Advances in Geological and Geotechnical Engineering Research
https://journals.bilpubgroup.com/index.php/agger

ARTICLE

Radio Direction Finding Method to Mitigate Tsunami Risk in Sierra Leone

Valentino Straser[1*], Daniele Cataldi[2], Gabriele Cataldi[2]

[1] *Faculty of Agriculture, University of Makeni, Fatima Campus, Makeni, 00232, Sierra Leone*
[2] *Group Radio Emission Project, Lariano, Rome, 00076, Italy*

ABSTRACT

In this study, the Radio Direction Finding method is proposed for the detection of electromagnetic signals, in the VLF band, to try to anticipate the occurrence of potentially destructive geophysical events. The experimentation concerns the interception of electromagnetic anomalies in Sierra Leone, in the five-day time window, associated with seismic events that could potentially generate tsunamis. The area of investigation is Sierra Leone, whose coastline is subjected to tidal wave hazards triggered by earthquakes generated in the Mid-Atlantic Ridge. Although Sierra Leone is not affected by recurrent earthquakes, there is nevertheless a low probability, estimated at 2 percent, of the occurrence of destructive earthquakes in the next 50 years. Also in estimates, the risk of rogue and potentially damaging waves is estimated to strike the Sierra Leone coast at least once in the next 10 years. The Radio Direction Finding experiment carried out continuously 24/7, has shown a close relationship between increased radio-anomalies, in the frequencies of 6,000 Hz, a time window between electromagnetic anomaly detection and the imminence of an earthquake, and higher frequency times for the risk of earthquake occurrence in the Mid-Atlantic Ridge.

Keywords: Tsunami; Radio direction finding; Destructive earthquakes; Mid-Atlantic ridge; Sierra Leone

1. Introduction

The problem of safety and loss of life, due to large geophysical events, has been a subject of study by international research centers and universities around the world for a number of years. Potentially destructive earthquakes and catastrophic tsunamis

*CORRESPONDING AUTHOR:
Valentino Straser, Faculty of Agriculture, University of Makeni, Fatima Campus, Makeni, 00232, Sierra Leone; Email: valentino.straser@gmail.com.

ARTICLE INFO
Received: 9 March 2023 | Revised: 25 April 2023 | Accepted: 28 April 2023 | Published Online: 12 May 2023
DOI: https://doi.org/10.30564/agger.v5i2.5617

CITATION
Straser, V., Cataldi, D., Cataldi, G., 2023. Radio Direction Finding Method to Mitigate Tsunami Risk in Sierra Leone. Advances in Geological and Geotechnical Engineering Research. 5(2): 64-75. DOI: https://doi.org/10.30564/agger.v5i2.5617

have prompted the scientific community and technology to experiment with methods and make devices to intercept preseismic signals. Research that has multiplied in recent decades has shown that we are confronted with a technological limitation that hopefully can be overcome as early as the next few years. In this study, a method, Radio Direction Finding (RDF), is proposed based on intercepting electromagnetic frequencies, identifying their propagation direction and potential source. The RDF method, still undergoing experimentation and technological evolution, was devised in 2017 in Rome, Italy, by physicists Daniele Cataldi and Gabriele Cataldi. Its application has been tested on both seismic events, including potentially destructive ones, and volcanic activity monitoring. The experimentation has recently started in Sierra Leone, a geologically ancient land that is rarely affected by strong earthquakes. Precisely for this reason, Sierra Leone represents an open-air laboratory for the study of potential catastrophic scenarios, induced by geophysical events, which could affect, especially, stretches of Atlantic Ocean coastline and the capital Freetown.

1.1 The electromagnetic seismic precursors (ESPs)

The study of electromagnetic emissions associated with earthquakes is based on mechanisms for the production of radio emissions generated by mechanical deformation, and the following fracturing of rocks present in the earthquake preparation zone in the preseismic phase. Electromagnetic anomalies were observed, for example, on March 11, 2011 before the earthquake that occurred in Japan [1], or those of the Peruvian earthquake of September 25, 2013 [2], or even those recorded on August 24, 2016 in Italy [3]. These cases are just some of the earthquakes preceded by electromagnetic emissions or electromagnetic anomalies recorded on a global scale [4-8]. It was 1890 when the British geologist John Milne, inventor of the eponymous horizontal seismograph, a professor at the Imperial College of Engineering in Tokyo and founder of the Seismological Society of Japan (SSJ), in his work entitled "Earthquakes in Connection with Electric and Magnetic Phenomena" [9], described some electrical phenomena magnetic and related to seismic activity. It was the first scientific publication ever in which they described a series of electromagnetic phenomena, about one hundred years later, the international scientific community renamed as "electromagnetic seismic precursors" or ESP [10]. In 2007, Gabriele Cataldi and Daniel Cataldi founded a scientific research project (Radio Emissions Project) dedicated to monitoring and study of Electromagnetic Seismic Precursors (ESPs) and, in a few years, they have developed an innovative electromagnetic tracking method, who was able to provide valuable data on the pre-seismic electromagnetic anomalies, meaning by this term also electromagnetic phenomena of solar origin and those of geomagnetic nature [11].

1.2 Theoretical basis on pre-seismic radio emissions

The pre-seismic radio signals are generated by a series of mechanisms that occur at the level of the lithosphere (Earth's crust) which have been well known and studied for years. They are mainly emitted by the micro-fractures that are generated on the seismic fault plane when the level of mechanical stress reaches such levels as to start breaking up the rocks. Studies confirming the production of radio frequency emitted by rocks placed under mechanical stress have also been conducted in recent years thanks to the funds allocated NASA (National Aeronautics and Space Administration) [3,4].

Microfractures are small cracks in the rock which, from a geological point of view, generally have a length of a few millimeters (or less) and a width of less than 0.1mm and are formed in the phases preceding the macrofractures. Since the size of a microfracture substantially depends on the homogeneity of the rock subjected to tectonic stress, it is evident that fractures of much more varied dimensions have also been observed. The first microfractures were observed in 1850 through transmitted light microscopy (TL), while only in 1960 it was possible to observe them through scanning electron microscopy (SEM) [11].

The creation of experimentally induced microfractures was demonstrated for the first time through triaxial compression tests [12] and currently, the study of microfractures produced in the laboratory has allowed us to provide important information on rock breaking processes and a better understanding of faults and formation of microfractures in nature [13]. Since the faults do not have a planar morphology but are irregular, they can be described graphically as a fractal [14]. This condition means that when tectonic stress accumulates, the geometric irregularities of the fault influence each other, leading to the formation of additional microfractures in the surrounding rock that has a different orientation than the main ones [15-17]. It is therefore evident that the volume of the Earth's crust involved in the creation of microfractures is larger than the area defined as the "earthquake preparation zone": According to some estimates, this volume could be between 24 and 520 times larger than the earthquake preparation area. The locally generated pre-seismic radiofrequency is an electromagnetic phenomenon caused by the tectonic stress that deforms and creates microfractures and macrofractures in the rocks present in the earthquake preparation area through the phenomenon of piezoelectricity [18]. The amplitude of the electromagnetic signals caused by the formation of microfractures of the rocks subjected to tectonic stress in the earthquake preparation area mainly depends on the density of the microfractures and their size; The morphology of the electromagnetic field depends on the orientation of the microfractures; on the other hand, the period of oscillation of the electromagnetic field (temporal modulation) depends on the geological characteristics of the fault and on the characteristics of the tectonic stress that determine a growth of the microfractures that does not proceed linearly. According to a study carried out in 2007 [19], the volume of the Earth's crust concerned issues pre-seismic electromagnetic due to the accumulation of tectonic stress, it has a much larger size than the volume of the affected Earth's crust solely on the production of micro-fractures (focal area of the earthquake). Taking as reference an earthquake of magnitude 6 and considering the volumes involved, this ratio is > 200:1. Subtracting the energy released by the seismic waves by the energy that theoretically is accumulated as a result of tectonic stress within the earthquake preparation zones, the result is that only a small part of the energy contained in the earthquake focal zone is converted into seismic waves. According to T. Lay and T. C. Wallace [20], only 1-10% of the energy and seismic moment contained in earthquake zone preparation is converted into seismic waves. It is therefore conceivable that 90% (or more) of this energy, or part of it, can be converted to radiofrequency. Taking as a reference an earthquake of magnitude 5, this has an energy and a seismic moment between 1012 Nm and 1018 Nm [20].

Over the decades, since the 1980s, the international scientific community has been concerned with the study of pre-seismic radio emissions by creating ad-hoc research projects. Some of them are listed below:

- EMSEV (Electromagnetic Studies of Earthquakes and Volcanoes). A project of the "Earthquake Prediction Research Center" of Tokai University (Japan) to promote cooperation among researchers in scientific research on earthquake prediction (2009).

http://www.emsev-iugg.org/emsev/

- EMV (Electromagnetic Variations). Greek project for monitoring electromagnetic seismic precursors active since 1987.

http://users.teiath.gr/gregkoul/

- SEMEP (Search for Electro-Magnetic Earthquake Precursors). A project established as a collaboration between the European Community and Russia in 2010 after a meeting at the Seventh Framework Programme (FP7).

https://cordis.europa.eu/project/rcn/96924/reporting/en; https://cordis.europa.eu/project/id/262005/reporting

- Pre-Earthquakes Project - The project was born out of an agreement between Italy (University of Basilicata), Germany, Turkey and Russia that dealt with the study of pre-earthquake radio emissions (2011-2012).

- iSTEP Project (integrated Search for Taiwan

Earthquake Precursor) Chinese scientific research project to study earthquake precursors (2002-2012).

T52D.08T/abstract

- Integrated Earthquake Frontier Project. Scientific project for the study of earthquake precursors created by the former Japanese Government Technology and Science Agency (JST) after the disastrous M7.3 earthquake that was recorded on January 17, 1995, in Kobe. Under this project, two agencies were sent to conduct 5 years of studies (1996-2001) on the feasibility of using electromagnetic seismic precursors: The RIKEN (Physical and Chemical Institute) and the NASDA (National Space Development Agency of Japan). This study project was named the "Earthquake Remote Sensing Frontier Project." https://ieeexplore.ieee.org/document/1177344

- SSTL (Small Satellite for Earthquake Prediction). Active between 2001 and 2003, it was the research project of the Surrey Space Center of the University of Surrey (England), dedicated to the study of ionospheric seismic precursors and carried out through electromagnetic background monitoring and space meteorology [21].

- Berkeley Seismological Lab. Scientific research laboratory at the University of California, Berkeley, under which electromagnetic seismic precursors are monitored and studied.

http://seismo.berkeley.edu

- Quake Finder Project. Scientific research project dedicated to elettromagnetic seismic precursors active since 2000 and subsidized by N.A.S.A.

https://www.quakefinder.com

- DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) Satellite. First project of the French National Center for Space Studies (CNES) to study ionospheric and environmental electromagnetic anomalies preceding earthquakes. Active between 2004 and 2010.

https://demeter.cnes.fr/en/DEMETER/lien4_science.htm

- CSES (China Seismo-Electromagnetic Satellite). Project operational since 2018, established in collaboration between China and Italy to study ionospheric electromagnetic anomalies associated with destructive earthquakes. The Chinese-Italian agreement involves the launch into orbit of an artificial satellite capable of making measurements of the Earth's geomagnetic field and solar wind ionic parameters.

http://cses.roma2.infn.it

- Stanford University, Department of Geophysics. Stanford University's Department of Geophysics has created an inter-graduate course dedicated to monitoring electromagnetic seismic precursors.

- MEMFIS (Multiple Electromagnetic Field and Infrasound Monitoring Network), complex geophysical monitoring project produced by the University of Bucharest, Romania, active since 2004 [22].

- QuakeSat. Stanford University nanosatellite, launched into space in 2003 (mission ended in 2005). It was equipped with a triaxial magnetometer and an electric field sensor. Instruments specifically designed to study electromagnetic seismic precursors.

https://www.quakefinder.com/

- INFREP (International Network for Frontier Research on Earthquake Precursors). European electromagnetic monitoring network for the study of earthquake-induced ionospheric disturbances [22].

1.3 Correlation between electromagnetic waves and earthquakes

Analysis of ambient radio frequency conducted since 1890 has led to the understanding that there are natural radio emissions, with wide bandwidth, that can be observed with greater intensity in the immediate vicinity of potentially destructive earthquake epicenters [23,24]. Laboratory experiments have shown that this pre-earthquake radio frequency is generated through direct piezoelectric effect when crystalline materials in the earthquake preparation zone polarize due to tectonic stress, generating a potential difference. Electromagnetic emission starts during deformation of crystalline materials and not only during their rupture (microfractures and macrofractures).

In this context, the greater the volume of the Earth's crust included in the earthquake preparation zone, the greater will be the intensity of radio emission generated through the direct piezoelectric effect

(Epicentral Ionic Emissions or EIE—Term coined by the Radio Emissions Project in 2012) [25,26]. When these radio emissions emerge from the Earth's surface, they propagate within the Earth-ionosphere cavity and can be detected through electromagnetic monitoring stations that can identify their geographical area of origin using Radio Direction Finding (RDF) technology. This scientific approach enables crustal diagnosis by identifying areas of the Earth's surface from which broadband pre-seismic radiofrequency is emitted, making it possible to identify areas of the Earth's surface within which a seismic event may occur. Since a pre-seismic electromagnetic source cannot be considered an isotropic electromagnetic source due to the characteristics of the Earth's crust and tectonic stress, it is evident that it is more convenient to study this pre-seismic electromagnetic phenomenon through a dense network of electromagnetic monitoring stations rather than through a few stations.

1.4 The risk of geophysical and catastrophic events in Sierra Leone

Sierra Leone is a West African state located on the coast of the Atlantic Ocean bordering Guinea to the north and east and Liberia to the southeast. It has a population of about 8,421,000 as of 2021 census. Sierra Leone has a low seismic hazard but, nevertheless, there is a 2 percent probability of potentially destructive seismic tremors occurring within the next 50 years. Probabilistic assessment has indicated very long return times of major seismic events, on the order of 475, 2475, and 9975 years [27]. The risk of coastal flooding, on the other hand, is classified as high, i.e., that potentially damaging waves may inundate the Sierra Leone coast at least once in the next 10 years. In fact, the Mid-Atlantic Ridge can generate major earthquakes with magnitudes that can reach and exceed M7.1, as in the case of the strong 1982 earthquake (https://earthquakes.zone/sierra-leone). The potential damage induced by geophysical events, is an element of concern for Sierra Leone, especially in terms of coastal effects, and the consequences on society, with economic losses, damage to structures, and loss of life [28]. The long lapse of time from the occurrence of disastrous tsunamis until now induces caution and consideration of potential pitfalls for the coastal population, and the capital Freetown, in the coming years. At least from a statistical point of view.

1.5 Seismotectonics and tsunamis

Sierra Leone is included in the fourth of the six seismotectonic provinces of the West African Craton [29], formed by three Archaic and Paleoproterozoic metamorphic and magmatic shields that include the Central African fault systems of Angola, DR Congo, Cameroon, and Chad, determined by the tectonic regime [30-32]. The Mid-Atlantic Ridge earthquakes are essentially related to an extensional tectonic regime, which, however, do not rule out an interaction with magmatic activity in the Ridge [33]. Recent studies have shown that the crust of the equatorial Atlantic Ocean, with a thickness of about 5.5 km, is predominantly magmatic, ranging in age from 8 to 70 Ma. The semi-diffusion of the ridge is about 16 mm/year, fed by three mega-transform faults running east-west, St. Paul, Romanche and Chain. The St. Paul transform fault system, which is related to tectonic activities of fracture systems and earthquakes that could potentially generate tsunamis on the Sierra Leone coast, includes four minor faults that collectively extend a total of about 600 km [34]. Seismic studies of the mid-Atlantic ridge have made it possible to interpret the structure of the oceanic crust and catalog historical earthquakes to draw up a map of seismic and potentially destructive tsunami risk [35-37]. The Atlantic Ocean, except for the Lisbon tsunami of 1755, does not generate transoceanic tsunamis due to the geodynamic conditions of the Mid-Atlantic Ridge, unlike the Pacific and Indian Oceans. Instead, Atlantic Ocean tsunamis have local significance and of their impact on cities and human activities, requiring an effective warning system for high risk on the coasts [38,39].

Looking at Sierra Leone's population density data for 2000, the majority of the population is concentrated on the coast, which faces the Atlantic Ocean where strong earthquakes and tsunamis can be produced [40].

2. Materials and methods

This study is based on electromagnetic monitoring of Sierra Leone through Italy's 24/7 Radio Direction Finding (RDF) network. The monitoring data were analyzed, modeled, and compared with the occurrence of earthquakes published on the network in real time.

The monitoring stations used for signal detection are in Italy at an average distance of about 4,900 km in the SSW direction,

1) RDF station in Pontedera, Pisa, Italy.
2) RDF station in Lariano, Rome, Italy.

The radio direction finding system

The detection system used by the research team is based on an electromagnetic monitoring system developed by the Italian Radio Emissions Project, starting in 2017. It consists of a series of electromagnetic sensors capable of detecting and recording the occurrence of electromagnetic signals of natural origin, and indicating their intensity, time duration and azimuth of origin, with respect to the geographical position of the detection station itself.

Such a network of sensors, deployed on Italian soil can triangulate radio signals emitted by a natural source, thanks to the technique of "radio triangulation", a technology from the 1920s of the last centuries, the technology of which was employed in this very project and is called Radio Direction Finding (RDF).

The RDF station, it is basically based on a series of loop antennas, positioned in orthogonal pattern, by a radio amplifier developed by Daniele Cataldi and Gabriele Cataldi, whose amplified signals are sent to the sound card of a PC, and processed there (**Figure 1**). Such a sensing system can generate an archive of dynamic and graphical spectrograms based on the electromagnetic signals detected by the antennas and of natural origin. At present, an RDF station can constantly document electromagnetic emissions from the Earth's crust (radio-nature), in the band between 0,000 Hz and 96 kHz; in this study, the electromagnetic signals monitored are those between the SELF band and the VLF band (0,000 Hz - 30 kHz). The range detected in the electromagnetic spectrum, where electromagnetic signals appear most frequently, potentially indicates a pre-earthquake signal that can anticipate strong earthquakes that can generate tsunamis [41].

Precursor signals (SEPs—Seismic Electromagnetic Precursors) are those of crustal, and local, origin, that is, generated by the Earth's lithosphere (crust), which due to the tectonic stress to which the rocks are subjected, generate electrical (ions) and electromagnetic (electromagnetic field—moving ions) emissions, which can then be picked up at a distance [7,42-44].

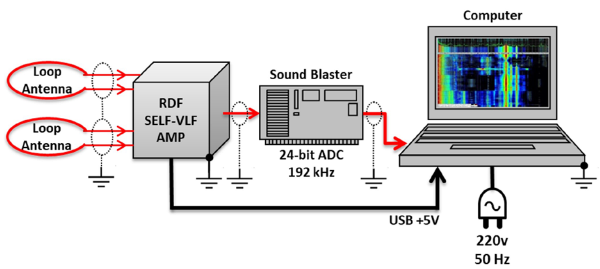

Figure 1. Schematization of the operation of an Italian RDF station, developed by the Radio Emissions Project. Credits: Radio Emissions Project.

3. Results

The electromagnetic monitoring, indicated by the RDF spectrograms with the yellow-green interference, covers the coast of Sierra Leone and, the capital Freetown, the area most exposed to tsunami risk. There were 55 spectrograms analyzed to compile the present study, in which electromagnetic signals having the monitored area as the direction of arrival were considered. The spectrogram shows an example of the data recorded by the Italian RDF network, and the azimuth of the electromagnetic signals. In this case it is an obvious signal recorded at 06:15 UTC on January 28, 2023, then terminated at 09:40 UTC on January 28, 2023. The RDF stations used for electromagnetic monitoring, carried out continuously 24/7, are those of Lariano (Rome) and Pontedera (Pisa), both located in Italy. The earthquakes considered in this study, with magnitude between 4.7 and 5.0, occurred in the Central Mid-Rigde of the Atlantic Ocean, in the period between January 28, 2023 and February 18, 2023 detected by the Italian RDF network (**Table 1**):

Table 1. Earthquakes list (http://earthquake.usgs.gov/).

N.	Date time (UTC)	Magnitude	Depth	Location	Region
1	2023-01-29 17:04:15.3	mb 4.9	10 km	8.63°N; 39.50°W	Central Mid-Atlantic Ridge
2	2023-02-01 03:14:25.1	mb 4.7	60 km	2.61°N; 30.85°W	Central Mid-Atlantic Ridge
3	2023-02-10 13:34:11.4	mb 4.9	10 km	7.57°N; 36.86°W	Central Mid-Atlantic Ridge
4	2023-02-12 07:08:23.6	mb 5.0	10 km	17.55°N; 46.56°W	Central Mid-Atlantic Ridge
5	2023-02-15 02:13:12	mb 5.3	10 km	8.016°N; 37.066°O	Central Mid-Atlantic Ridge
6	2023-02-15 02:14:32	mb 5.1	10 km	7.883°N; 36.988°O	Central Mid-Atlantic Ridge
7	2023-02-16 18:35:50	mb 4.6	10 km	7.576°N; 36.782°O	Central Mid-Atlantic Ridge
8	2023-02-17 02:11:31	mb 5.3	10 km	1.079°N 28.081°O	Central Mid-Atlantic Ridge
9	2023-02-18 14:07:43	mb 4.7	10 km	7.365°N 36.037°O	Central Mid-Atlantic Ridge

4. Discussion

Analysis of the electromagnetic data, in the SELF-VLF band, indicate that fluctuations in the duration (in hours) of the radio-anomalies in the RDF spectrograms can be associated with earthquakes in the monitored area, in a time window ranging from a few minutes to a little more than two hours. The RDF spectrograms show that earthquakes occur at a decrease and then by an increase in radio-anomalies, lasting several minutes. The increase in the duration of radio-anomalies is accompanied by an increase in the number of earthquakes, especially when we consider those radio signals that possess an extremely low frequency (0.001 to 3 Hz band). Data indicate that increases in the electromagnetic frequency of signals are always close (temporally) to earthquake events, in this case M4.5+ that occurred off Sierra Leone (Atlantic Ocean). The largest number of M4.5+ earthquakes occurred within a time frame in which the radio-anomalies recorded at very low frequencies presented peaks that raised these values on the order of tens of times. This is a condition that can be considered normal precisely because in this case changes in electromagnetic frequency are associated with an increase in energy accumulated at the crustal level and capable of generating more earthquakes as well as higher magnitudes. Earthquakes are associated with electromagnetic frequency of radio-anomalies, which occurs at 6,000 Hz (**Figure 2**).

The duration of radio-anomalies recorded by Italian RDF stations (**Figure 3**), expressed in minutes, shows that most electromagnetic emissions of crustal origin have a duration ranging from a few minutes to 125 minutes (average). It can be hypothesized that the variation in the duration in minutes of these electromagnetic emissions may be associated with the extent and amount of energy stored in the fault.

Another important data point is the UTC time within which radio-anomalies are emitted. **Figure 4** shows that the time at which signals are most frequently recorded is between about 04:48 UTC and about 12:24 UTC, as in the case of 3 out of 4 earthquakes that occurred in that time range.

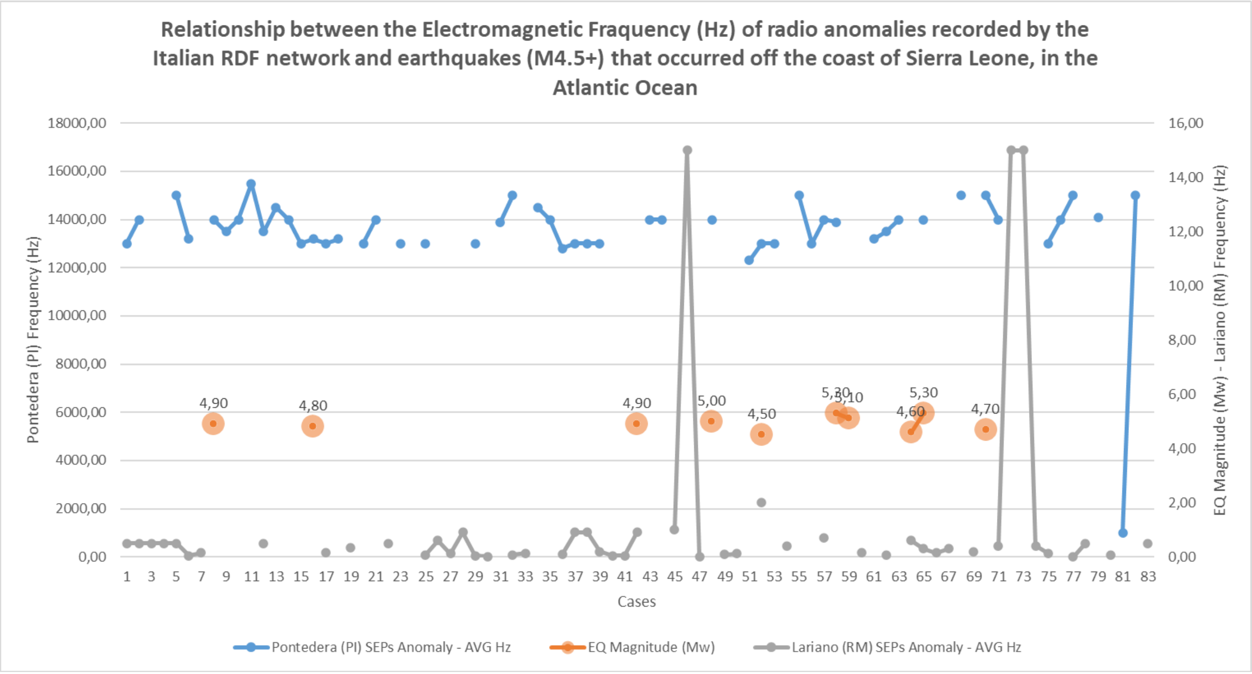

Figure 2. The graph shows the electromagnetic frequency of radio-anomalies recorded by Italian RDF stations, which appeared in the Atlantic area facing Sierra Leone, and the number of earthquakes that always occurred in the same area monitored by the Italian RDF network. Credits: Radio Emissions Project.

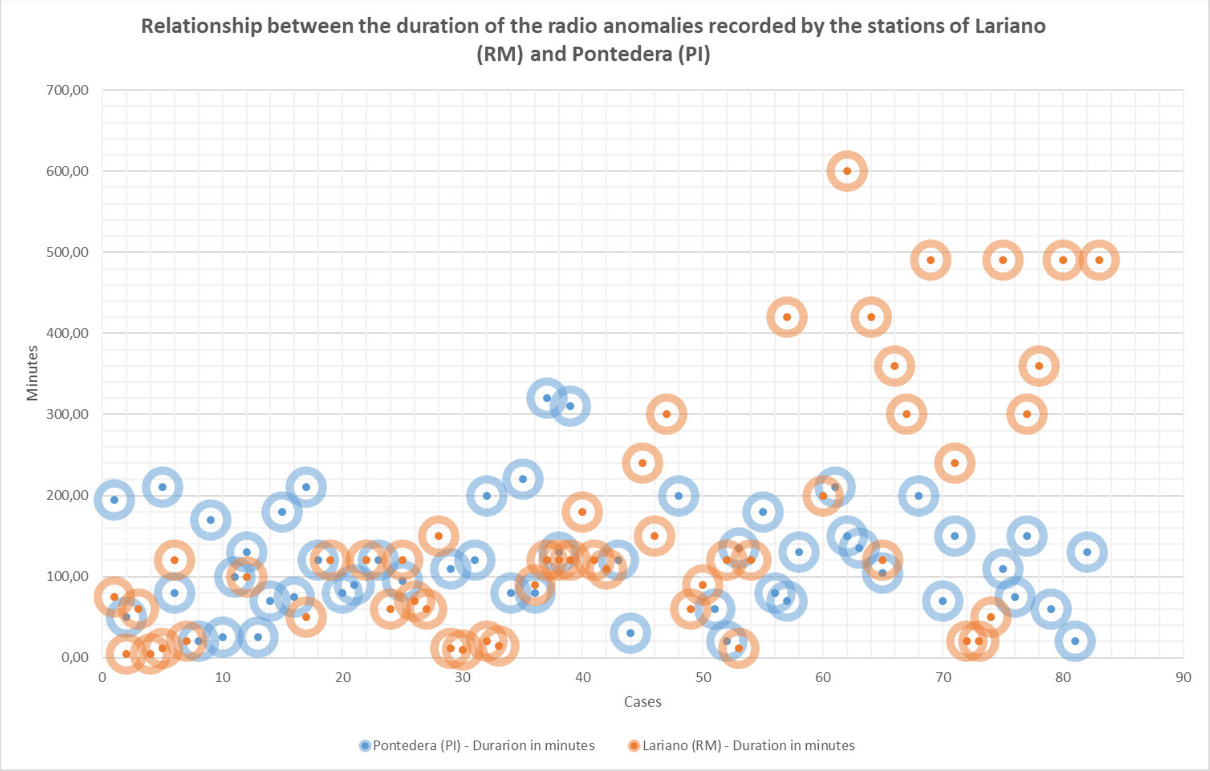

Figure 3. The graph shows the distribution of the duration in minutes of radio-anomalies recorded by Italian RDF stations. Credits: Radio Emissions Project.

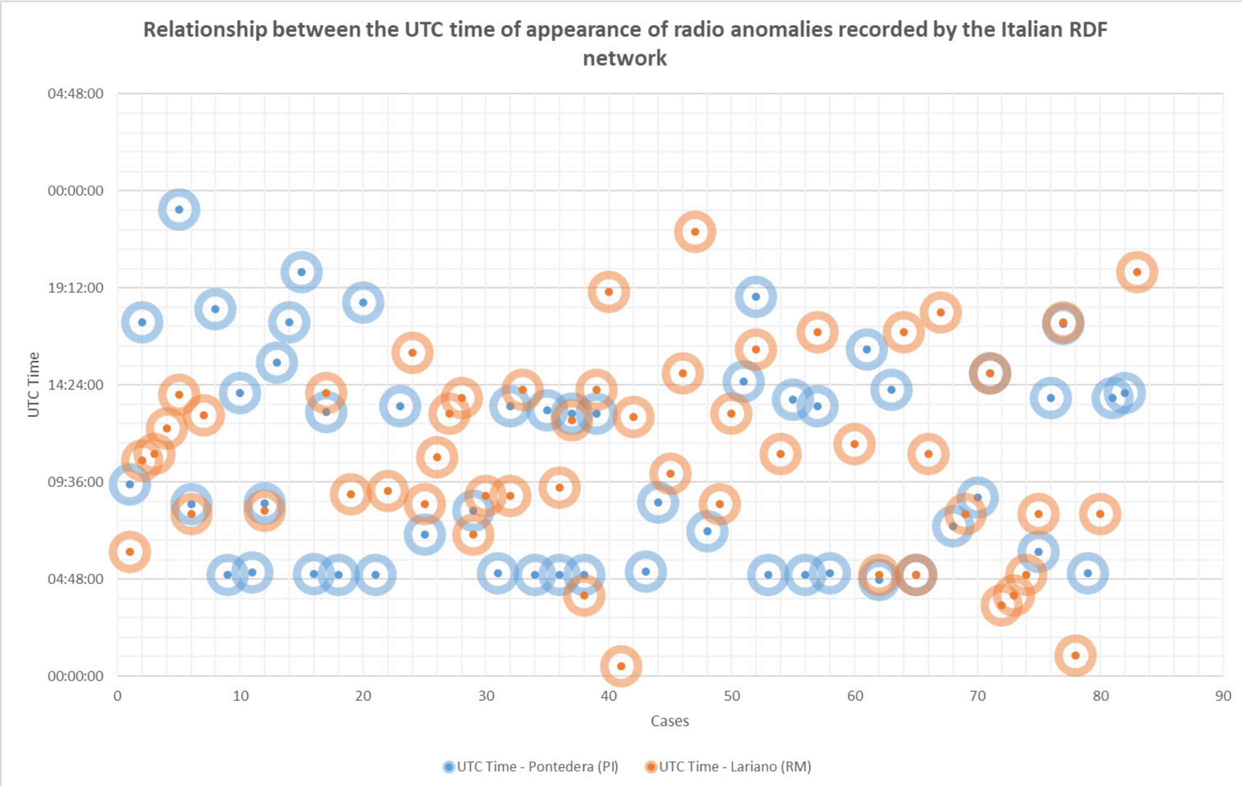

Figure 4. The graph shows the distribution of UTC time at which radio-anomalies recorded by Italian RDF stations occurred. Credits: Radio Emissions Project.

5. Conclusions

The study provided significant indications of the emission of electromagnetic signals with an azimuth of arrival located in the Atlantic area facing Sierra Leone, converging in the frequency of 6,000 Hz, the time (UTC) of occurrence of such signals, and their duration.

Analysis of the evolution of these radio emissions related the variation in the duration in minutes of these signals to the occurrence of earthquakes, as well as the average temporal location of these signals throughout the day. Knowing the time of emission of electromagnetic signals, the mechanism of which is still to be interpreted, is particularly useful in activating warning signals for the potential risk of an earthquake occurrence, especially in the area of the capital Freetown.

The present study, which is still partial due to the paucity of data to be modelled, can be enhanced in the future with the expansion of the Radio Direction Finding network by placing monitoring stations in Sierra Leone as well, supporting the Italian and Malaysian to develop warning system for the risk of strong earthquakes and tsunamis that may endanger the safety of people, especially in the centres that populate the coastal area of Sierra Leone.

Author Contributions

Valentino Straser has the main responsibility, and initiative based on several years of study of seismic precursors, especially in the electromagnetic field. The co-authors supported the present study with data collection and providing the essential devices for real-time monitoring signals Radio Direction Finding.

Conflict of Interest

The author and co-authors declare that they have no conflicts of interest.

Funding

This research received no external funding.

Acknowledgments

We express sincere thanks to Carlo Magretti for technical support in acquiring data for the preparation of this study and anonymous reviewers who enabled us to improve this paper.

References

[1] Straser, V., 2011. Radio wave anomalies, ULF geomagnetic changes and variations in the interplanetary magnetic field preceding the Japanese M9.0 earthquake. New Concepts in Global Tectonics Newsletter. (59), 78-88.

[2] Cataldi, D., Cataldi, G., Straser, V., 2014. Variations of the electromagnetic field that preceded the Peruvian M7.0 earthquake occurred on September 25, 2013. EGU General Assembly 2014; 2014 Apr 27 - May 2; Vienna.

[3] Straser, V., Cataldi, G., Cataldi, D., 2016. SELF and VLF electromagnetic signal variations that preceded the Central Italy earthquake on August 24, 2016. New Concepts in Global Tectonics Journal. 4(3), 473-477.

[4] Ohta, K., Izutsu, J., Schekotov, A., et al., 2013. The ULF/ELF electromagnetic radiation before the 11 March 2011 Japanese earthquake. Radio Science. 48(5), 589-596.
DOI: https://doi.org/10.1002/rds.20064

[5] Bernard, P., 1992. Plausibility of long distance electrotelluric precursors to earthquakes. Journal of Geophysical Research: Solid Earth. 97(B12), 17531-17546.

[6] Pulinets, S., Boyarchuk, K., 2004. Ionospheric precursor of earthquakes. Springer: Berlin. pp. 315.

[7] Straser, V., Cataldi, D., Cataldi, G., 2019. Registration of pre-seismic signals related to the mediterranean area with the RDF system developed by the radio emissions project. International Journal of Engineering Science Invention (IJESI). 8(03), 26-35.

[8] Straser, V., Cataldi, D., Cataldi, G., 2019. Radio Direction Finding (RDF)-Geomagnetic monitoring study of the Himalaya Area in search of pre-seismic electromagnetic signals. Asian Review of Environmental and Earth Sciences. 6(1), 16-27.

[9] Milne, J., 1890. Earthquakes in connection with electric and magnetic phenomena. Transactions of the Seismological Society of Japan. 15, 135-162.

[10] Straser, V., Giuliani, G.G., Cataldi, D., et al., 2020. Multi-parametric investigation of pre-seismic origin phenomena through the use of RDF technology (Radio Direction Finding) and the monitoring of Radon gas stream (RN222). An International Journal for New Concepts in Geoplasma Tectonics. 8(1), 11-27.

[11] Anders, M.H., Laubach, S.E., Scholz, C.H., 2014. Microfractures: A review. Journal of Structural Geology. 69, 377-394.

[12] Brace, W.F., Paulding Jr, B.W., Scholz, C.H., 1966. Dilatancy in the fracture of crystalline rocks. Journal of Geophysical Research. 71(16), 3939-3953.

[13] Scholz, C.H., 2002. The mechanics of earthquakes and faulting. Cambridge University Press: Cambridge. pp. 471.

[14] Power, W.L., Tullis, T.E., Brown, S.R., et al., 1987. Roughness of natural fault surfaces. Geophysical Research Letters. 14(1), 29-32.

[15] Chester, F.M., Chester, J.S., 2000. Stress and deformation along wavy frictional faults. Journal of Geophysical Research: Solid Earth. 105(B10), 23421-23430.

[16] Wilson, J.E., Chester, J.S., Chester, F.M., 2003. Microfracture analysis of fault growth and wear processes, Punchbowl Fault, San Andreas system, California. Journal of Structural Geology. 25(11), 1855-1873.

[17] Faulkner, D.R., Mitchell, T.M., Jensen, E., et al., 2011. Scaling of fault damage zones with displacement and the implications for fault growth processes. Journal of Geophysical Research: Solid Earth. 116(B5).

[18] Wang, J.H., 2020. Piezoelectricity as a mechanism on generation of electromagnetic precursors before earthquakes. Geophysical Journal

International. 224(1), 682-700.
DOI: https://doi.org/10.1093/gji/ggaa429

[19] Sgrigna, V., Buzzi, A., Conti, L., et al., 2007. Seismo-induced effects in the near-earth space: Combined ground and space investigations as a contribution to earthquake prediction. Tectonophysics. 431(1-4), 153-171.

[20] Lay, T., Wallace, T.C., 1995. Modern global seismology. Academic Press: Cambridge. pp. 521.

[21] Pulinets, S., Boyarchuk, K., 2005. Ionospheric precursors of earthquakes. Springer: Berlin.
DOI: https://doi.org/10.1007/b137616

[22] Moldovan, I.A., Moldovan, A., Biagi, P.F., et al., 2012. The INFREP European Vlf/Lf Radio monitoring network—Present status and preliminary results of the Romanian Motinoring System. Romanian Reports in Physics. 64(1), 263-274.

[23] Cataldi, G., 2020. Precursori Sismici – Monitoraggio Elettromagnetico. Kindle-Amazon.

[24] Cataldi, G., 2021. Radio Emissions Project – A new approach to seismic prediction. Kindle-Amazon.

[25] Cataldi, D., Cataldi, G., Straser, V., 2019. Radio Direction Finding (RDF)-Pre-seismic signals recorded before the earthquake in central Italy on 1/1/2019 west of Collelongo (AQ). Geophysical Research Abstracts. (21), 1-1.

[26] Neishtadt, N.M., Eppelbaum, L.V., Levitski, A.G., 2006. Application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics: Review of Russian and Israeli experiences. Geophysics. 71(2), B41-B53.

[27] Irinyemi, S.A., Lombardi, D., Ahmad, S.M., 2022. Seismic hazard assessment for Guinea, West Africa. Scientific Reports. 12(1), 1-12.
DOI: https://doi.org/10.1038/s41598-022-06222-7

[28] Sierra Leone's pliability to crisis and disaster: A shock resistance model [Internet]. SSRN Electronic Journal. Available from: https://ssrn.com/abstract=3864467

[29] Meghraoui, M., IGCP-601 Working Group. 2016. The seismotectonic map of Africa. Episodes Journal of International Geoscience. 39(1), 9-18.

[30] Abouchami, W., Boher, M., Michard, A., et al., 1990. A major 2.1 Ga event of mafic magmatism in West Africa: an early stage of crustal accretion. Journal of Geophysical Research: Solid Earth. 95(B11), 17605-17629.

[31] Black, R., Caby, R., Moussine-Pouchkine, A., et al., 1979. Evidence for late Precambrian plate tectonics in West Africa. Nature. 278(5701), 223-227.

[32] Caby, R., Andreopoulos-Renaud, U., Pin, C., 1989. Late Proterozoic arc—continent and continent—continent collision in the Pan-African Trans-Saharan Belt of Mali. Canadian Journal of Earth Sciences. 26(6), 1136-1146.

[33] Bergman, E.A., Solomon, S.C., 1990. Earthquake swarms on the Mid-Atlantic Ridge: Products of magmatism or extensional tectonics?. Journal of Geophysical Research: Solid Earth. 95(B4), 4943-4965.
DOI: https://doi.org/10.1029/JB095iB04p04943

[34] Wang, Z., Singh, S.C., 2022. Seismic evidence for uniform crustal accretion along slow-spreading ridges in the equatorial Atlantic Ocean. Nature Communications. 13(1), 7809.
DOI: https://doi.org/10.1038/s41467-022-35459-z

[35] Teza, E., Scordilis, E.M., Papazachos, C.B., et al., 2016. An earthquake catalog of mid-Atlantic Ridge. Bulletin of the Geological Society of Greece. 50(3), 1258-1269.

[36] Craig, T.J., Jackson, J.A., Priestley, K., et al., 2011. Earthquake distribution patterns in Africa: Their relationship to variations in lithospheric and geological structure, and their rheological implications. Geophysical Journal International. 185(1), 403-434.
DOI: https://doi.org/10.1111/j.1365-246X.2011.04950.x

[37] Francis, T.J.G., Porter, I.T., 1971. A statistical study of Mid-Atlantic Ridge earthquakes. Geophysical Journal International. 24(1), 31-50.

[38] Murty, T.S., Nirupama, N., Nistor, I., et al., 2005. Why the Atlantic generally cannot gener-

ate transoceanic tsunamis. SET Journal of Earthquake Technology, Technical Note. 42(4), 227-236.

[39] Alaneme, K.K., Okotete, E.A., 2018. Critical evaluation of seismic activities in Africa and curtailment policies–a review. Geoenvironmental Disasters. 5, 1-17.
DOI: https://doi.org/10.1186/s40677-018-0116-2

[40] Socioeconomic Data and Applications Center (SEDAC)—A Data Center in NASA0s Earth Observing System Data and Information System (EOSDIS)—Hosted by CIESIN at Columbia University [Internet]. Available from: https://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density/maps/2?facets=region:africa

[41] Straser, V., Cataldi, G., Cataldi, D., 2015. Radio-anomalies: Tool for earthquakes and tsunami forecasts. EGU General Assembly Conference Abstracts. 17, 2508.

[42] Straser, V., Cataldi, D., Cataldi, G., 2018. Radio direction finding system, a new perspective for global crust diagnosis. New Concepts in Global Tectonics Journal. 6(2), 203-211.

[43] Rabeh, T., Cataldi, D., Adibin, Z.Z., et al., 2020. International study Italy-Malaysia pre-seismic signals recorded by RDF—Radio Direction Finding monitoring network, before earthquakes: Mw 6.3, occurred at 111 km SW of Puerto Madero in Mexico and Mw 6.3, occurred at 267 km NW of Ozernovskiy in Russia, November 20, 2019. New Concept in Geoplasma Tectonics. 8(2), 105-118.

[44] Cataldi, D., Straser, V., Cataldi, G., 2021. Crustal relaxing—a new seismogenesis phenomenon associated with seismic trigger on a global scale. International Journal of Social Relevance & Concern (IJSRC). 9(7), 137-163.
DOI: https://doi.org/10.26821/IJSRC.9.7.2021.9711