Schumann Resonance spectral characteristics: A useful tool to study Transient Luminous Events (TLEs) on a global scale

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ABSTRACT: The background Schumann Resonance (SR) spectra require a natural stabilization period of ~10-12 minutes for the three modal parameters, namely, the frequency, intensity and Q-factor to be derived from Lorentzian fitting. Before the spectra are computed and the fitting process is initiated, the raw time series data need to be properly filtered for local cultural noise, narrow band interference as well as large transients in the form of global Q-bursts. Mushtak and Williams [2009] describe an effective technique named as Isolated Lorentzian (I-LOR), in which, the contribution from local cultural and various other noises are minimized to a great extent, and enabling the problem of inter-modal interference to be more effectively addressed in the SR background spectra. An automated technique based on median filtering of time series data and the rejection of events exceeding 16 core standard deviations (CSD) (where 'core' pertains to the central portion of the "spectral power content") from the average of the period of interest has also been developed by Mushtak et al. [2012]. This cleaning of data before obtaining the modal parameters is essential for work related to the background SR, for example, finding the source strength of tropical 'chimney' regions by inversion of multi-station data. The methodology used for removing the effect of Q-bursts from background SR spectra could also be used to search for big sprite-producing positive lightning flashes in mesoscale convective systems worldwide. These special lightning flashes are known to have greater contribution in the ELF range (below 1 kHz) compared to negative CG strikes [Cummer 2006]. The global distributions of these Q-bursts have been studied by Huang et al., [1999] and Hobara et al. [2006] by wave impedance methods from single station ELF measurements at Rhode Island, USA. The present work aims to demonstrate the effect of Q-bursts on SR spectra using GPS time-stamped observation of TLEs and average energy data from the VLF World Wide

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Lightning Location Network (WWLLN). It is observed that the Q-bursts selected for the present work do alias with the background spectra over a five second period, through the amplitudes of these Q-bursts are far below the 16 CSD limit so that they do not strongly alias the background spectra of 10-12 minute duration. The extent of this aliasing is yet to be investigated thoroughly. It is expected that the spectral ELF methodology could be used effectively to detect TLEs globally with a small number of networked stations, especially during daylight conditions, when optical measurements of sprites are not possible.

INTRODUCTION

It is known that the background and transient activity in Schumann Resonances (SR) are physically linked [Williams et al., 1999]. However, it is not completely known how ELF transients affect the background SR spectra within a stabilization period of several minutes. Mushtak et al. [2012] described how the background SR modal parameters could be sanitized by rejecting the time series containing the Q-bursts above 16 core standard deviation (CSD) technique. The 16 CSD method could also be used to filter out the local cultural noise that can spoil the background SR spectra. The motivation of this work is to investigate whether one large ELF transient from a positive lightning stroke (Q-burst) has sufficient energy to alias the background spectra within a given time period, thus modifying its background spectral shape.

When using Schumann resonance (SR) electromagnetic observations for monitoring global background lightning activity, it is essentially important to sanitize the experimental material from any non-background elements. Even though the actual data to be used in such an inversion problem are the resonance characteristics: namely frequency, intensity, and quality factor of several first SR modes-- the sanitizing requirement makes it necessary to start the processing directly with the initial time series.

Obvious candidates to be sanitized are local interferences of various kinds: external man-made, weather-related, internal equipment-related, etc. These elements can be relatively easily identified and eliminated. Other candidates for sanitizing are of less obvious nature. In this category are transients, strong signatures produced by intensive lightning discharges whose impulsive signatures dwarf the background levels. Since the transients are of the same lightning origin as the background component, there is a temptation to include their parent discharges into the background ensemble as its high-energy "tail". These transients are easily capable of aliasing the background spectral signature.

## METHODOLOGY OF CLEANING BACKROUND TIME SERIES

To demonstrate local interference and estimate the transients' effect on the background SR parameters, we examine observations from two stations: "BLK" (Belsk, Poland) and "NCK" (Nagycenk, Hungary), separated by a small distance (in ELF terms, of course) of about 550 km, which provide an opportunity to both exclude local interference and estimate the transients' effect on the background SR

parameters. The initial experimental material (figure 1) is presented in 12-minute intervals, further called "periods" from the initial electric time series registered at both stations during ten days in January 2009.
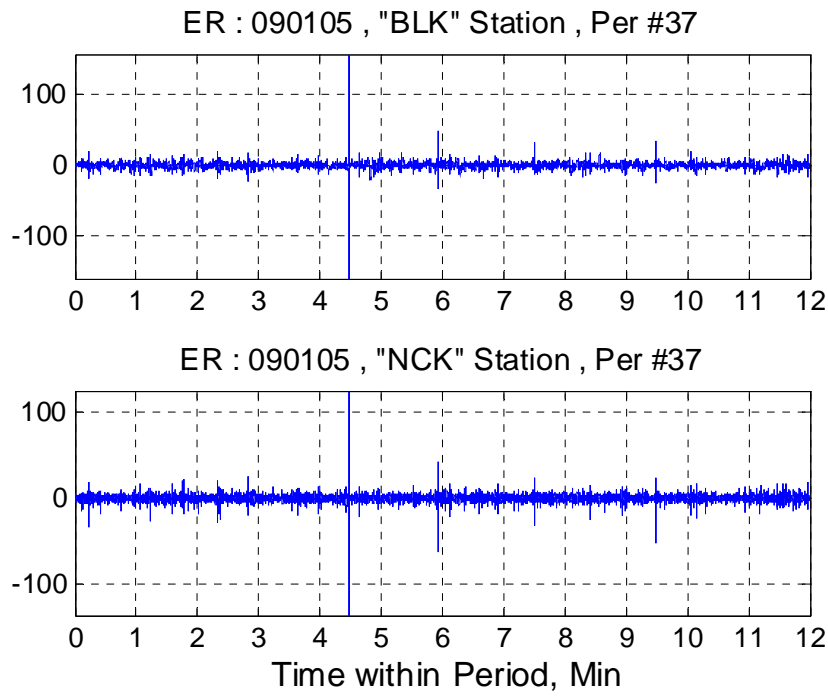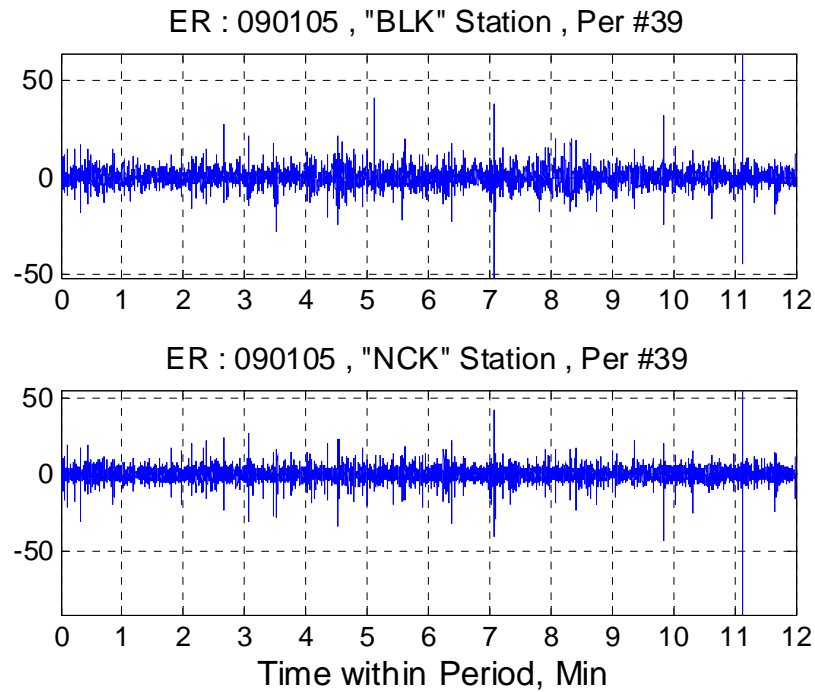

Figure 1: Examples of 12-minute electric time series registered simultaneously at two "ELF-close" locations and containing: (A) two medium transients (B) a super-strong transient signature

To identify the presence of contaminating elements, each 12-minute period is divided into 144 portions, hereafter called "segments". One such segment containing a transient is shown in figures 2.
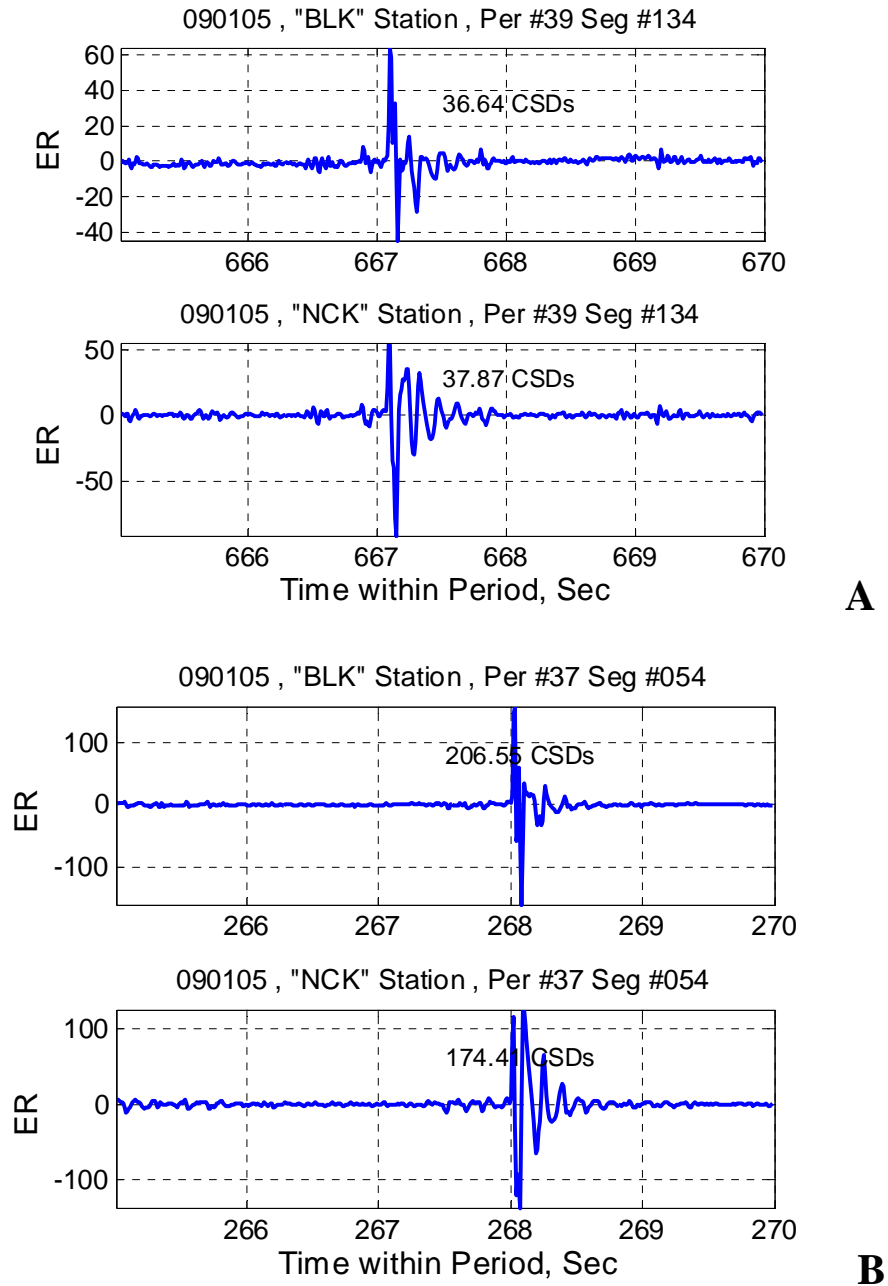

Figure 2: Examples of a medium transient (A) and a super-strong transient (B) registered simultaneously at two "ELF-close" locations within 5-sec segments

For each segment, the spectral power density (SPD) is calculated and integrated over the first four SR modes into the spectral power content (SPC) and the histogram of the SPCs (figure 3) for the given period is analyzed.
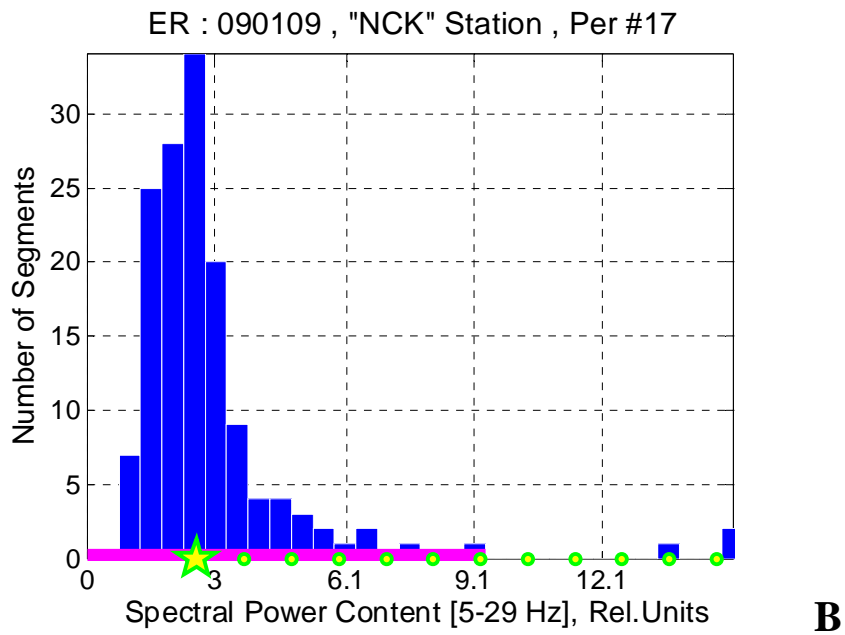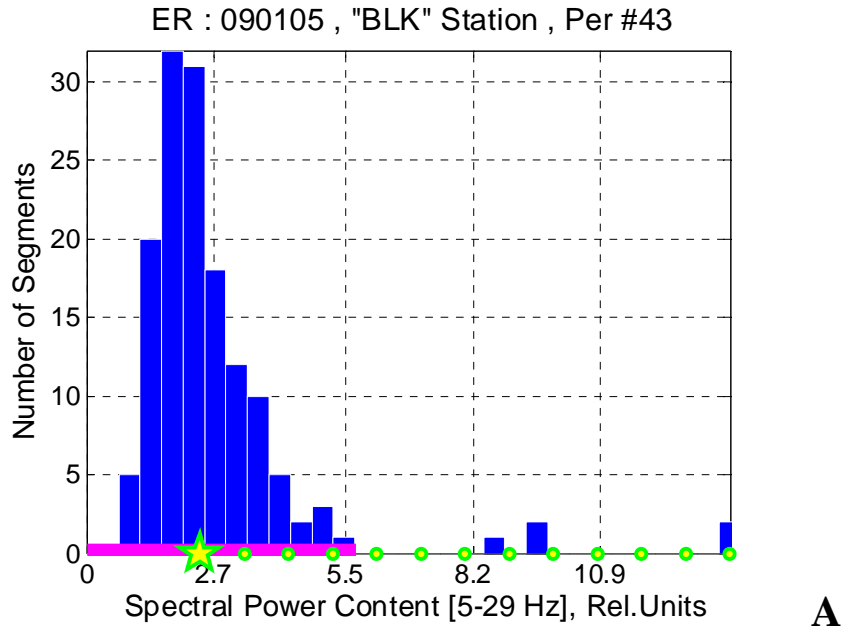

Figure 3: Examples histograms of spectral power content from 12 minute (144 5-sec segments) data segments in Figure 1. The core distributions are indicated by magenta bars, the core means and standard deviations by stars and circles, respectively

The general form of the SPC histograms is a "core" distribution (marked by magenta bars in figure 3 and associated mainly with the background contribution) followed by segments with SPCs of questionable origins from the "background" point of view. To investigate this "tail", the core mean value (CMV, stars in figure 3) and the core standard deviation (CSD, circles in figure 3) of the core distribution are computed. The stabilization diagrams (figures 4 and 5) – defined as the dependence of SR parameters (modal frequencies and intensities) from the threshold, expressed in CSDs, the contributions of the segments with SPs beyond this threshold are eliminated. (In the diagrams, the deviations of the modal frequencies and intensities from their values at 16 CDs are shown.)
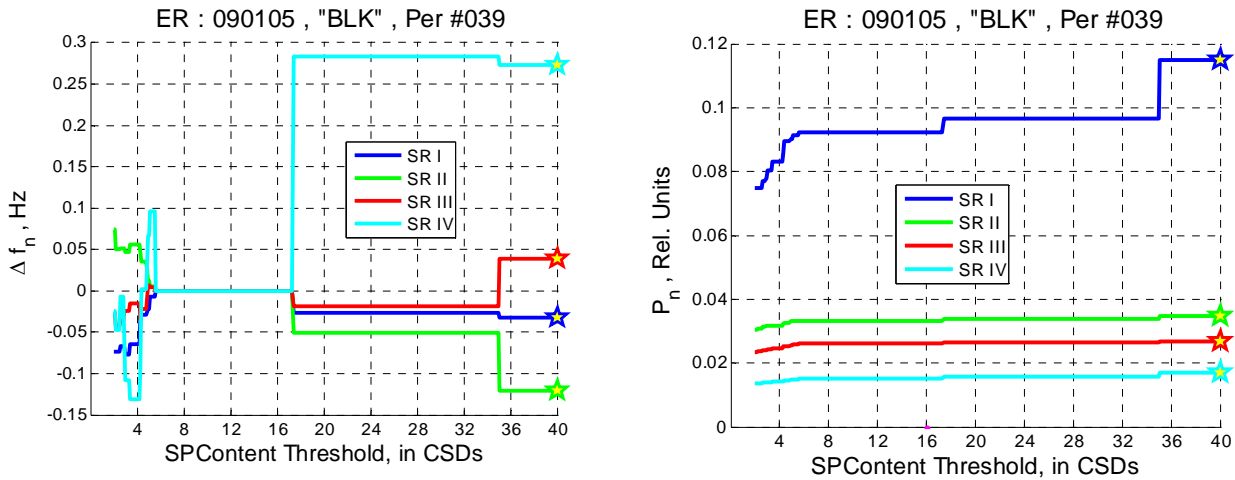
**Figure 4: The stabilization diagrams for period #039 on January 05, 2009. The pentagrams show the un-sanitized (raw) SR parameters. The effects of two transients are clearly seen**
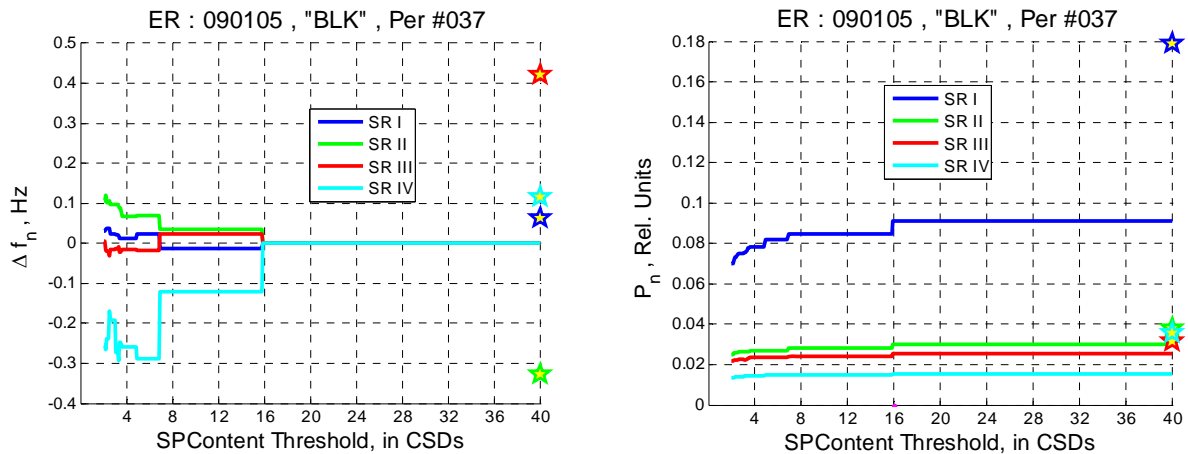
Figure 5: The stabilization diagrams for period #037 on January 05, 2009. The pentagrams show the un-sanitized (raw) parameters. The effect of a strong transient is demonstrated

The general form of a stabilization diagram (figures 4 and 5) shows an initial portion where the background is underrepresented, due to which the SR parameters vary within this portion of the diagram. The portion is followed by the proper stabilization interval, where the background is presented to its full extent; and then, sometimes, by the destabilization interval due to the presence of the non-background elements that do distort the previously stabilized SR parameters.

In figure 6 are shown stabilization intervals for the same day of January 2009 from the "BLK" and "NCK" locations. A quantitative correlation between stations can be seen. These plots as well as the results for other days and stations show that the threshold of 16 CSDs is, as a rule, located within the stabilization interval. An event originating from either cultural noise or from a large natural Q-burst transient in a segment with SPC beyond this threshold is causing a distortion of SR parameters and so is to be considered a non-background element, and so needs to be eliminated.
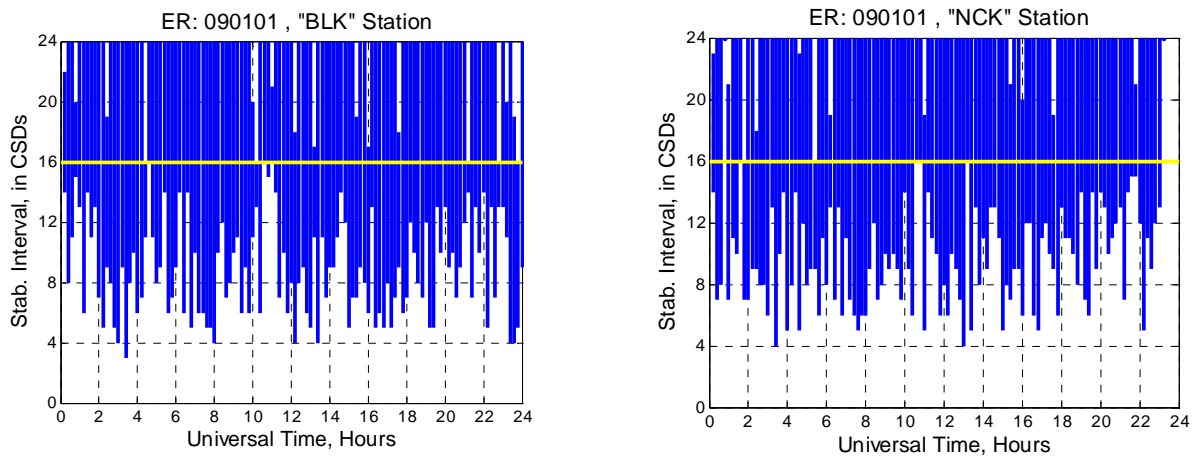
Figure 6: Stabilization intervals vs. universal time for electric SR observations at two "ELF-close" locations

The distorting effect of local interference is usually evident and besides, can be eliminated by simply comparing the SPCs from two "ELF-close". In contrast, the influence of a transient event may be more subtle and the record cannot be sanitized by this comparison procedure. Nevertheless, "the rule of 16 CSDs", despite the empirical nature of both the CSD and the rule itself, is efficiently working for the transient events as well, whether they be medium (period #39) or super-strong (period #37) events. As a result, the 16 CSDs threshold can be accepted as a "frontier" between the background and transient global lightning populations.

DATA SELECTION FOR THE PRESENT STUDY

For the present study, 4 kHz-sampled ELF data in the SR band from Rhode Island (RI), USA is used along with video camera observations of sprites from the Ebro Delta in northeastern Spain. The data from the World Wide Lightning Location Network (WWLLN) are also used to identify the parent stroke and its average VLF energy. All the data are time stamped in UT using GPS synchronization. Initially, thirty five

sprite events were selected spread over eight days from the years 2011 to 2013. Out of the eight days, six days of ELF data were available from RI. Twenty one possible ELF events were identified from the ELF time series data that could have possible correlation with the causative Q-burst lightning near Ebro Delta. Out of these twenty one events, nine events were selected to search for the causative strokes from the WWLLN data base. Based on the average energy of the parent Q-burst identified from the WWLLN data, three most powerful strokes were considered for final analysis in the present work. The parameters for the three selected events are furnished in Table 1.

Table 1: The sprite and WWLLN parameters for three selected ELF events

| Date (YYYYMMDD)	Sprite detection time (UT)	Sprite latitude (Degree)	Sprite longitude (Degree)	peak current(kA)	WWLLN detection time (UT)	WWLLN latitude (Degree)	WWLLN longitude (Degree)	WWLLN average energy (kJ)	WWLLN energy uncertainty (kJ)
20111120 (event 1)	03.35.51.289	40.8818	0.6579	51	03.35.51.2893	41.1002	0.5753	32	13
20111120 (event 2)	03.42.50.711	40.8801	0.6579	49	03.42.50.7118	40.9217	0.736	120	72
20111120 (event 3)	03.49.07.085	40.9982	0.5353	122	03.49.07.086	40.9636	0.5516	59	32

OVSERVATIONAL RESULTS

The three selected sprite events and corresponding ELF time series are shown in figure 7a, 7b and 7c. The observed sprite from Ebro Delta is shown in the upper panel. In the lower panel, the ELF time series from RI is plotted. The red line indicates the time of occurrence of the sprite event. Note the finite delay of 20-25 ms between the time of occurrence of the sprite and the peak Ez amplitude of the ELF transient arriving at the RI station. This time is consistent with the propagation delay along the great circle path between the causative Q-burst origin around Ebro Delta and the RI station.
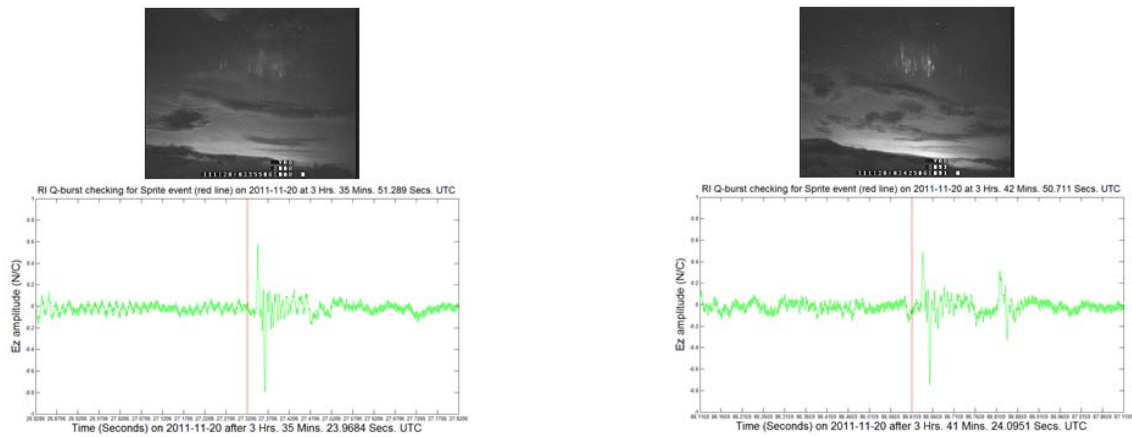

7a

7b
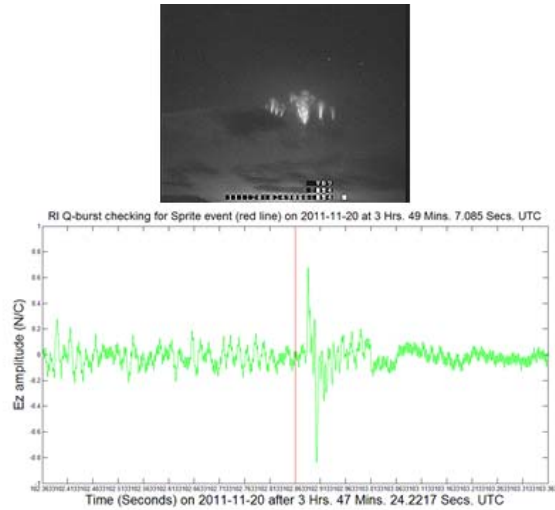
7c

Figure 7: The sprite events and corresponding ELF time series from Rhode Island. The red line indicates the time of occurrence of the sprite event

The temporal correlation of WWLLN-measured VLF energy [Hutchins et al., 2013] of the sprite causative Q-burst with the ELF transient is shown in figure 8a, 8b and 8c for a five-second time segment containing the ELF transient. The average energies of the three Q-burst events are 32, 120 and 59 kJ respectively. The red rectangular box shows the most energetic WWLLN stroke within the selected time interval and that corresponds to the sprite-producing Q-burst.
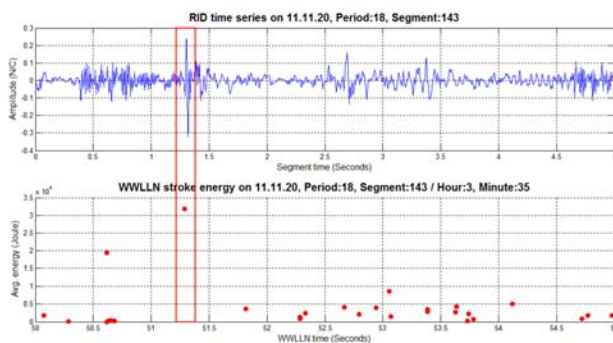
8a
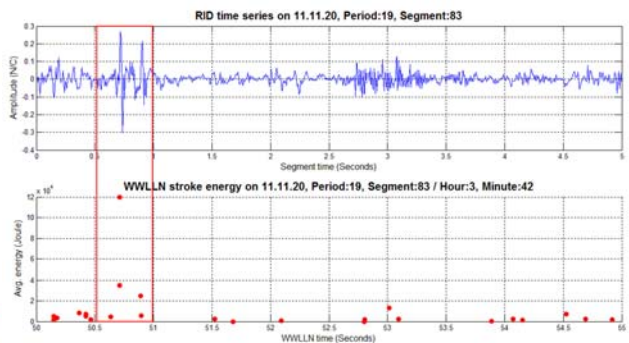
8b
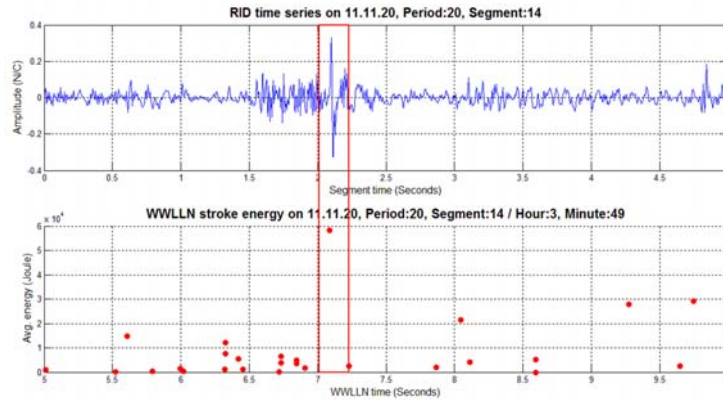
8c

Figure 8: The sprite events and corresponding WWLLN-computed average VLF energy. The red box contains the causative stroke detected by the WWLLN and the ELF transient

Now, the background spectrum is computed for a five-second segment and the transient is included so that the total segment becomes six seconds. The analysis is performed considering the background segment before and after the selected transients. The results are shown in figure 9a to figure 9f. In all the cases, we should not consider the third mode as it is contaminated by 20 Hz interference. The observation is summarized below:

Event 1, background segment after transient (figure 9a):

Due to the transient, first mode amplitude becomes 30% more than the background value. Higher modes above the third mode exhibit greater amplitude compared to the background spectra.

Event 1, background segment before transient (figure 9b):

Due to the transient, the first mode amplitude becomes 30% greater than the background value. Higher modes than the third mode have more amplitude compared to the background spectra.

Event 2, background segment after transient (figure 9c):

Due to transient, the second mode shows a shift in frequency. Higher modes above the third mode have greater amplitude compared to the background spectra.

Event 2, background segment before transient (figure 9d):

Due to transient, the second mode shows 20% increase in amplitude. Higher modes above the third mode show greater amplitude compared to the background spectra.

Event 3, background segment after transient (figure 9e):

Due to the transient, the first as well as the second mode amplitude becomes 30% more than the background value. Higher modes above the third mode show greater amplitude compared to the background spectra.

Event 3, background segment before transient (figure 9f):

Due to the transient, the first mode amplitude becomes 30% greater than the background value. Higher modes above the third mode show greater amplitude compared to the background spectra.

In summary, for the three cases we selected for the present study, for all the cases, the transients do alias the five-second background spectra in increasing the first and/or second mode amplitude. The common feature is that all the higher modes above the third mode show greater amplitude compared to the background spectra.


9a   **9b**

9c

9d

9e

9f
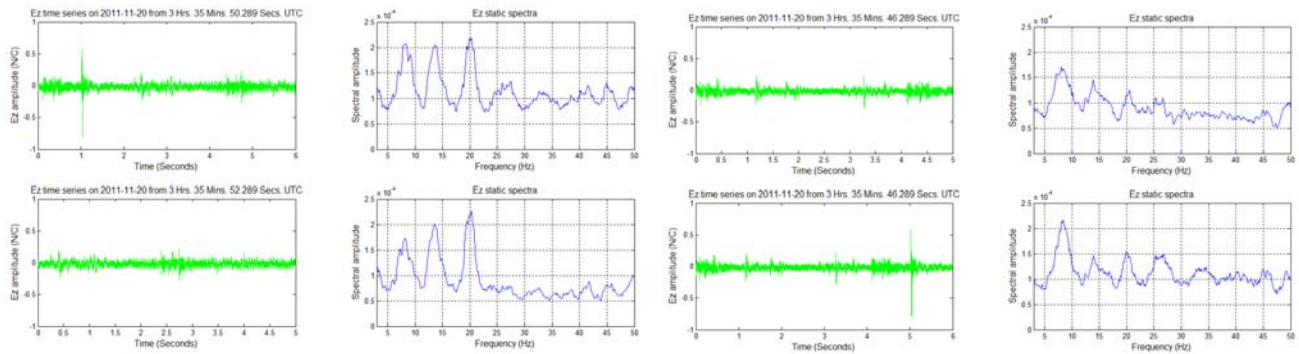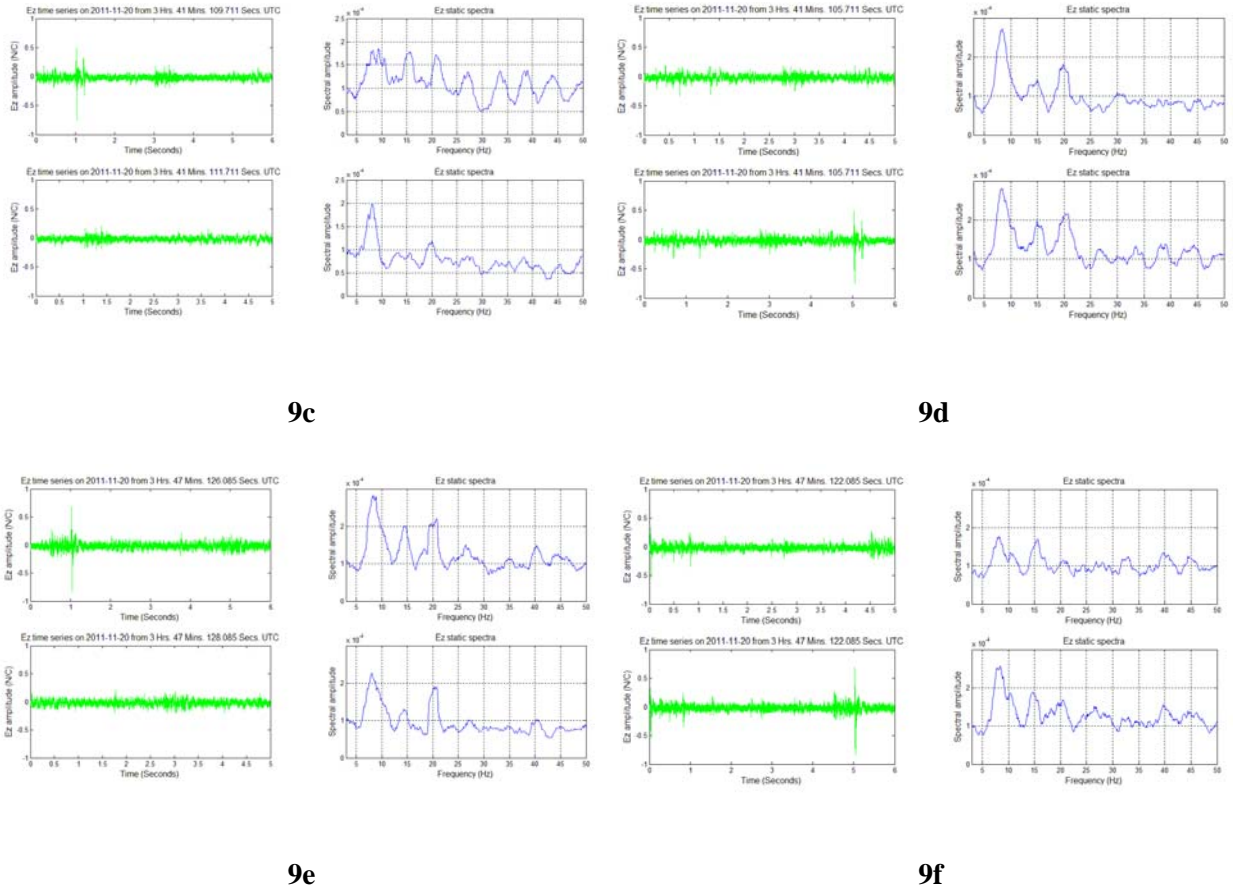
Figure 9: Five-second segment time series and spectral analysis for the three selected transient events

The same analysis is now performed on a one-minute time series segment that first does not include the transient. Then the transient is included for duration of one additional second. The analysis is shown in figure 10a, 10b and 10c. No aliasing over the one-minute time period is discernible. This finding indicates that the selected transients may not be of sufficient amplitude to alias over one minute even if they are capable of aliasing over five-second segments.
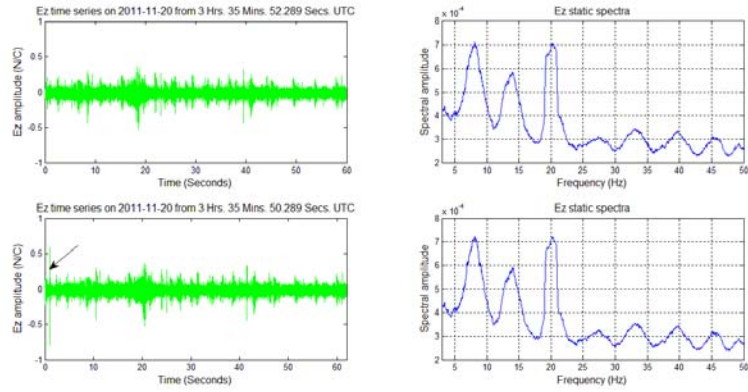
10a
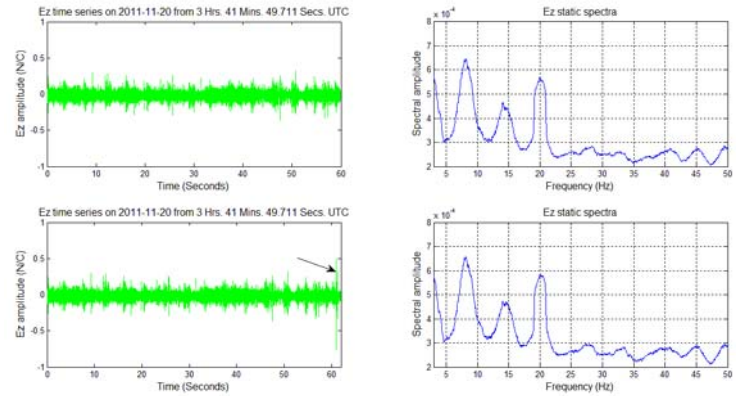
10b
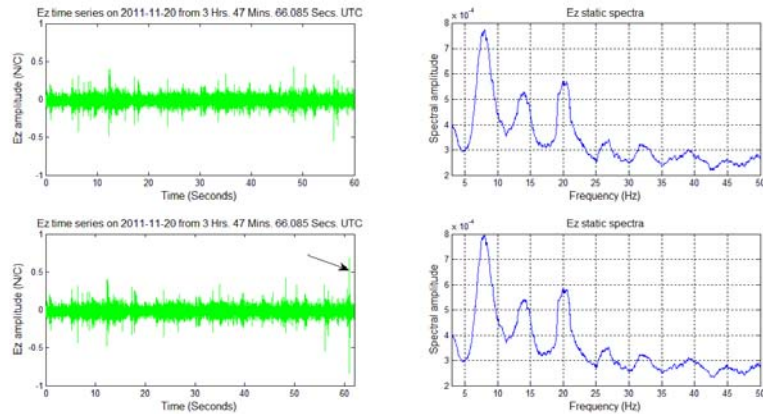
10c

Figure 10: One-minute segment time series and spectral analysis for the three selected transient in parts (a), (b) and (c), respectively

DISCUSSION

The analysis of three selected Q-bursts events show that the amplitudes of these events do not exceed 16 CSD over five second intervals. So, we can discern an aliasing effect over five-second intervals, but when the time interval is extended to one minute, the aliasing becomes undetectable. Since the events are below 16 CSD, it is unlikely that they would have discernible footprints in the 12-minute background spectra.

It is to be noted that the CSD criteria pertain to 'giant' Q-bursts that have sufficient energy within the time domain for which we compute the background, so that it can alias with the background spectra over that time domain. The criteria is first applied to a five-second segment to test if it can significantly (above 16 CSD) alias with the five-second spectra, and if so, the complete five-second segment is discarded from the average FFT of 144 segments. This way, we include only those five-second segments within a 12-minute period that contain lightning stokes having amplitudes comparable to background activities (irrespective of whether those lightning strokes manifest as Q-bursts, but not having sufficient energy to change the background spectrum significantly).

The stabilization diagram (figure 5) clearly shows that within an amplitude window of the CSD of around 5-17, the modal parameters are unaffected by the CSD selection criteria. If the transient amplitude was greater than a threshold value, severe aliasing took place so that the SR modal background parameters over five-second intervals were affected. It is to be noted that selection threshold below 5 CSD, the modal parameter computations also shows destabilization and becomes 'underrepresented'. This means, below 5 CSD, we start to remove the background components also and thus it affects the modal parameters. Above 16 CSD, we start to include large transients and thus again spoiling the background character.

It is also to be noted that a moderate transient with respect to the 16 CSD criteria is around 40 CSD and for a giant transient, it is around 200 CSD (figure2). In comparison to that, the three present cases have modest amplitudes, and below 16 CSD. So, they might not have sufficient amplitude even in a five-second window to alias with the background considerably, but still show some indication of aliasing. If we had found any sprite event having very large average energy with respect to WWLLN median TLE producing energy is concerned, those transients could have contained sufficient energy to fulfill the 16 CSD criteria.

In this context, one question that must be addressed is why 16 CSD appears to be a universal threshold for aliasing of the SR background by Q-burst transients? Let us assume

A_B = amplitude of background signal, A_Q = amplitude of Q-burst signal, T_B = duration of background

segment used to compute FFT and T_Q = duration of Q-burst transient

We assume that when the spectral energy of the Q-burst transient is comparable to the spectral energy of the background signal, we will then have interference problems (spectral aliasing of background signal) Since spectral energy is proportional to the square of amplitude, this condition amounts to

$$A_B{}^2 T_B = A_Q{}^2 T_Q$$
$$A_Q / A_B = sqrt(T_B / T_Q) \qquad\qquad (1)$$

Now, if we take a 6-minute window to compute the background FFT, and assuming that the Q-burst transient shows three round trips around the world, this quantity can be evaluated as

$$sqrt(6(60)/0.4) = sqrt(900) = 30$$

This result is within a factor of two of the factor 16 CSD (standard deviations of the background amplitude).

It is worth mentioning that maybe there could be some fundamental interaction between background and transients phenomena, such as an accumulation of charge imbalance that leads to the ultra large transient. This interaction also deserves a thorough study.

The long-standing working hypothesis is that the transients represent the mesoscale lightning "tail" in the diurnal variation, with the background signal coming primarily from the earlier late-afternoon convective activity (of ordinary thunderstorms). The presence of the mesoscale "tail" may rest on the meteorological tendency for late afternoon convective scale thunderstorms to amalgamate into late evening mesoscale convective systems. As the former entities are excellent producers of background SR signal, whereas the latter ones are exceptional producers of energetic transients of the kind observed as "spoilers" in the experimental results.

CONCLUDING REMARKS

Based on the analysis, we conclude that the giant Q-bursts do not destroy the SR background spectra completely, but can modify their spectral content, and thereby alias the spectral input to a background inversion method. The extent of this modification is yet to be investigated thoroughly, by gaining access to natural transients of still greater amplitude than those studied here. Though, the present three sprite generating cases did not have sufficient energy to alias the longer time series data, it is planned to compare the modeled spectra over the great circle path between the source and observer, with the observed ~10-12 minute spectra, to distinguish variable propagation effects from source characteristics. It is expected that the spectral ELF methodology could be used effectively to detect TLEs globally with a small number of networked stations, especially during daylight conditions, when optical measurements of TLEs are not generally feasible.

ACKNOWLEDGMENTS

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