Assessing Time Synchronization in Global ELF Station Networks Based on ELF Transients

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Abstract

This study focuses on the time synchronization between 15 Extremely Low Frequency (ELF, 3 Hz–3 kHz) stations operated by 6 scientific institutions, which is critical for accurate detection and localization of ELF transients and their corresponding source lightning stroke. After identifying the transients by applying an amplitude threshold on the filtered time series, time synchronization was assessed by comparing the time differences between transients detected at paired stations. Most stations demonstrated proper synchronization, but significant timing discrepancies were found at the Eskdalemuir (ESK) station, requiring timestamp corrections to ensure reliable future use of the data.

Keywords: ELF station network, ELF transients, time synchronization.

Motivation

The motivation for this research stems from the critical importance of accurate time synchronization between ELF stations in detecting and localizing extremely powerful lightning discharges producing globally observable signals known as ELF transients or Q-bursts (Ogawa et al., 1966; Guha et al., 2017). Since ELF stations detect the electromagnetic signal emitted by lightning, they offer a powerful means to study global lightning activity (Sátori et al., 2009; Price et al., 2004). However, discrepancies in timing between stations can undermine the accuracy of such observations, hindering our ability to effectively localize and monitor lightning activity. This study aims to examine the time synchronization between ELF stations operated by different scientific institutions, drawing attention to potential problems.

Data and Methods

For the present study, measurements from 15 ELF stations operated by 6 scientific institutions were used. The most important information about these stations are listed in Table I, while their locations are shown in Figure 1.

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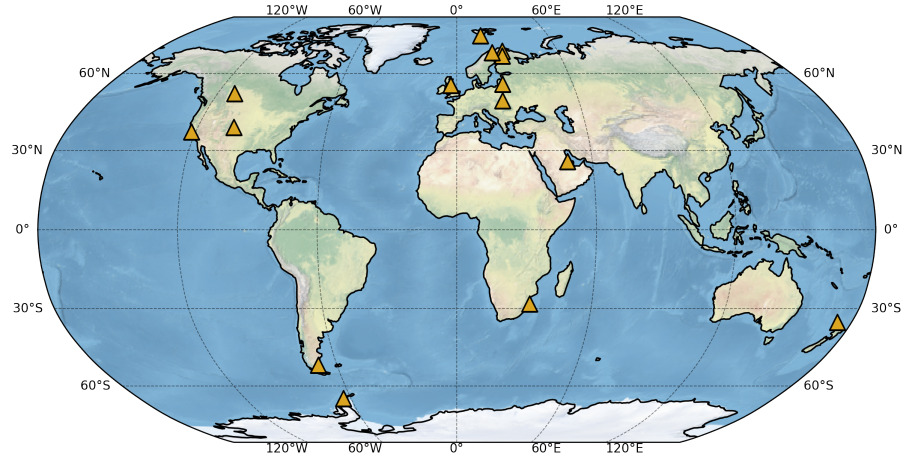

Fig. 1. Map showing the locations of the 15 ELF stations used in the study (marked by orange triangles).

Each station is equipped with a pair of induction coil magnetometers, one aligned with the geographic north and the other perpendicular to it. The Alberta (ALB), Baisogala (BAI), Boulder Creek (BOU), Hluhluwe (HLU), Hofuf (HOF), and Northland (NOR) stations are operated by the Heartmath Institute (https://www.heartmath.org/gci/). Vernadsky station (VRN) is located in Antarctica and is operated by the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine. The Eskdalemuir (ESK) station is operated by the British Geological Survey, while the Hornsund (HRN) station in Svalbard is maintained by the Institute of Geophysics of the Polish Academy of Sciences. The Hugo (HUG), Hylaty (HYL), and Patagonia (PAT) stations are part of the World ELF Radiolocation Array (WERA), operated by the Krakow ELF group (http://www.oa.uj.edu.pl/elf/). The Kevo (KEV), Kilpisjärvi (KIL), and Sodankylä (SOD) stations are part of the Finnish pulsation magnetometer chain, operated by the Sodankylä Geophysical Observatory (https://sgo.fi/). More detailed information on the stations are available in Bozóki et al. (2023).

To effectively work with the data from different stations, standardized, one-hour time series were generated from the raw data files of various formats. In this step, the measured data were processed by applying a Finite Impulse Response (FIR) bandpass filter, which also corrected for the amplitude response of the recording systems. Based on the available information on the bandwidth and amplitude response of the measurement systems, the bandwidths of the FIR filters were chosen as follows: 2–45 Hz for the ALB, BAI, BOU, ESK, HLU, HOF, HRN, HUG, HYL, NOR, PAT, and VRN stations, and 2–31 Hz for the KEV, KIL, and SOD stations.

Table I. ELF Stations Used in the Study.

Station	Code	Country	Latitude (°)	Longitude (°)	Sampling (Hz)
Alberta	ALB	Canada	51,89	-111,47	130
Baisogala	BAI	Lithuania	55,63	23,70	130
Boulder Creek	BOU	USA	37,19	-122,12	130
Eskdalemuir	ESK	UK	55,29	-3,17	100
Hluhluwe	HLU	South Africa	-28,05	32,32	130
Hofuf	HOF	Saudi Arabia	25,94	48,95	130
Hornsund	HRN	Svalbard	77,0	15,6	100
Hugo	HUG	USA	38,89	-103,40	887
Hylaty	HYL	Poland	49,19	22,55	887
Kevo	KEV	Finnland	69,75	27,02	250
Kilpisjarvi	KIL	Finnland	69,05	20,79	250
Northland	NOR	New Zealand	-35,11	173,49	130
Patagonia	PAT	Argentina	-51,59	-69,32	887
Sodankyla	SOD	Finnland	67,43	26,39	250
Vernadsky	VRN	Antarctica	-65,25	-64,25	320

By using the standardized data files as input, the identification of transients was performed for each station. The input required for this process includes the total magnetic field, an amplitude threshold for detecting the transients and a merging threshold. The main steps of this process include determining a vector of time intervals during which the magnetic field exceeds the threshold, merging nearby time intervals, finding the maximum within the merged time intervals, and displaying the number of detected ELF transients. The output of this process is a list containing all the transients detected in the data file with the corresponding timestamps, as well as the transient's peak amplitude in pT, eccentricity and ELF azimuth in degrees. After generating the transient lists for each station, the time synchronization was assessed by pairing the transients detected at different stations. Two stations were always selected, one of which was designated as the reference station, against which the time synchronicity of transients appearing at the other station was examined. For each transient detected at the reference station, the closest event in time at the other station was identified, the time difference between these events was calculated, and these time differences were plotted.

Results

The proper synchronization of station timing is crucial, especially for applications like determining the location of source lightning strokes. The timing is typically well-synchronized among stations operated by the same group (as they generally use the same measurement system), but discrepancies may arise between different station systems. Figure 2 illustrates the timing verification between the HRN station operated by the Geophysical Institute of the Polish Academy of Sciences and the BAI station operated by the Heartmath Institute. The figure shows the time differences between the transients detected closest in time at the two stations between 13 January 2019 and 31 January 2019. Ideally, this difference should be very close to 0 second, or more precisely, within a few tens of milliseconds, depending on the distance between the two stations. The few events outside this range were likely recorded only by one station, so there is no corresponding event at the other station. Based on Figure 2, the HRN and BAI stations are properly synchronized. Figure 3 shows the pairing of the HRN station and the ESK station operated by the British Geological Survey. It can be observed that in this case, the typical time differences are not within the window of a few tens of milliseconds but are around 50 seconds. Additionally, there is a stepwise increase in the typical time differences over the days. Based on this, it can be concluded that the timing of the ESK station shows a gradually increasing shift of around 50 seconds, at least during the examined period. In this form, the measurements from this station are not suitable for localization purposes, and the timestamps require precise correction. We now know that the ESK system was not intended for this type of study, and that it is probably very old compared to other stations.

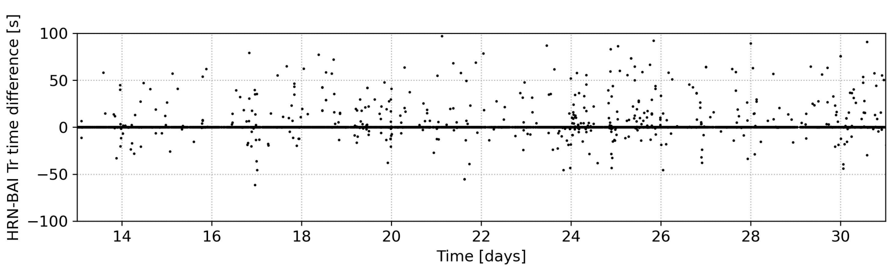

Fig. 2. The time differences between the transients detected closest in time at the HRN and BAI stations between 13 January 2019 and 31 January 2019. The horizontal axis shows the days, and the vertical axis shows the time difference in seconds.

We examined the time differences for all possible combinations of station pairs. Aside from the ESK station, issues only appeared in the plots of the pairs involving the South African HLU station. This is most likely due to the station's location, as there is significant lightning activity close to the station in the studied period. This is supported by the fact that this problem is only observed when HLU is the reference station. The timing of the other 13 station was found to be adequate based on our investigation.

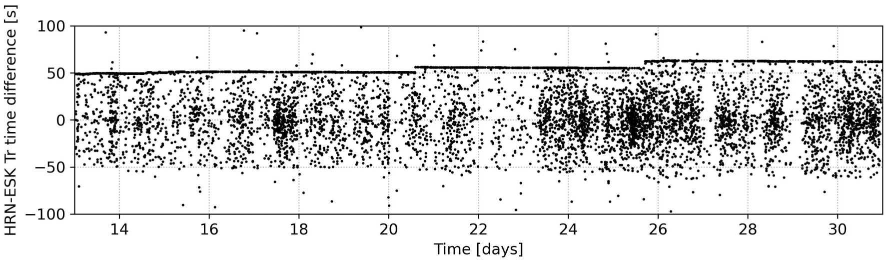

Fig. 3. The time differences between the transients detected closest in time at the HRN and ESK stations between 13 January 2019 and 31 January 2019. The horizontal axis shows the days, and the vertical axis shows the time difference in seconds.

Conclusions

This research confirmed that the majority of the examined ELF stations have proper time synchronization, which is critical for accurately localizing the source lightning stroke of ELF transients. However, significant timing discrepancies were found at the Eskdalemuir (ESK) station, requiring corrections to ensure reliable use of the data. Identifying such synchronization issues is essential for the effective observation and analysis of global lightning activity.

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