Graphical Schemes Designed to Display and Study the Long-term Variations of Schumann Resonance

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***Abstract*—This work proposes and illustrates a graphical approach aimed at studying a wide range of features of the ELF horizontal magnetic field signal recorded at the Sierra Nevada station (Spain). In addition to the traditional long-term variations in the parameters of the first three Schumann resonances (their amplitudes, central frequencies and widths), many other properties such as the saturations of the magnetometers, anomalous values for the parameters or spectra with any kind of particularities are taken into consideration in this work. These features can provide us with complementary information about the long-term variation of Schumann resonances, give an estimation of the extent up to which the results obtained are reliable and be correlated with the occurrence of lightning events or with changes in the electrical properties of the ionosphere. The scheme proposed in this work allows to instantaneously display the variations of all these features within a desired period of time.**

***Index Terms*—Schumann resonance, signal processing, ELF transient events**

I. Introduction

Schumann resonance (SR) is a natural electromagnetic phenomenon that attracts scientific interest due to its applications to trace the ocurrence and the evolution of environmental phenomena and atmospheric events [1]. This resonance belongs to the Extremely Low Frequency (ELF) band of the EM spectrum (the three first resonances are in the range 6-25 Hz). A magnetic field measurement station with two horizontal magnetometers oriented in North-South and East-West directions, respectively, was placed in Sierra Nevada, Spain (37°02′N, 3°19′W) to study this resonance [2]. This station has been working since March 2013, with some short periods of interruption.

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The vast majority of works where recordings of the SR are analysed focus only on the long-term variations of the central frequencies and the aplitudes of the first resonances, and they do not pay attention to other features of the recordings which could both give additional information and provide an estimation of how reliable the results obtained from the long-term analysis are.

Some graphical approaches to visualize and study this alternative information, applied to the SR measurements from the Sierra Nevada ELF station, are exposed in this work together with a brief analysis of the results that can be obtained. The alternative information studied involves spectra which show a particular anomaly, the levels of saturation of the magnetometers in different periods of time, anomalous values for the parameters, and the correlation of the exact times at which saturations are detected in the magnetometers with a recording of lightning events. These graphical tools have been developed using Python.

II. Background

A unified methodology for processing SR measurements has recently been proposed in [3]. In this paper, both a consideration about how the SR parameters (the central frequencies, amplitudes and half peak widths) should be defined and a procedure to obtain them from the raw magnetic field recorded at the Sierra Nevada ELF Station are explained in detail.

The scheme explained in that paper, which is based on the Welch method, is applied to each 10 minute interval of the signal measured by both magnetometers, providing a time series of the parameters that characterize the SR (central frequencies, amplitudes and half peak widths for each one of the three first resonances) and their evolution through a minimun square fit using three Lorentzian functions. The scheme also provides the percentage of the 10 second Hanning

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windows -in which each 10 minute interval is split- that contain any saturation.

All the information considered to be of interest for further analysis is stored in a .npz (numpy) file for each month and for each magnetometer. These files are approximately 40 MB in size each and make it unneccesary to continue working with any other data files. The design of tools to analyse the evolution of the different parameters and information starts at this point, making use of the files generated after the signal processing.

III. Display and Study of Different Magnitudes Related to SR Measurements

A. *Diurnal variations*

The diurnal variation of the parameters of the SR accounts for the evolution and movements of the main thunderstorm nuclei in the globe and for the day-night asymetry in the ionosphere. The first factor is considered to be of greater importance in the behavior of the diurnal variations and makes it neccesary to introduce a correction function when measurements from stations located at different places are to be compared. The diurnal variation of the parameters of SR is different in each season of the year. In Fig. 1 the diurnal and seasonal variation is illustrated, and in Fig. 2 a time-frequency analysis (spectrogram) is shown.

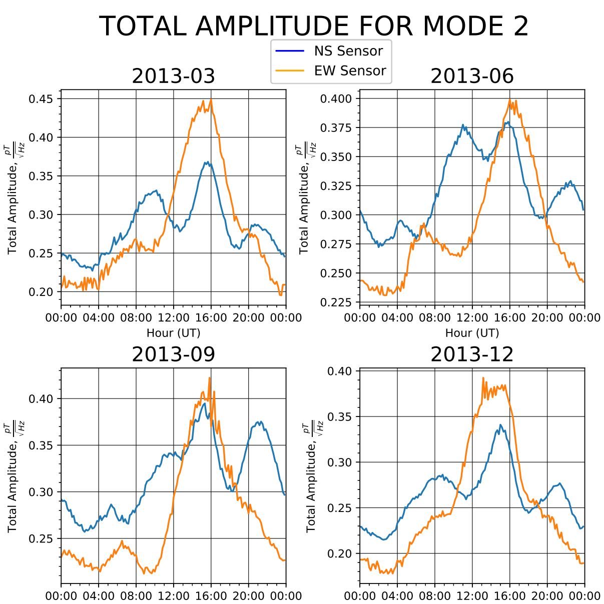

Fig. 1. Average diurnal variation of the total amplitude of the second resonance peak in January, April, July and September 2017.

B. *Masked intervals*

Most ELF stations have interruptions or gaps in which data are not properly recorded and cannot be used to study SR. In other periods of time, it can be observed that the values of some parameters provided by the processing method are unusual and unacceptable. It may happen as a consequence of a local phenomenon close enough to the station, a bad performance of the processing method or other reasons.

Both the gaps in the recordings and the anomalous parameter values must be removed (masked) from the long term analysis so that they do not affect the results, but it is convenient to keep a register of those intervals that have been removed to have information about the number or percentage of unmasked intervals that remain after the masking process (and an estimation of the significance of the results obtained), the time of the day at which more intervals are masked and the most common reasons why these intervals are considered invalid. In Fig. 3 and Fig. 4 a proposed plot to trace the masked interval is shown.

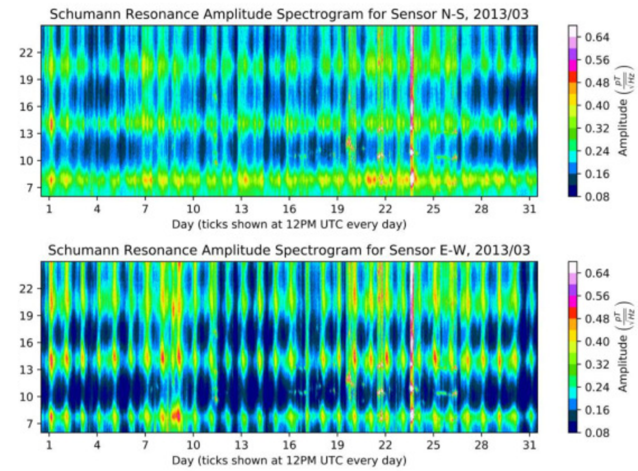

Fig. 2. Time-frequency analysis of the SR recorded in March 2013.

C. *Statistical representations*

In addition to the average value, the statistical distribution of the values of a parameter can be of interest, for example to justify which values must be considered anomalous for a parameter. Fig. 5 and Fig. 6 show the statistical distributions of the central frequency of the first mode for both sensors.

D. *Percentage of saturation*

The percentage of saturation for each 10 minute interval is the number of Hanning windows within it that contain at least one saturation of the magnetometer. All those windows that contain any saturation are not taken into account in the processing to calculate the parameters of the interval. In the Sierra Nevada station, the saturation limit is ± 10 V. The length of the Hanning windows is 10 seconds and they are overlapped so that the first half of a Hanning window overlaps the second

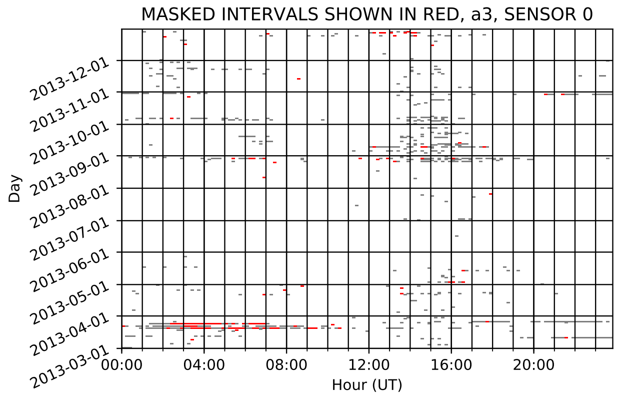

Fig. 3. Mask plot from March 2013 to December 2013. The masked intervals where an anomalous value of the amplitude of the third resonance for sensor NS (sensor 0) has been obtained are in red. The intervals with any other anomalous parameter are in grey.

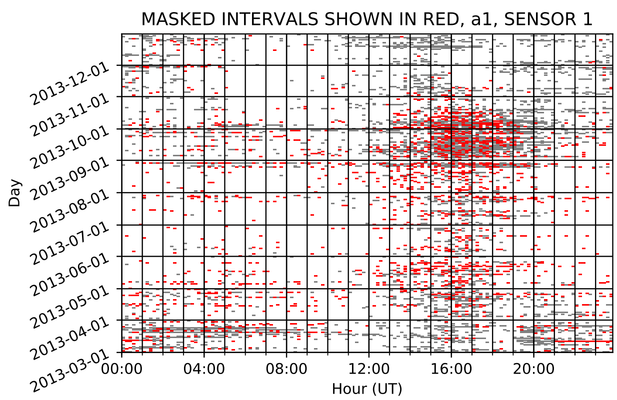

Fig. 4. Mask plot from March 2013 to December 2013. In this plot, the intervals with an anomalous amplitude the first resonance for sensor EW (sensor 1) are in red, and the other anomalies are shown in grey. This sensor was more affected by anomalous parameter values in 2013.

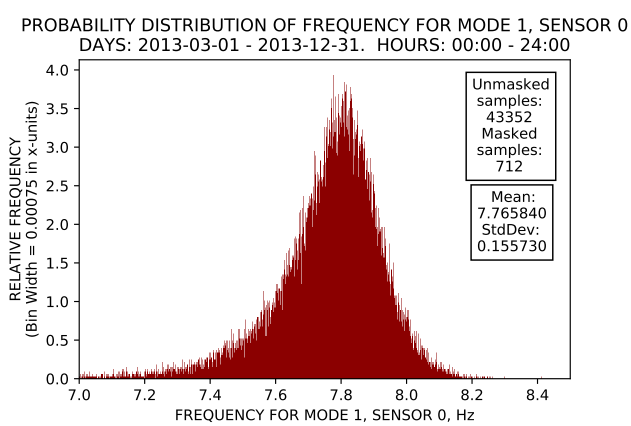

Fig. 5. Statistical distribution of the values obtained for the central frequency of the first resonance (NS sensor) between March 2013 and December 2013.

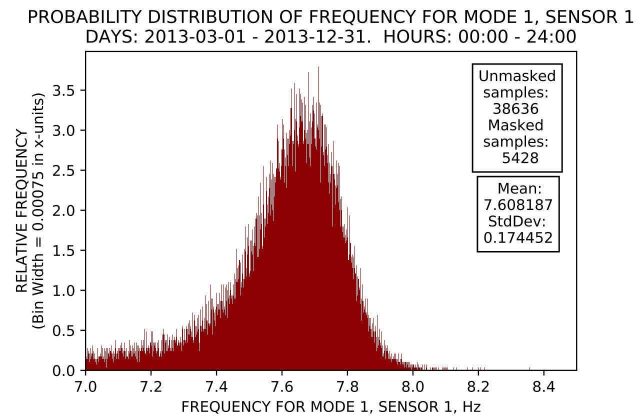

Fig. 6. Statistical distribution of the values obtained for the central frequency of the first resonance (EW sensor) between March 2013 and December 2013. Figures 5 and 6 indicate that different mask limits for the central frequency of the first resonance should be considered in both sensors.

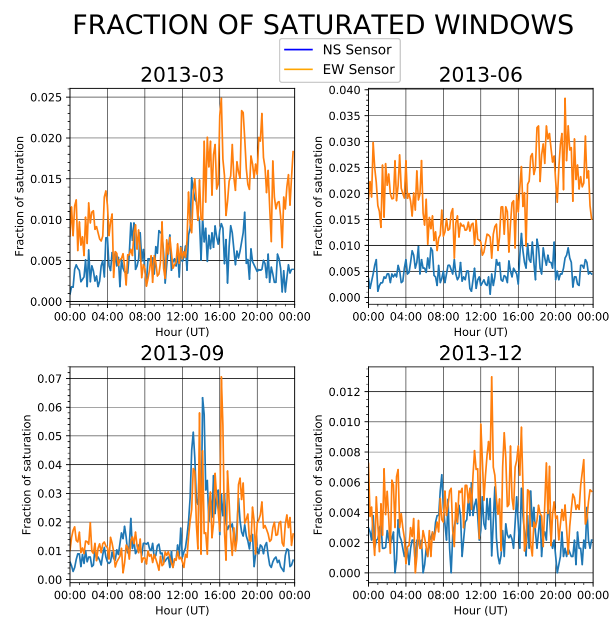

Fig. 7. Average percentage of saturation for each time of the day. Some intervals with high percentage of saturation correspond to blurred regions in the plot of the diurnal variations of the parameters in Fig. 1, for example 2013-09 16:00 or 2013-12 13:00 for EW sensor.

half of the previous one (except for the first Hanning window of each 10 minute interval).

The percentage of saturation is thus an estimator of the fraction the total duration of an interval that has been used for obtaining the parameters. This magnitude can also be an indication of the amount of lightning events ocurring close to the ELF station or strong lightning events ocurring in any place of the world, and also provides a fraction of the total time of each 10 minute interval that has been used to calculate the parameters.

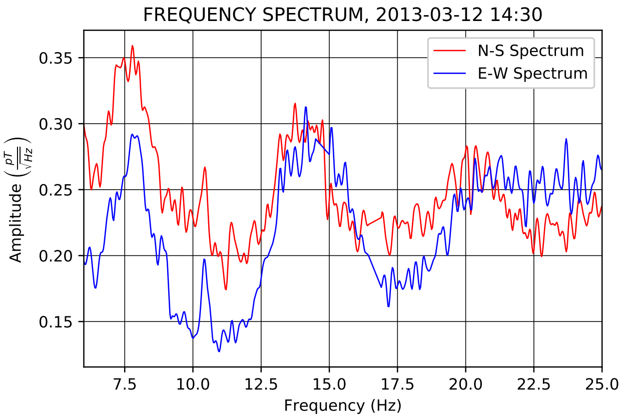

Fig. 8. An anomalous peak is observed in both sensors at 10.5 Hz for this interval. Also, the third resonance is not clearly observed in EW spectrum.

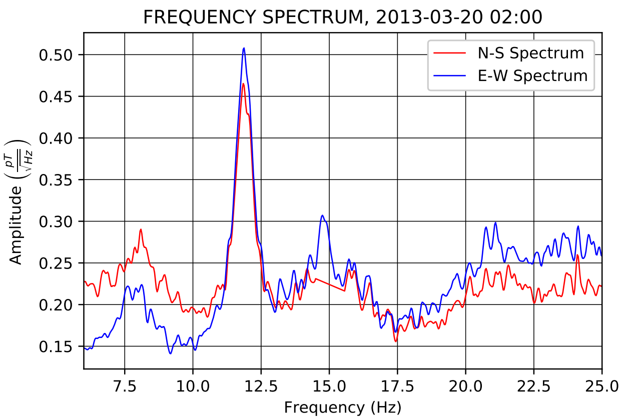

Fig. 9. An anomalous peak is observed in both sensors at 12.0 Hz for this interval. Also, there is a rise in the amplitude of both spectra in the range 22.5-25 Hz.

An plot of the saturation percentage and its diurnal and seasonal evolution is shown in Fig. 7.

E. Anomalous spectra

In addition to those intervals for which the parameters obtained after their processing are unacceptable, there are other intervals that show some particularities. An identification and classification of these particular intervals has been performed so that we can instataneously access this information and compare it with any other atmospheric parameter of interest, such as the charge concentration in the lower ionosphere.

Examples of anomalous spectra are given in Fig. 8, 9 and 10. The origin of these anomalies is unknown, but we expect it to be natural, and not anthropogenic, due to its shape [5].

F. Correlation of saturations with lightning events

The transient events observed in the measured ELF recordings (Q-bursts) have been taken into consideration in previous works [1], [4]. They are expected to be caused by close lightning events to the ELF station, by intense events in any

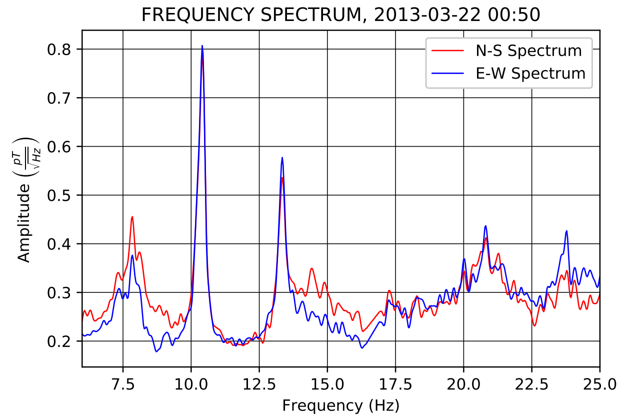

Fig. 10. Anomalous peaks are observed in both sensors at 10.5 and 13.0 Hz for this interval. Also, there are smaller anomalous peaks at 21.0 and 23.5 Hz.

place of the world or by other local phenomena. A scheme to detect the exact time at which saturations are detected in our measurements and plot the immediately previous and following samples has been developed. The scheme also allows to obtain a list of the lightning events that have taken place at a very similar time to the saturation.

We can select the saturation limit that we want to study the transient events recorded that reach up to a certain amplitude different from 10 V, as well as the time lapse in which lightning events are considered to be a posible cause for the transient event. In Fig. 11 a screenshot of this virtual environment is shown. The option of plotting the places where the lightning events have ocurred in a world map is offered, as shown in Fig. 12. All the relevant information can also be stored for further study. The lightning event data shown in Fig. 11 have been obtained from the World Wide Lightning Location Network (WWLLN).

IV. Results

Some results that can be obtained using the graphical schemes explained in this work are listed below:

1) For some time intervals, the parameters obtained after the fit are anomalous. The amount of anomalous parameter values is different for each magnetometer. Different ranges of accepted values could have to be established for the same parameter in magnetometers NS and EW.
2) The monthly average percentage of saturation for every time of the day is usually below 5%. High values of the percentage of saturation are related to less smooth variations of the SR parameters.
3) Some intervals of the recorded signal show different kinds of particularities. They can be classified and stored for later study and correlation with other data.
4) Saturations and transient events can be identified in the recorded signal and they can be used to identify which lightning event could have caused that registered event.

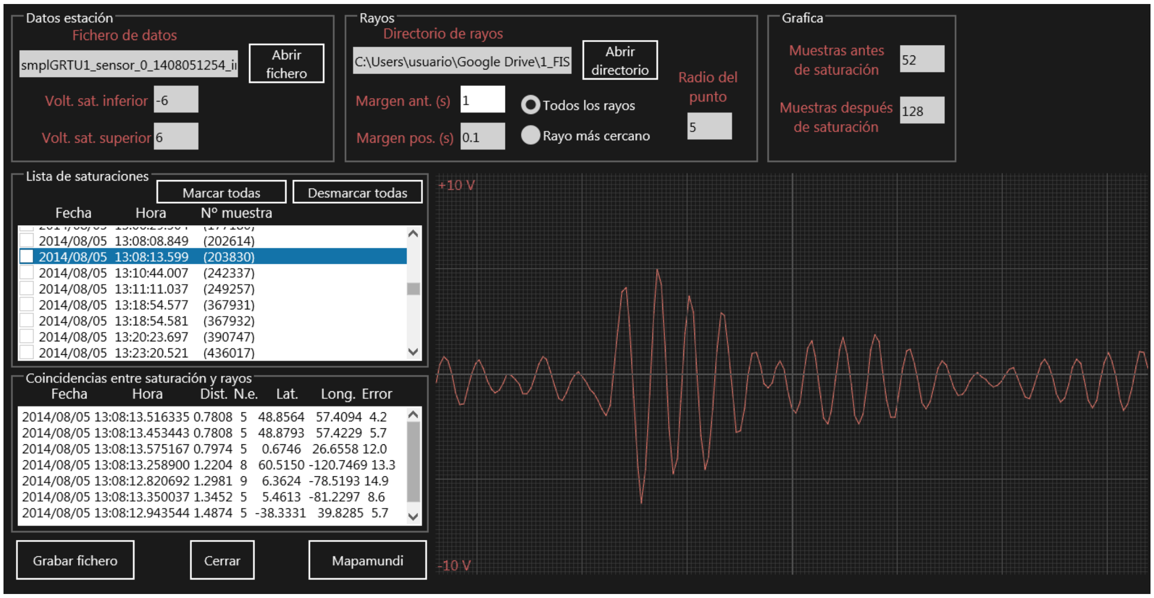

Fig. 11. Working environment design to correlate the transient events recorded at the Sierra Nevada ELF station with a list of lightning events. In the figure, the transient events with an amplitude equal or greater than ±6 V are taken into consideration, and the lightning events that occur from 1 s before to 0.1 s after the transient event is detected are accepted as posible causes for the transient event. A plot of the event is also shown.

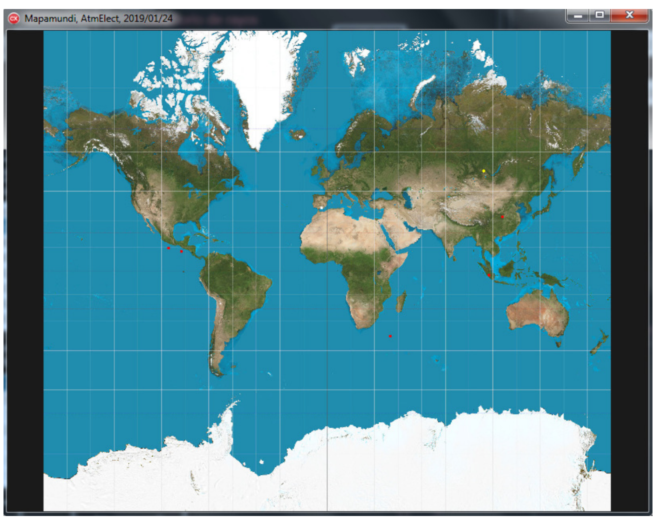

Fig. 12. The location of the ELF station (in Granada, Spain) is marked with a white dot, where as the lighning events that could cause a certain transient event are marked with a red dot, except for the closest lightning event which is marked in yellow. In this case, the closest lightning event took place in the North of China, and other events took place off the South coast of Mexico, in the South East of China, in Indonesia and in the South West Indian Ocean.

Saturations are found not to be always caused by close lightning events.

V. Conclusions

1) The alternative information that can be obtained from the recording of SR, involving the masked time intervals, the statistical representations of the time series of the SR parameters, the percentage of saturation of each time interval, the anomalous SR spectra and the correlation of the saturations of the magnetometers with lightning events, provides additional information to the study of the long term variations of the SR parameters.
2) The design of the graphical schemes exposed in this work has largely simplified the study, allowing the user to display the information so that it can be quickly analysed together with the long term variations of the SR.

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