Analysis of VLF/LF signal using Complex Wavelet Transform during Geomagnetic storm

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Abstract:

Very Low Frequency (VLF) signals play significant role in the analysis of various related with earth and space interaction sometimes it is related to earthquakes. At VLF frequency range, the lower ionosphere and the Earth's surface acts a good conductor known as Earth Ionosphere Waveguide (EIW). Geomagnetic storms cause anomalous changes in ion concentration of lower atmosphere and directly affect the propagation of VLF signals. By study these changes it is possible to study the process related with earth and ionosphere. In this work we have try to study VLF signal during geomagnetic storms with Complex wavelet transform methods.

1. Introduction

VLF signals are propagated within the spherical waveguide formed between the Earth and the ionosphere Known as Earth Ionosphere Waveguide (EIWG). Such signal is said to be propagating ‘‘subionospherically’’. The upper and the lower edge of EIWG are strongly affecting the propagation conditions for the VLF signal. As the conducting ground (land, sea, or ice) is essentially unchanging with time it is the upper boundary that drives most of the temporal variability in the amplitude and phase of manmade transmitters observed from a distant location. The upper boundary of the waveguide is the ionized D-region at 70-85 km and shows variations caused by local changes in ionization rates at altitudes below the D-region caused by space weather events. During undisturbed conditions the amplitude and phase of fixed frequency VLF transmissions varies in a consistent way and thus space weather events can be detected as deviations from the ‘‘quiet day curve.’’

Diurnal behavior of VLF signals over long distances (> 5000 km) was first observed by Yokoyama and Tanimura (1933) and diurnal phase variations by Pierce (1955). The amplitude and phase of VLF transmitter signals observed at any point can be used to probe ionospheric processes that occur near$\sim 85\ km$, the inferred night time upper reflection height of the waves. Early investigation of VLF emissions by Storey (1953) and Allcock (1957) disclosed an association between magnetic disturbances and VLF emissions. This association has been examined from ground stations by Aarons et al. (1960), Laaspere et al. (1964), and others. The main theme of this paper is to study the variation in VLF signal amplitude during geomagnetic storms using data from the SID monitoring stations. Ground based studies have shown that the occurrence of VLF signal amplitudes during geomagnetic storms is partly controlled by ionospheric propagation conditions, particularly absorption and reflection at the base of the ionosphere.

4.2 D_{st} Index

D_{st} is consider to be the best indicator of the ring current intensities and it is very sensitive index to represents the degree of geomagnetic storm. The value of D_{st} are obtained from the longitudinal average of H variations measured at middle and low latitude observation. It represents the axially symmetric disturbed magnetic field at the dipole equator on the Earth's surface. Major disturbances in D_{st} are negative and measured in nT (nano Tesla). Classifications of geomagnetic storm on the basis of D_{st} value are given in Table 1.

Table 1
Classification of Geomagnetic Storm

SN.	*D_{st} value*	*Storm type*
1.	$> -20\, nT$	*Low*
2.	$-20\, nT > D_{st} > -50\, nT$	*Medium*
3.	$-50\, nT > D_{st} > -100\, nT$	*High*
4.	$< -100\, nT$	*Extreme*

Decrease in magnetic field is mainly produced by equatorial current system in the magnetosphere usually referred to as the ring current. The neutral sheet current flowing across the magnetospheric tail makes a small contribution to the field decreases near the Earth. Positive variations in D_{st} are mostly caused by the compression of the magnetosphere from solar wind pressure increases.

3. Complex Wavelet Transform

Complex Wavelets Transforms (CWT) use complex valued filtering (analytic filter) that decomposes the real/complex signals into real and imaginary parts in transform domain. Complex wavelets provide more detail information in transient signal detection than real valued wavelets. Often the wavelet transform of a real signal with complex wavelet is plotted in modulus phase form rather than real and imaginary representation, which is very important in the analysis of signal amplitude. The real and imaginary coefficients are used to compute amplitude and phase information, just the type of information needed to accurately describe the energy localization of oscillating functions (Wavelet basis).

Gabor introduced the Hilbert transform into signal theory, by defining a complex extension of a real signal $f(t)$ as:

$$x(t) = f(t) + j\, g(t) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $g(t)$ is the Hilbert transform of $f(t)$ and denoted as $H\{f(t)\}$ and $j = (-1)^{1/2}$.

The signal $g(t)$is the 90° shifted version of $f(t)$ as shown in Fig. 1 (a). The real part $f(t)$ and imaginary part $g(t)$ of the analytic signal $x(t)$ are also termed as the 'Hardy Space' projections of original real signal $f(t)$ in Hilbert space. Signal $g(t)$ is orthogonal to $f(t)$. In the time domain $g(t)$ can be represented as (Hahn, 1996)

$$g(t) = H\{f(t)\} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{f(t)}{t-\tau}\, d\tau = f(t) * \frac{1}{\pi t}) \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

If $F(\omega)$ is the Fourier transform of signal $f(t)$ and $G(\omega)$ is the Fourier transform of signal $g(t)$, then the Hilbert transform relation between $f(t)$ and $g(t)$ in the frequency domain given by

$$G(\omega) = F\{H\{f(t)\}\} = -jsgn(\omega)F(\omega)) \qquad \ldots\ldots\ldots\ldots\ldots (3)$$

where, $-j\, sgn(\omega)$ is a modified 'signum' function.

This analytic extension provides the estimate of instantaneous frequency and amplitude of the given VLF signal $x(t)$ as:
Magnitude of

$$x(t) = \sqrt{(f(t)^2 + g(t)^2} \qquad \ldots\ldots(4)$$

Angle of

$$x(t) = \tan^{-1}[g(t)/f(t)] \qquad \ldots\ldots(5)$$

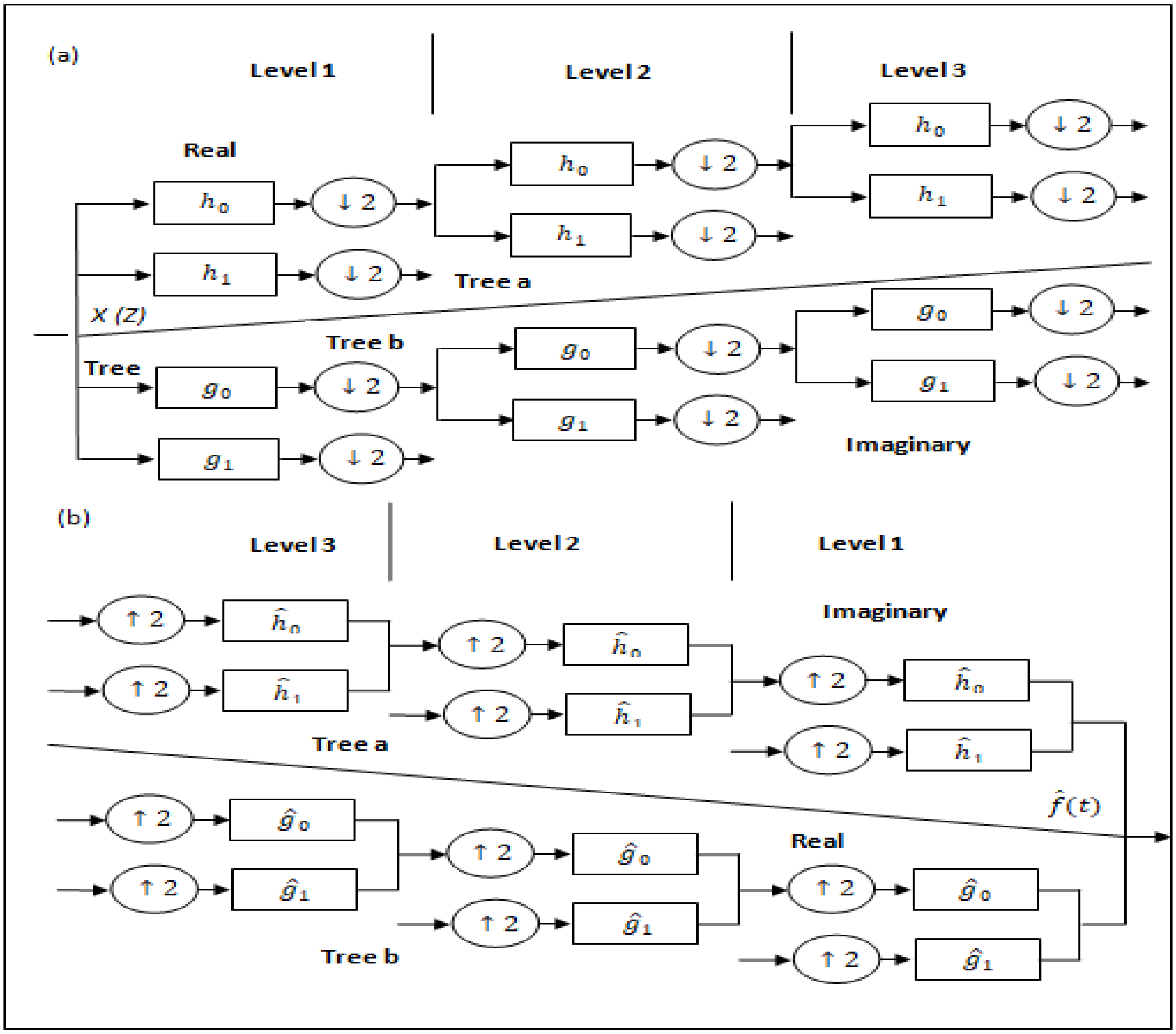

Fig.1 Three Level (a) Analysis filter bank for Dual Tree-CWT (b) Synthesis filter bank for Dual Tree-CWT

The other unique benefit of this quadrature representation is the non-negative spectral representation in Fourier domain, which leads toward half the bandwidth utilization. The reduced bandwidth consumption is helpful to avoid aliasing of filter bands especially in multivariate signal processing applications. The reduced aliasing of filter bands is the key for shift invariant property of CWT. In one dimension the so called dual tree complex wavelet transform provides a representation of a signal $x(n)$in terms of complex wavelets composed of real and imaginary parts which are in turn wavelets themselves.

4.4 Data source for VLF signal and D_{st}index

Sub-ionospheric VLF signal during the geomagnetic storm taken under consideration are obtained from Sudden Ionospheric Disturbances (SID) monitoring station available at website: http://sidstation.loudet.org. Through monitoring of the propagation of radio communication signals this station aims to detect some of the ionospheric effects resulting from solar flares. Those effects are known as Sudden Ionospheric Disturbances (SID). This station is an amateur observatory located in France and operational since early 2006. It has received the American Association of Variable Star Observers (AAVSO) code A118 in July 2006 and provides data to a coordinated network of observers around the world. The list of VLF/LF transmitter taken under consideration has been given in table 2.

Table 2
Location and call sign for VLF transmitter

Call Sign	***Fre (Hz)***	**Locatar**	**Location**	**Co-Ordinate**
ICV	*20270*	JN40uw	Isola di Tavolara, Italy	$40.55^{\circ}\ N, 9.43^{\circ}E$
DH038	*23400*	JO33tb	Rhauderfehn, Germany	$53.04^{\circ}\ N, 7.38^{\circ}W$
NAA	*24000*	FN64ip	Cutler, ME	$44.38^{\circ}\ N, 67.16^{\circ}E$
NRK	*37500*	HP83su	Grindavik, Iceland	$63.51^{\circ}\ N, 22.28^{\circ}E$

In order to identify the effect of geomagnetic storm on the VLF signal we consider 10 day D_{st}data during the commencement of storm. D_{st} index for the day of storm are obtained from the Word Data centre, Kyoto, Japan (http://swdcdb.kugi.koyotee.ac.jp)

5. Results and Discussion

During the month of August 2011, strong geomagnetic storm of $D_{st} \leq -107\, nT$ is occurred. The anomalous decrease in VLF signal amplitude transmitted for NRK, NAA and DH038 transmitter are studied. Variation in D_{st} index is illustrated in the top panel of Fig. 4.2. Periods when the D_{st} index dipped below $-100\, nT$ for the periods of geomagnetic storm of August 6, 2011 is shown by rectangular well for all signal. Modulus and phase plot for all observed signal were illustrated in Fig. 4.3 - 4.5. The periods of geomagnetic storm was presented by circle in the all figures. The modulus maxima and the phase crossings point out the locations of anomalous decrease in all VLF signals. Nevertheless, the phase information reveals isolated this decrease in signal amplitude more accurately than does the modulus. Also the phase plot shows different kinds of transition points of the analyzed signal i.e. local maxima and inflection points. Amplitude of Wavelet coefficient modulus for scale a = 32 is also minimum during geomagnetic storm showing decrease in amplitude at particulars scale (a =32 i.e. frequency = 0.72).

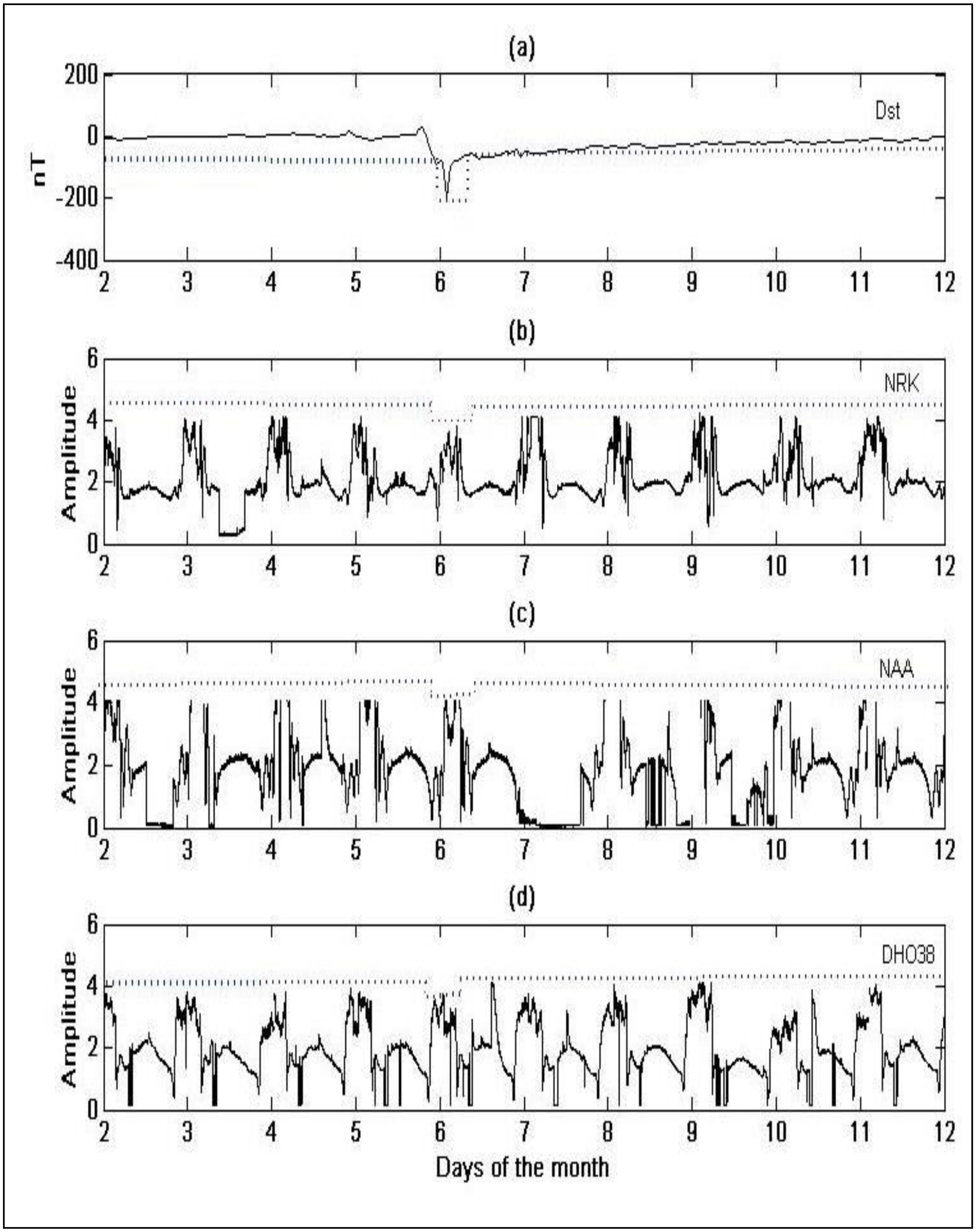

Fig. 2 Geomagnetic storm August, 2011

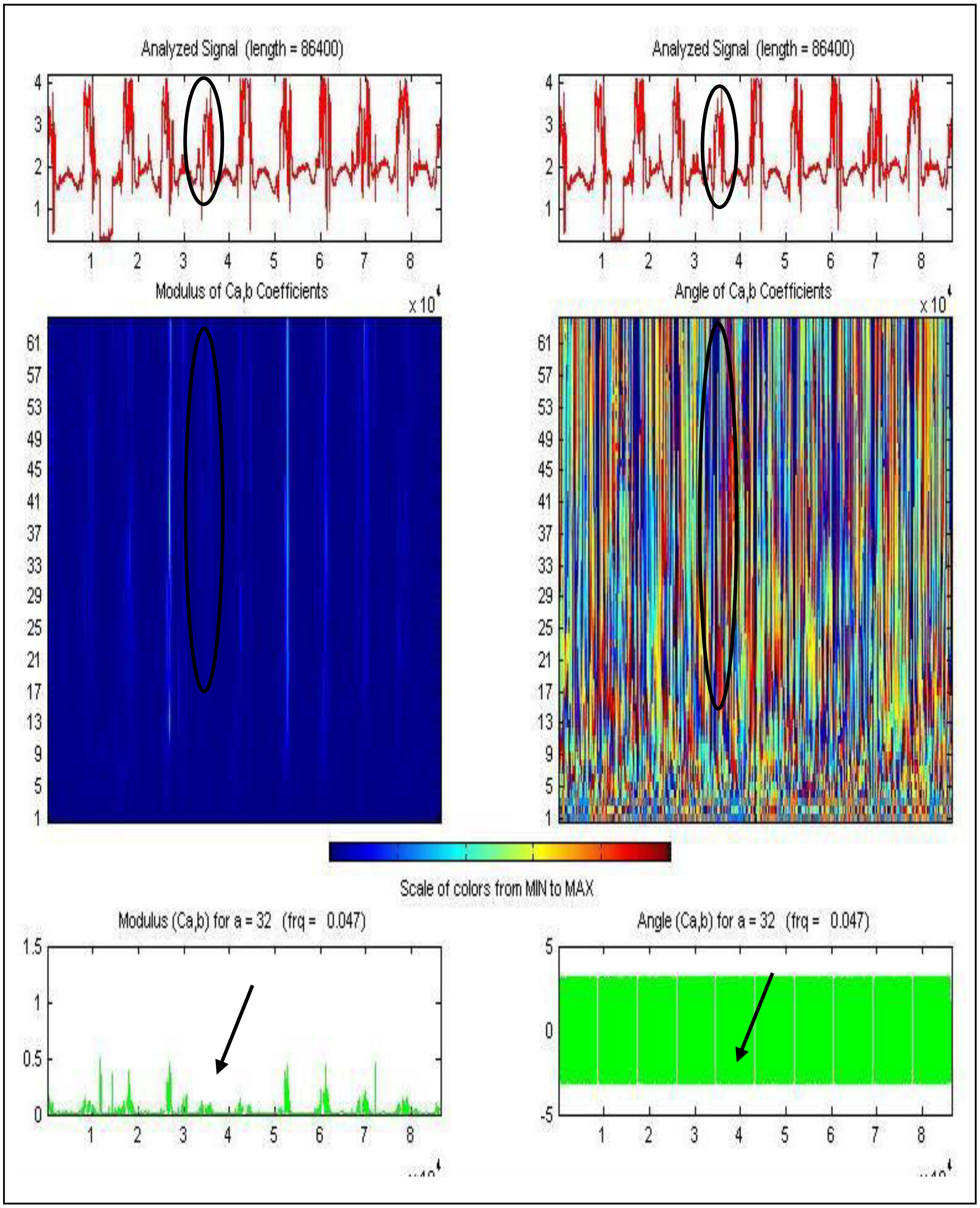

Fig. 3 Complex wavelet transform of NRK transmitter signal using cgau1 Input signal (Top panel), Modulus and Phase plot of wavelet transform coefficients (scale a = 62) scales (Middle panel), One coefficient line ($a = 2^5 = 32$)

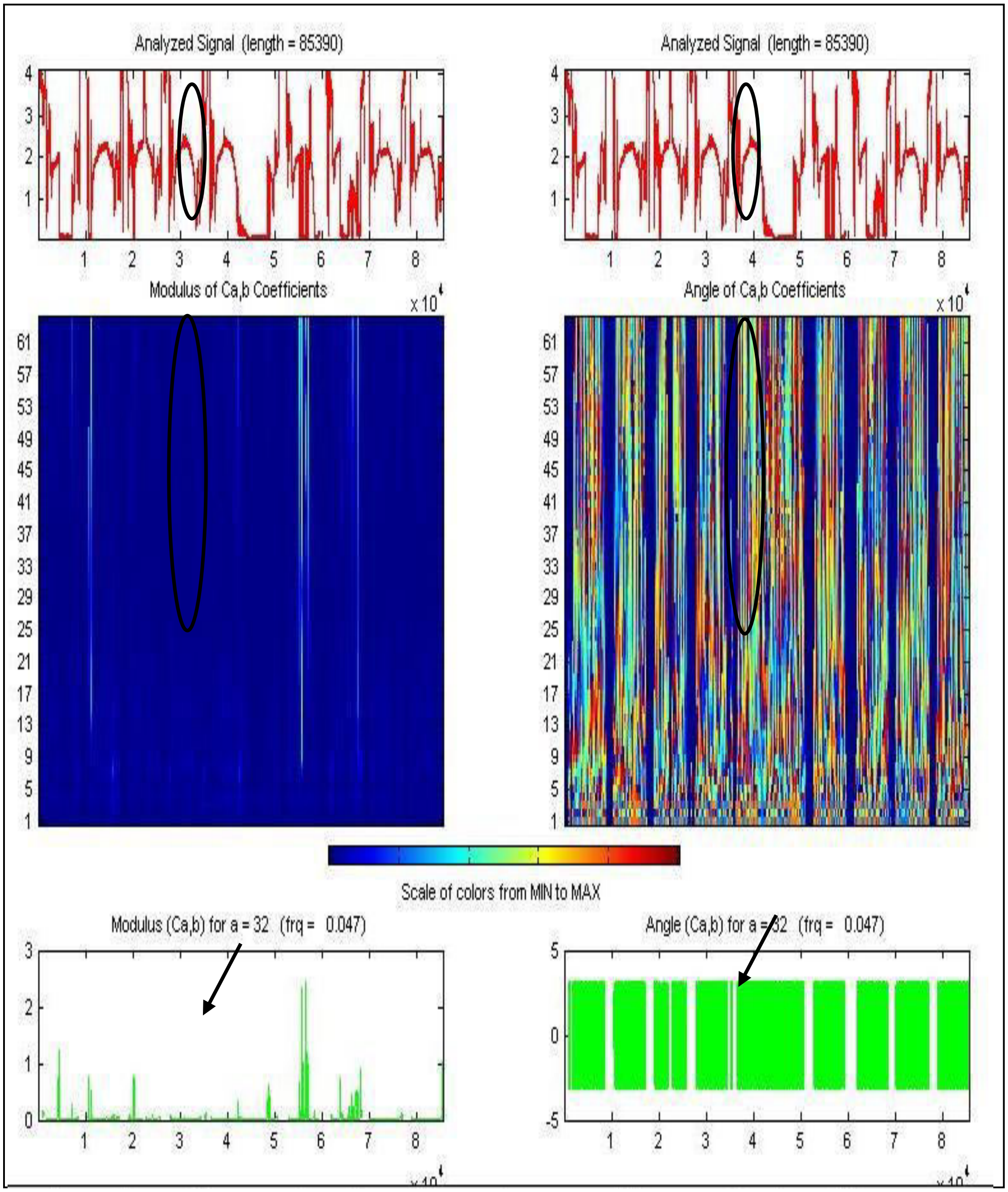

Fig. 4 Complex wavelet transform of NAA transmitter VLF signal using cgau1 Input signal (Top panel), Modulus and Phase plot of wavelet transform coefficients (scale a = 62) scales (Middle panel), One coefficient line ($a = 2^5 = 32$)

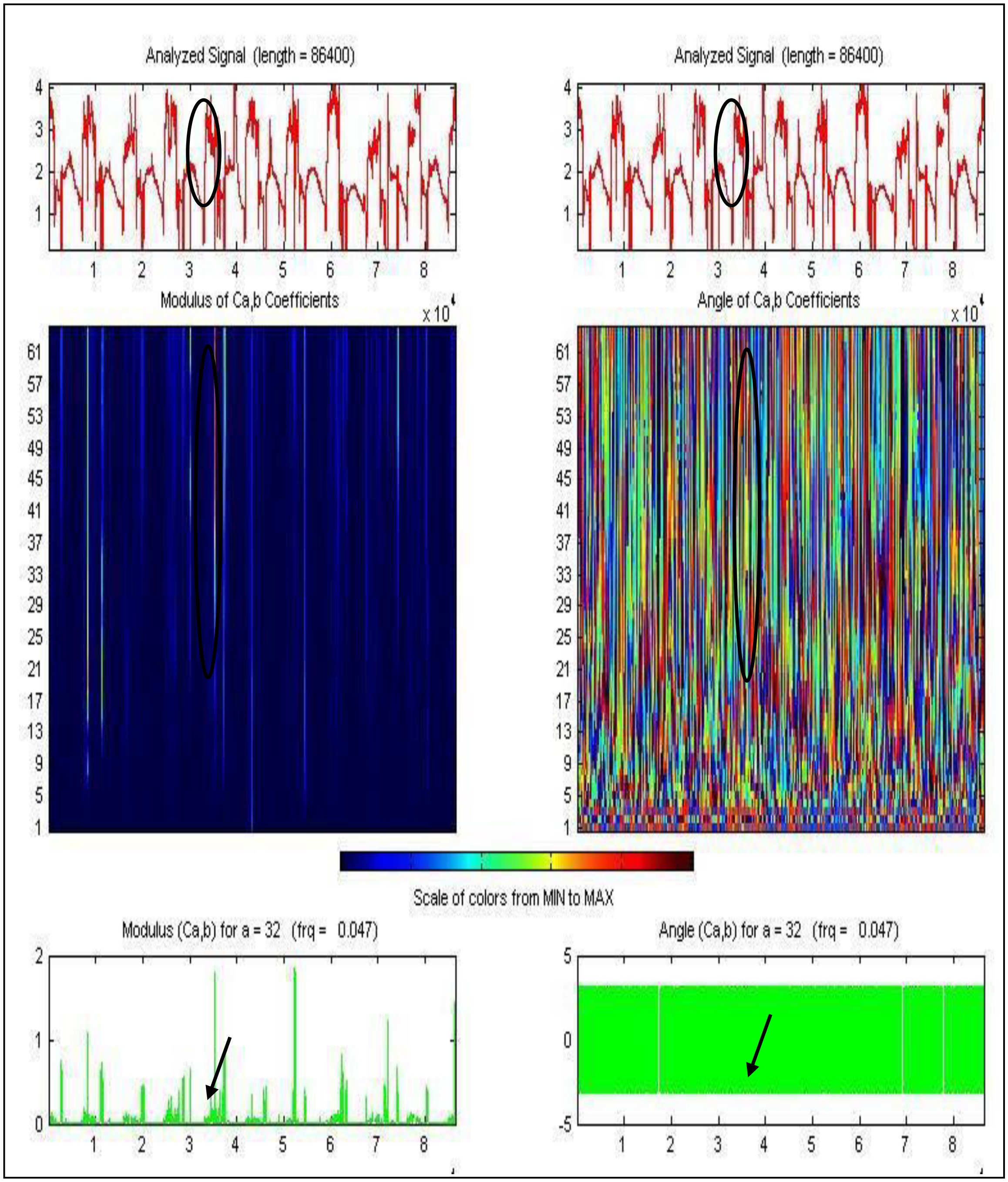

Fig. 5 Complex wavelet transform of DH038 transmitter VLF signal using cgau1 Input signal (Top panel), Modulus and Phase plot of wavelet transform coefficients (scale a = 62) scales (Middle panel), One coefficient line (a = 2^5= 32)

6. Conclusion

We applied complex wavelet transform technique for the analysis of VLF signals observed at SID monitoring station during selected major geomagnetic storm. For this analysis, we examined the 10 days data during the storm which include the day on which anomalies observed. It is found that during storms the VLF/LF signals showed decrease in amplitudes in comparison to the regular daily variations observed at morning time considerably. The result of these changes is that the variations in the signal amplitudes are around half of the normal daily values. The spectra were very similar for all three stations during the quiet periods. This contrasts with the differences seen in the spectra of the geomagnetic-disturbed days. All the spectra of the signal shows less intense region at the day of geomagnetic storm. Beloglazov and Remenez (1982) explain the effects of strong geomagnetic activity in the propagation of VLF/LF signal. The characteristics of the waveform of the NRK signal anomalies appear identical during the L'Aquila earthquake and during periods of strong geomagnetic activity the resulting spectra are different. This effect is observed due to strong enhancement in electron density profile during geomagnetic storm.

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