Whistlers

Various types of whistlers:
1. Short
2. Multiflash
3. Multipath
4. Sharp
5. Diffuse
6. Riser
7. Twin
8. low dispersion, high dispersion
9. banded, hooks, etc. and many more types

have been observed at high and low latitude stations
Spectrogram of different type of Whistlers – observed in India
Whistler Occurrence Rate

- The whistler occurrence rate depends on the local time, season and location.
- Whistlers are more common during the night than day, because of high absorption in the daytime ionosphere.
- They are more frequent at locations where lightning storms are common, or at points magnetically conjugate to regions of lightning activity.
- The latitudinal dependence of whistler occurrence rate shows a maximum around geomagnetic latitudes ~ 45°.
- The lower latitude cut-off of whistler is found to be ~10°.
- The occurrence rate exhibits a strong dependence on geomagnetic activity.
Radio Atmospherics
“Sferics”
Radio Atmospherics

Also called as “Earth Songs”

- Natural source of these Electromagnetic pulses are lightning discharge form thunder storm.
- The energy radiated by these waves lies in the ELF/VLF frequency range (30-3000Hz and 3-30kHz). The maximum energy lies in audio frequency range.
- Radio engineers referred these waves as “Radio noise” because these waves limits the system performance of radio transmission lines.
- They have many kinds depending on the sounds produced by them, The most common are:
  - Sferics
  - Tweeks
  - Whistlers
- For the first two signals it is waveguide mode propagation and for the third signal it’s the magneto-ionic mode propagation
• The natural lightning impulse radiates energy in the ELF/ VLF range travel over thousand of km through the conducting boundary of the earth-ionosphere waveguide, to be received as signals which do not exhibit dispersion are called sferics.
The dynamic spectra of sferics are characterized by vertical lines indicating the simultaneous arrival of all frequencies. On spectrogram it may extend from a few kHz to several tens of kHz. It produces crisp sharp clicking sound when signal presented to loudspeaker.

Why these waves do not show dispersion???
D-region remote sensing by Sferics observations

- Cummer et al 1998-Assumption: D-region electron density can be described by a two parameter exponential profile,

\[
N_e(h) = 1.43 \times 10^7 \exp(-0.15h') \cdot \exp[(\beta - 0.15)(h - h')] \text{ cm}^{-3}
\]

Here \(h'\) is reference height in km and \(\beta\) is sharpness factor in km⁻¹

- By the use of LWPC model on sferic spectrum for different combinations of \(h'\) and \(\beta\) have been calculated to find out most closely match for the observed sferic spectrum.
The observed and best fit modeled sferic spectrum:

The measured D-region electron density profile

For this type of study we need a good understanding of LWPC propagation model
Tweek Radio Atmospherics
Tweeks are VLF/ELF electromagnetic waves originated in the distant lightning and propagates in the Earth-ionosphere waveguide over long distances (> 1000 km) with very low attenuation (2-3 dB/1000km) through multiple reflections (Wood and Inan, 2002).

Also called as guided waves.

It sound like “tweet” when the signal is presented to loudspeaker.

These signals shows the strong dispersion near the cutoff frequency of the waveguide ~ 1.8 kHz (Mikhailova, 1988).
The dynamic spectra of a tweek shows a vertical line at the higher frequencies with a curved section (called “hook”) appearing at ~ 2 KHz.

The tweek duration is roughly proportional to its path—the longer the path in EIWG the longer will be the tweek.
**Tweek Dispersion:**

✓ A important features of tweeks and a reason for its distinct sound from other radio atmospherics.

**Why Dispersion in tweeks ?**

- Tweeks traveling via multiple reflection in the Earth-Ionosphere Waveguide.
- Every waveguide has a cutoff frequency because of its physical size, the closer wave to its cutoff, the slower it travels. So its shows “dispersion”.

**Waveguide Propagation**

- In waveguide EM waves appears as modes. The three types of mode specifying the polarization of Electric and magnetic fields are: TE, TM, TEM
- TE and TM also has higher order modes like TE\(_2\), TM\(_2\)……
- Distinct modes are function of frequency, boundary reflection and having different cutoff frequency and attenuation rate.

✓ As Earth-Ionosphere waveguide is not a perfect conductor so modes are not pure
- Modes in real EIWG are: qTE, qTM, qTEM.
The group velocity $v_{gn}$ for the different modes of propagation is given by (Ohtsu, 1960):

$$V_{gn} = c \left(1 - \frac{f_{cn}^2}{f^2}\right)^{1/2}$$

Where $f_{cn}$ is cutoff frequency of $n^{th}$ mode and $f$ is wave frequency.

The night time ionospheric cutoff frequency of first mode~1.8 kHz.
Tweek Modes

Mostly tweaking generated from vertical lightning discharges which preferentially excite qTM and qTEM waveguide modes (Cummer, 1997).
By analyzing the dispersive part of tweeks we can estimate:

A. Reflection height (h) of lower region (D-region) of ionosphere

B. Night time Electron density (N)

C. Propagation distance (d) in Earth-Ionosphere wave-guide
Set of Equations used in study of lower ionosphere

1. Electron density:

\[ N = 1.66 \times 10^{-2} f_c \]  [el/cm³]

Here \( f_c \) is the cutoff frequency for first mode

2. Reflection height

\[ h = \frac{nc}{2 f_c} \]  [km]

3. distance

\[ d = dTc \left(1 - \frac{f_{cn}^2}{f^2}\right)^{1/2} \]  [km]

Here \( dT \) is the dispersion time measured from tweek
How to measure dispersion time $dT$?

$\frac{dT}{dT} = t_d - t_o$

$\text{dT} = \text{Dispersion time}$
$\text{t}_o = \text{Arrival time of tweek before dispersion}$
$\text{t}_d = \text{Arrival time of tweek after dispersion}$
Tweek Applications

- Calculation of lower Ionospheric height, Electron density based on tweek measurements.
- Identification of source location of causative Lighting Discharges based on tweek study.
- Ionospheric diagnostics based on tweek measurements.
Whole night variations of D-region electron density, reflection height, and propagation distance of tweeks (Maurya et al 2009)
TWEEN EXAMPLES

During March-May, 2007

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

/\checkbld

Reflection height & propagation distance for each mode in the example has been calculated and given in table...
<table>
<thead>
<tr>
<th>Tweek</th>
<th>Mode</th>
<th>Cut-off Frequency (kHz)</th>
<th>Mean Frequency ($f_{cn}/n$) (kHz)</th>
<th>Reflection Height (Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1</td>
<td>1.5893</td>
<td>1.5893</td>
<td>94.38</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.2321</td>
<td>1.6160</td>
<td>92.81</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.8750</td>
<td>1.6250</td>
<td>92.30</td>
</tr>
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<td></td>
<td>4</td>
<td>6.5893</td>
<td>1.6473</td>
<td>91.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8.3036</td>
<td>1.6607</td>
<td>90.32</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>10.0893</td>
<td>1.6815</td>
<td>89.20</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>1.6260</td>
<td>1.6260</td>
<td>92.25</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.3036</td>
<td>1.6518</td>
<td>90.81</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.0893</td>
<td>1.6964</td>
<td>88.42</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.8393</td>
<td>1.7098</td>
<td>87.72</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8.6607</td>
<td>1.7321</td>
<td>86.59</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>1.6607</td>
<td>1.6607</td>
<td>90.32</td>
</tr>
<tr>
<td></td>
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<td>3.4107</td>
<td>1.7053</td>
<td>87.95</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.2679</td>
<td>1.7557</td>
<td>85.42</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.2231</td>
<td>1.8053</td>
<td>82.96</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>1.6250</td>
<td>1.6250</td>
<td>92.30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.4107</td>
<td>1.7053</td>
<td>87.95</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.3750</td>
<td>1.7783</td>
<td>83.72</td>
</tr>
</tbody>
</table>
One contradiction from the table is Mean cutoff frequency increases with mode number and this causes decrease in reflection height for higher modes.

This observation is also supported by Singh & Singh 1996, Ohya et al, 2002.

S Kumar et al 2009 has shown Mean cutoff frequency decreases with mode and reflection height is high for higher modes.

<table>
<thead>
<tr>
<th>Spectrogram</th>
<th>Time (LT hrs)</th>
<th>Mode number</th>
<th>Cut-off frequency ($f_c$ kHz)</th>
<th>Tweak reflection height $h$ (km)</th>
<th>Electron density $n_e$ (el/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>23:00:37.39</td>
<td>1</td>
<td>1.794</td>
<td>83.6</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.794</td>
<td>83.6</td>
<td>58.3</td>
</tr>
<tr>
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<td></td>
<td>3</td>
<td>1.794</td>
<td>84.5</td>
<td>86.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.779</td>
<td>84.3</td>
<td>115.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>1.758</td>
<td>85.3</td>
<td>143.3</td>
</tr>
<tr>
<td>b</td>
<td>22:01:42:308</td>
<td>1</td>
<td>1.814</td>
<td>82.6</td>
<td>29.6</td>
</tr>
<tr>
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<td>2</td>
<td>1.759</td>
<td>85.3</td>
<td>57.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.754</td>
<td>85.5</td>
<td>85.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>1.749</td>
<td>85.8</td>
<td>113.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>1.758</td>
<td>85.3</td>
<td>143.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>1.741</td>
<td>86.1</td>
<td>170.5</td>
</tr>
</tbody>
</table>
Source location/direction finding of Causative Lightning
From the simultaneous observation of Tweeks at Indian station

**Allahabad**
Geomag. Lat. 16.49N
Geomag. Long. 155.34E

**Nainital**
Geomag. Lat. 20.48N
Geomag. Long. 153.34E

Date: June 13, 2007; Time: 15:00:00 – 19:00:00 UT

Local Night time: 20:30:00 – 00:30:00 LT

Analysis of 526 pairs (1052 total) of tweeks observed simultaneously at both sites during the period
Examples of Tweek atmospherics Analysed

Allahabad N/S Antenna, 13-Jun-2007

Nainital N/S Antenna, 13-Jun-2007

Allahabad N/S Antenna, 13-Jun-2007

Nainital N/S Antenna, 13-Jun-2007
for ALLAHABAD site

Allahabad, 13 June 2007

Reflection Height

Height (km)

Time (UT)

Electron Density

Electron Density (el/m³)

Time (UT)
for NAINITAL site

Reflection Height

Electron Density
Distance traveled by tweeks from source lightning discharge w.r.t. ALLAHABAD site

(geomag. lat. 16.49N; geomag. long. 155.34E)
Distance traveled by tweeps from source lightning discharge w.r.t. NAINITAL site

(Geomag. Lat.20.48N Geomag. Long.153.34E)
The calculated distance traveled were then used to locate the source position of causative lightning discharge of Tweeks.

This is fixed by the intersection of two circles drawn by the distance traveled (propagation distance) from Allahabad and Nainital stations.

Ohya et al., 55, 627, 2003, Earth Planets Space
The location of the tweek atmospherics were confirmed by looking into WWLLN Lightning data.
Source Position of Tweeks observed on 06/13/08 at 15:00:00 UT
Color Coded Night-time D-region Electron Density distributions from Tweeks analysis: 06/13/08 at 19:00:00 UT
Lightning generated tweek atmospherics has the unique advantage of being capable of estimating lower ionosphere electron densities (reflection heights) in a wide area surrounding observation site (~1000 – 15000 km).

The method is useful for detecting changes in reflection heights, electron density in the D-region ionosphere, which could correspond to abnormal geophysical conditions.
**Morphological features**

- VLF emissions are observed in the low latitude ground stations mostly during night time due to heavy absorption in the D region ionosphere during daytime.
- Emissions occur during winter season between November and March.
- VLF emissions at low latitude is very low as compared to middle and high latitudes.
- The activity is enhanced during the period of magnetic storms.

**Applications of VLF emissions alongwith Whistlers**

- Electron density distributions in the outer ionosphere
- Ionosphere-protonosphere coupling
- Magnetospheric electric field
- Dynamics of the earth’s magnetosphere
- Explorations of other planetary atmospheres
- Distance and directions of lightening using spherics and tweeks
How Important is VLF study in Indian Low latitude region?

Figure 1.5: Optical Transient Detector Seasonal Flash Density (a.) December-February, (b.) March-May, (c.) June-August, (d.) September-October [Adapted from images available through the Global Hydrology Resource Center]
India is a very interesting location for several reasons like:

- Conjugate region of India lies in the Indian Ocean
  - Less lightning activity expected

- Also, the height of the magnetic field lines (~800 km max.) connecting conjugate regions lies in the ionosphere
  - Probable absorption of signals

Not enough VLF activity expected
Continuous monitoring of these waves allow for the quantitative physical analysis of electromagnetic phenomena in the ionosphere and magnetosphere such as:

- Radio atmospheric,
- Whistlers,
- VLF emissions,
- Lightning induced electron precipitation (LEP),
- Cosmic gamma-ray flares,
- Solar flares
- Geomagnetic storms, etc.,
- VLF waves as precursors to Earthquakes
Spectral forms of Emissions apart from Whistler

1. **Hiss**
2. **Discrete Emissions**
   - **Rising tones**
   - **Falling tones**
   - **Hook.**
   - **Combinations.**

3. **Periodic emissions**
   - **Dispersive**
   - **Non-dispersive**
   - **Multiphase**
   - **Drifting**

4. **Chorus**

5. **Quasi-periodic Emissions**

6. **Triggered Emissions**
Spectrogram of different type of Emissions – observed in India

Generation mechanism of VLF emissions are poorly understood, and they remain the focus of intense research activity.
Some examples of observation

Fig. 1. Dynamic spectrum of diffused whistlers recorded at Varanasi on January 11, 1998 at 0142 h LT.

Spectrogram of Hissler (Ref: Singh et al., GRL, 2004)
Non-Ducted Whistlers

With the advent of the Satellites, VLF receivers were placed on rockets and satellites. These space borne receivers detected whistlers whose paths deviated from the Earth's magnetic field line.

Such whistlers are called as **unducted** or **nonducted** whistlers.

By nature of their propagation mode, these are mainly observed by satellites.
Whistler observed onboard DE 1 satellite

These observations have led to new understanding of whistler-mode propagation and to the deduction of important plasma parameters in space.

- **Two mode of Propagation:**

  - **Pro-resonance (PR) mode of propagation:** It is characterized by large wave normal angles along the propagation path. The wave normal angle increases rapidly along the ray path and reaches the resonance cone.

  - **Pro-longitudinal (PL) mode of propagation:** It is characterized by propagation with the wave normals of the waves inside a characteristic cone relative to the geomagnetic field.
Low – Mid - High Latitude