Submodal anomalies in Schumann resonance phenomenon possibly associated with earthquakes

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Abstract: Schumann resonance (SR) observations have been carried out at a low latitude station Bichpuri, Agra (Geograph. Lat. 27.2°N, Long. 78°E), India using a set of 3-component search coil magnetometer and accessories since 01 April, 2010. Here, we analyse the data for a period of one year from 01 January to 31 December, 2013 in search of possible anomalies in SR data associated with earthquakes. We find that unusual submodal amplitude enhancements ≈ 10-15 dB, frequency shifts in the range 1 Hz-4 Hz, precursory period ≈ 7 days and duration of the anomaly ≈ 6 hours occurred beyond third and fourth SR bands associated with 03 major earthquakes (M ≥ 6.0). The earthquakes occurred in neighbouring countries of China and Pakistan around India in the months of July and September, 2013. We show that the anomalies appeared as a result of constructive interference maxima at the receiver between the direct ELF waves generated from African and South Asian thunderstorm centers and reflected from the disturbances over epicentres of earthquakes.

Key words: Schumann resonance, earthquakes, anomalies

1. Introduction:

The most exciting electromagnetic phenomenon in the extremely low frequency (ELF) band occurring in the earth-ionosphere space is that of Schumann resonance (SR). The reason for this phenomenon to occur is the interaction between direct and round the globe ELF waves generated from lightning discharges. The phenomenon appears as resonant lines caused by standing waves at the frequencies of 8, 14, 20, 26... Hz which are known as SR modes. The phenomenon was predicted first in 1950 (Schumann, 1952) and then experimentally verified in 1960 (Balser and Wagner, 1962). Since then considerable amount of work has been done in this field and it has been shown that the study of SR is extremely useful to know the global distribution of thunderstorm activities, ground surface temperature, study of lower ionosphere, forecast of monsoon etc. The early experimental and theoretical work done on this topic has been reviewed thoroughly and described elaborately in an excellent monograph produced by Nikolaenko and Hayakawa (2002). The results of some very interesting recent studies related with morphology and varying geophysical conditions are given by a number of workers (Price and Melnikov, 2004, Penchony et al, 2007, Greenberg and Price, 2007, Williams and Satori, 2007, De at al., 2009, Ondraskova et al, 2009, Nickolaenko et al, 2011, Singh et al, 2014).

The Japanese group led by Professor Masashi Hayakawa of the University of Electro-Communication, Japan has reported some very interesting results on the association of SR anomalies with earthquakes and suggested a possibility that the SR characteristics may be used to study the earthquake precursory phenomena also (Ohta et al., 2003; Hayakawa et al., 2005; Ohta et al., 2009). For these studies, they have used the ULF/ELF data obtained at Nakatsugawa station in Japan (Geograph. lat. 35°25’ N, long. 137°32’ E) and found that anomalies in the form of amplitude enhancements occurred in 3rd and 4th harmonics of SR due to large (M > 6.0) Chi-Chi earthquake occurred in Taiwan. They have also examined the frequency shifts and direction of arrival of the affected signals.

In this paper, we report some evidences of SR submodal anomalies associated with earthquakes by analysing SR data for a period of one year from 01 January to 31 December, 2013 obtained at a low...
latitude field site at Bichpuri, Agra (Geograph. lat. 27.2° N, long. 78° E). We show that due to 03 large magnitude earthquakes (M ≥ 6.0) occurred in neighbouring countries around India distinct anomalies in the form of amplitude enhancements, frequency shifts, and other changes in SR characteristics are reflected in association with third and fourth resonance bands of the SR. We also propose a possible mechanism in which submodal anomalies are produced due to earthquakes.

2. Experimental setup and data analysis method:
   The details of the experimental setup and data analysis techniques have been described by Singh et al. (2014) and Kumar and Singh (2014). Here, we describe them briefly as follows;

   We employ a 3-component search coil magnetometer having 03 induction coils which are buried 1m down the earth along North-South (X-component), East-West (Y-component), and vertical directions (Z-component). The frequency range of the magnetometer is 0.01-30 Hz with magnetic noise level varying between 20 pT/Hz$^{1/2}$ and 0.04 pT/Hz$^{1/2}$. The whole system has been imported from Lviv Center of Institute of Space Research, Ukraine in the name of LEMI-30 unit with a software LEMI-30i. The sampling rate chosen is 64 Hz and the recorded data on PC are in the form of amplitude-time which may be seen in frequency-time (dynamic spectra) by performing spectral analysis using FFT available in MATLAB software with 1024 words of data length (temporal resolution = 16 sec, frequency resolution = 0.06 Hz) at a time. The power spectral density (PSD) of the input signal is estimated using Welch spectral technique (Welch, 1967) which uses averaged modified periodograms. The PSD are performed for each 1h data (230400 data points) and a Hamming window of 1024 data points with sliding of half the window is used to compute the modified periodogram of each segment. An example of dynamic spectrum and corresponding PSD obtained from X-component of the magnetometer recorded on 27 September, 2013 is shown in Fig. 1a and 1b respectively.

![Fig. 1. (a) Dynamic spectra of SR observed at Agra on 27 September, 2013 (b) corresponding PSD showing SR bands. The submodal anomalies at 23.4 Hz and 27 Hz may be seen clearly.](image-url)
Table 1: Details of major earthquakes occurred during 2013

| Date       | Time (UT) | Lat. (deg.) | Long. (deg.) | Depth (km) | Magnitude | Region              | Distance from Agra (km) | Radius of influence zone (km) |
|------------|-----------|-------------|--------------|------------|------------|----------------------|--------------------------|-------------------------------|
| 21/07/2013 | 23:45:56  | 34.5°N      | 104.2°E      | 10         | 6.2        | Gansu, China         | 2621                      | 463                          |
| 24/09/2013 | 11:29:48  | 27.0°N      | 65.7°E       | 10         | 7.4        | Pakistan             | 1217                      | 1520.5                       |
| 28/09/2013 | 07:34:10  | 27.2°N      | 65.9°E       | 20         | 6.8        | Pakistan             | 1196                      | 839.5                        |

It may be noted here that, although we have chosen a best possible location for installing the sensors in the Agricultural fields of the Bichpuri Campus of R.B.S. College, Agra (about 12 km west from Agra city in rural area) where electrical and electromagnetic disturbances are low, the data quality does suffer from such disturbances. However, these problems are occasional and we do take adequate precaution in selecting the data. Especially, the problem arises due to train movements about 300 m away from the sensors. But the noises due to train movements (at specific times) appear as spikes on the dynamic spectrum and are so insignificant that they do not appear in the PSD. Thus, we have clear SR peaks and other characteristics in the frequency-time spectrograms and corresponding PSDs.

3. Results and Discussion:

As mentioned earlier, we have analyzed the SR data obtained at our station for a period of one year from 01 January to 31 December, 2013 to look for anomalies in the data associated with earthquakes. For this purpose, we first considered the earthquake data obtained from Indian Meteorological Department (IMD), India website www.imd.gov.in corresponding to the criteria adopted by us which included large magnitude (≥ 6.0), shallow depths (≤ 20 km) and nearer to our station with epicenters in India or in neighbouring countries of Bhutan, China, Pakistan, Afghanistan, etc. We find that the three earthquakes that satisfy this criteria occurred in the countries of China and Pakistan in the months of July and September, 2013. The details of these earthquakes are given in table 1 and their locations are shown on the map of Fig. 2 with solid circles along with the observing station Agra by a star. Along with the details of the earthquakes, the table also shows the distances of epicenters from Agra station and radii of the influence zones which are calculated by the expression $R = 10^{0.43M}$ where $M$ is the earthquake magnitudes (Dobrovolsky et al., 1979). There were two more earthquakes occurred with epicenters at Pakistan-Iran border and Sichuan (China) in the month of April, 2013 of large magnitudes of $M = 7.8$ and 6.6, but they are not considered here because of large depths of occurrence at 46 km and 29 km respectively.
Then, we examined the SR data in detail first in all the months of year 2013. We found that there were no SR modal or submodal anomalies occurred in any month except July and September in which earthquakes mentioned in table 1 occurred. Hence, we study these anomalies carefully and report the results here. We find that anomalies occurred as enhancements in submodal amplitude in some cases after SR third band (SR3) and in other cases after both the SR third band (SR3) and SR fourth band (SR4). An example of such anomalies may be seen in the PSD of Fig. 1b. Such submodal anomalies in the form of amplitude enhancements are also seen in both Fig. 5a and 5b (normal and abnormal conditions) of Hayakawa et al. (2005). These anomalies are not explained and we explain them in this paper. For clarity in presentation, we amplify the signal amplitude between 20 Hz and 30 Hz and show the result in Fig. 3.

As seen from this figure, the submodal bands occurred after SR3 (20 Hz) and SR4 (26 Hz) at the frequencies of 23.4 Hz and 27.0 Hz respectively with enhancements of more than 10 dB. Now we analyze the data in detail for average enhancements in amplitude, duration of anomalies, precursory days, and frequency shifts. In Fig. 4a and 4b we show, the occurrence of exceptionally large enhancements before and after the respective earthquakes in the months of July and September, 2013. The dark and white histograms indicate the enhancements for the anomalies associated with the SR3 and SR4 bands respectively. As may be noted from Fig. 4a, there were no anomalies associated with SR4 bands and the amplitude enhancements increased up to 12 dB. However, Fig. 4b shows anomalies associated with both the bands and large enhancements ≈ 15 dB for SR4 than SR3.

Figs. 5a and 5b show the duration and precursory days of anomalies associated with the earthquakes under consideration. From the top panel, the duration is ≈ 6 hrs for the large earthquakes occurred in September than that occurred in July. Similarly, the precursory days are 7 days for the earthquakes of magnitude 7.4 but if we include this to the effect of the later earthquake (M = 6.8) the precursory days for M = 6.8 is 11 days. In the next Fig. 6 we show the average frequency shifts from SR3 and SR4 associated with respective earthquakes in the two months. The gaps in the top Fig. 6a are due to non-availability of data. Here, we find that average frequency shift is large ≈ 3.5 Hz for SR3 but it occurred after the earthquake, whereas negative shifts < 1 Hz (with negligible enhancements not shown in Fig. 4a). Fig. 6b shows the average frequency shifts for the two bands associated with the large earthquakes occurred in the month of September. Here, the shift increases from 2 Hz to 4.1 Hz for SR3 and 1.5 Hz to 2.5 Hz for SR4 before the occurrence of the two earthquakes.

From the above results we find that all the anomaly parameters are higher for the earthquakes in September than those occurred in July, 2013. There may be two reasons for this. One reason is that two big earthquakes occurred in this month within a span of 04 days. Since locations of the two earthquakes are close to each other, it is possible that the one that occurred on 28 September (M = 6.8) may be the
The aftershock of the earlier one that occurred on 24 September (M = 7.4). The other reason may be that the observing station lies very well in the area of influence of the earlier one and close to that of later.

Hayakawa et al. (2005) have reported the frequency shift ≈ 1 Hz in the 4th band associated with Chi-Chi earthquake. If we compare our result of Fig. 6b with that obtained by Hayakawa et al. (2005), we find that submodal anomalies occurred at higher frequencies between 1 Hz and 2.5 Hz. Further, the anomalies after 3rd band lies at higher frequencies in the range of 2 Hz to 4.1 Hz. The occurrence of these submodal anomalies depends on source observer geometry as do the SR modes. In order to explain the occurrence of submodal anomalies we make a similar assumption as that done by Hayakawa et al. (2005) in which it is shown that ELF waves from the South American thunderstorm are scattered in the atmosphere by a conducting disturbance over the earthquake region and interact with the direct waves to produce strongest effect (constructive maxima) as SR anomalies.

We have examined all possible paths of propagation from 03 different thunderstorm centers of Asia, Africa, and America, their scatterings from the disturbances in the atmosphere over the epicenters of earthquakes and then strongest effect at the receiver over Agra. We find that for the anomaly observed...
in July corresponding to Chinese earthquake, the African Center is the most contributing, while for the anomalies observed in September corresponding to Pakistan earthquakes it is South Asian center most contributing. The analysis of Y-component data shows that the submodal anomalies in the above cases are very feasible with low enhancements suggesting thereby that the signals have travelled mostly in E-W direction i.e. the direction in which the thunderstorm sources exist. While the submodal frequency in the case of July earthquake is found to be 23.4 Hz which matches very well with the observed anomaly in Fig. 1b, the submodal frequencies are larger about 51 Hz for September earthquakes which is not good but not very bad either. The detailed geometry is shown in the last Fig. 7a, b. Please note that the locations of the ELF sources (Thunderstorms), earthquakes, and observing station in the figure are symbolic for clarity and they should not be compared with their positions on the map.

Now the question may be asked about the reality of the anomalies. In order to answer this it may be mentioned here that the anomalies occurred in the months of July and September only when there occurred the three large earthquakes (M ≥ 6) with shallow depths and in the region of the observations. The July to September months correspond to large thunderstorm activities in the region. These conditions are similar to that in which SR anomalies were observed at Nakatsuwa station in Japan corresponding to Chi-Chi earthquake in Taiwan. We have also mentioned earlier that a major source of disturbances at our observational site is the movement of trains about 300 m away. However, the noises due to train movements appear as spikes in the data and sometimes as narrow horizontal line at 16 Hz which are easily identified. Further, they are not associated with power lines (frequency 50 Hz) as the fluctuations in power line frequencies are very rare in this area. Moreover, anomalies at 27 Hz and above cannot be associated with power lines. Hence, the anomalies reported in this paper are real and convincing.

4. Conclusion:
Employing a set of 3-Coponent search coil magnetometer, we have studied SR submodal anomalies in the form of enhancement of amplitudes above third and fourth resonance band frequencies observed in the month of July and September, 2013 out of the whole year of data analysis from 01 January to 31 December, 2013. We find the amplitude enhancements between 10 and 15 dB and frequency shifting from SR modes between 1 Hz and 4 Hz for the two bands. We show that these anomalies occurred in association with large earthquakes (M > 6.0) in China and Pakistan as a result of constructive interference between the direct ELF signals generated from the African and South Asian sources.
reaching the observational site at Agra and those reflected from the disturbances in the atmosphere (ionosphere) over the seismic region reaching the observational site.

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