A VLF/LF facility network for preseismic electromagnetic investigations

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Abstract. Earthquakes are one of the most frequently occurring natural disasters. Many indications have been collected on the presence of seismo-ionospheric perturbations preceding such tragic phenomena. Radio techniques are the essential tools leading the detection of seismo-electromagnetic emissions by monitoring at very low frequency (VLF, 3-30 kHz) and low frequency (LF, 30-300 kHz) sub-ionospheric paths between transmitters and receivers (Hayakawa, 2015). In this brief communication, we present the implementation of a VLF/LF network for searching earthquake electromagnetic precursors. The proposed system is comprised of a monopole antenna including a preamplifer, a GPS receiver and a recording device. This system will deliver a steady stream of real-time amplitude and phase-measurements and a daily recording VLF/LF data set. A first implementation of the system was done in Graz, Austria, the second one will be in Guyancourt, France, a third one in Réunion, France, and a fourth one in Moratuwa, Sri Lanka. In the near future, we are planning on expanding of our network for enhanced monitoring and increased coverage.

1 Introduction

Earthquakes (EQs) are one of the most dangerous and unavoidable natural disasters. Large magnitude EQs can cause casualties and damage millions worth of properties. EQs are ruptures along faults caused by a sudden release of energy after stress accumulations in the Earth's crust, i.e., in the upper part of the lithosphere. The major regions of EQs occurrence are: (a) Atlantic-Indian Ocean ridges, (b) Pacific regions, Southeast and Middle Asia, (c) Middle East and (d) South Europe. The seismicity is linked to the tectonic activity of the Earth: the large-scale convection currents in the mantle lead to relative displacements, slow deformations, and stresses in the lithosphere which result in episodes of rupture or subduction, that are source of earthquakes of various magnitudes. A map of the distribution of the seismicity all around the world, for magnitudes $M \geq 4$, is given by Keilis-Borok (2002, Figure 1). Most of EQs are considered weak hence the life on solid ground does not get affected by these events. Under specific conditions, they can cause tsunami which can be disastrous. Therefore, it is of utmost importance to the welfare of society to predict them to save lives and to minimize the damages.

During the past few decades, an important progress has been devoted to the quest for earthquake precursors (e.g., Cicerone et al., 2009; De Santis et al., 2019) and more particularly to the study of seismo-electromagnetic precursors. Recent reviews by Parrot (2018) and Hayakawa (2015) emphasize on the space and the ground-based observations that are covering a large spectral domain, from a few Hz to several hundred kilohertz. The investigations of seismo-electromagnetic emissions allow providing, before earthquake happenings, microscopic information on the lithosphere. In addition, such electromagnetic waves can propagate over considerable distances in the lithosphere. These two properties, i.e. precursory occurrence and long distance propagation, are fundamental for short-term EQ prediction (Hayakawa and Hobara, 2010).

In this work, we consider electromagnetic (EM) precursors observed in the VLF and LF bands by electric field experiments onboard satellites or by ground stations. One important feature of the seismic EM precursors is the study of the ionospheric disturbances observed above the earthquake regions. The basic method consists in analyzing amplitude and phase variations related to the propagation of the transmitter's subionospheric VLF/LF signal. Usually the transmitter signal is mainly reflected by the ionospheric D- and E-layers and detected by the ground stations. Hayakawa et al. (1996) proposed the most confident indication on the seismic ionospheric disturbances using the so-called terminator time (TT) method. The authors showed in the case of the Kobe EQ on 17 January 1995 a significant shift in time of the diurnal variation (amplitude and/or phase) around local sunrise and sunset. Later on, Yoshida et al. (2008) suggested that the shift in time is due to an occurrence of interference between ground- and sky-waves. This interpretation of the TTs observed shift leads to evaluate the ionospheric height. In addition, the TT method has been applied to derive the VLF modal interference distance by Samanes et al. (2015) using a long-term database (2007 to 2011) recorded by South America VLF Network (SAVNET, Raulin et al., 2009). This distance is estimated from two successive TTs minima of VLF transmitter amplitude linked to nighttime wave propagation in the Earth-ionosphere waveguide. This study allowed deriving the undisturbed height of the nighttime waveguide estimated to be in the order of 88 km. Moreover, seismic ionospheric disturbances are found to exhibit particular behaviours when investigating, the trend, the dispersion and nighttime fluctuation of NAA transmitter as reported by Hayakawa et al. (2011). The authors found, about 12 days before 2010 Haiti EQ (magnitude 7.0 and depth 10 km), a noteworthy reduction in trend and simultaneous intensifications of dispersion and nighttime fluctuation. Besides Earth's tide effect has been mentioned about two months before the main shock, which can only be considered for a huge EQ.

Additionally several investigations showed a drop of the amplitude of the transmitter signal several days before the earthquake occurrences using different methods in the treatment of the radio signal like the wavelet (e.g., Biagi et al., 2019) and the spectral techniques (e.g., Boudjada et al., 2017). Similar studies also show a reduction of the VLF signal phase noise during the preparatory time of EQs (e.g., Nina et al., 2021). In the model by Molchanov et al. (2006) the pre-seismic ionospheric disturbances are linked to an upward energy flux of atmospheric gravity waves generated by the EQs preparatory zone. The relationship between the radius of earthquake preparation zone ρ and the earthquake magnitude M is given by: $\rho[\mathrm{km}] = 10^{0.43\,M}$ (Dobrovolsky et al., 1979). Bowman et al. (1998) obtained a similar relation.

In the following, after a presentation of the scientific objectives, we describe the VLF/LF reception system and give an example of observations. Then we discuss the relevance of the sites chosen for the antennas setting-up.

2   Scientific Objectives

The main scientific objective is the detection of seismic EM precursors derived from the amplitude and the phase of the VLF/LF transmitter signals. Therefore the seismic preparation zone should be localized between the transmitter and the reception stations within an area given by the Dobrovolski radius. The solar and geomagnetic activities contribute in the disturbance of the sub-ionospheric VLF/LF wave when it propagates in the waveguide between the Earth's surface (ground or seawater) and the ionospheric D- and E-layers. The propagation conditions, in particular in the D-layer, may be affected by natural ionospheric currents, which has the effect of modifying the amplitude and the polarization of the wave. Resonance phenomena can also appear at particular frequencies (Maxworth et al., 2015). As a consequence, we need a better categorization and characterization of the electromagnetic environment surrounding the VLF/LF reception station.

3   VLF/LF Reception System

The VLF/LF system we plan to implement will consist of a monopole antenna equipped with a preamplifier, a GPS receiver and a sound card to digitize the received signal. This device will be identical in all respects to the VLF/LF reception system set up at the Space Research Institute in Graz (Austria) in order to study as major scientific objective the earthquake precursors. Figure 1 displays a schematic of the system.

The receiving antenna (Procom BCL 1-KA) will be of monopole type (length 92 cm), omnidirectional, vertically polarized and designed for a frequency band 10 kHz - 100 MHz. It is equipped with a preamplifier that must be connected by a 50 Ω coaxial cable to a junction box that separates the DC-current from the 12 V power supply and the RF-signal. The radio signal will then be sent to a sound card to be digitized. The model used is Focusrite Scarlett 2i2 with a chosen sampling frequency of 192 kHz and a 24-bit digitized output. A GPS receiver module with a PPS output (pulses per second) allows precise synchronization of the radio signal thanks to the minimal jitter. Finally the output of the sound card is connected (by a USB cable) to a PC running under a Linux operating system (CentOS). An especially dedicated software, called UltraMSK, will lead the recording of the detected transmitter signals and will deliver a daily data file. Figure 2 displays photos of the new reception system. The UltraMSK is a software app (radio receiver) in a particular hardware configuration (Clilverd et al., 2009) capable of measuring amplitude and phase of VLF/LF radio transmitters as detailed in www.ultramsk.com.

The VLF/LF system simultaneously measures the amplitude and the phase of several transmitters (planned are up to 20 channels) with a chosen temporal resolution of 1 s. For the electric field antenna as outdoor element it's important to have hemispherical view, i.e., there are no or at least minimal shadowing effects due to the surrounding area and (intermittent) electromagnetic interferences from the environment. This makes the site selection a crucial issue, in particular if the facility is located in urban area which in parallel enables benefits in terms of maintenance.

The proposed system has heritage from a predecessor facility (Schwingenschuh et al., 2011). It was possible to keep the VLF/LF measurement service without interruption for more than 10 years (Eichelberger et al., 2020), i.e., a full solar cycle. Short power line interruptions were bridged by an uninterruptible power supply (UPS).
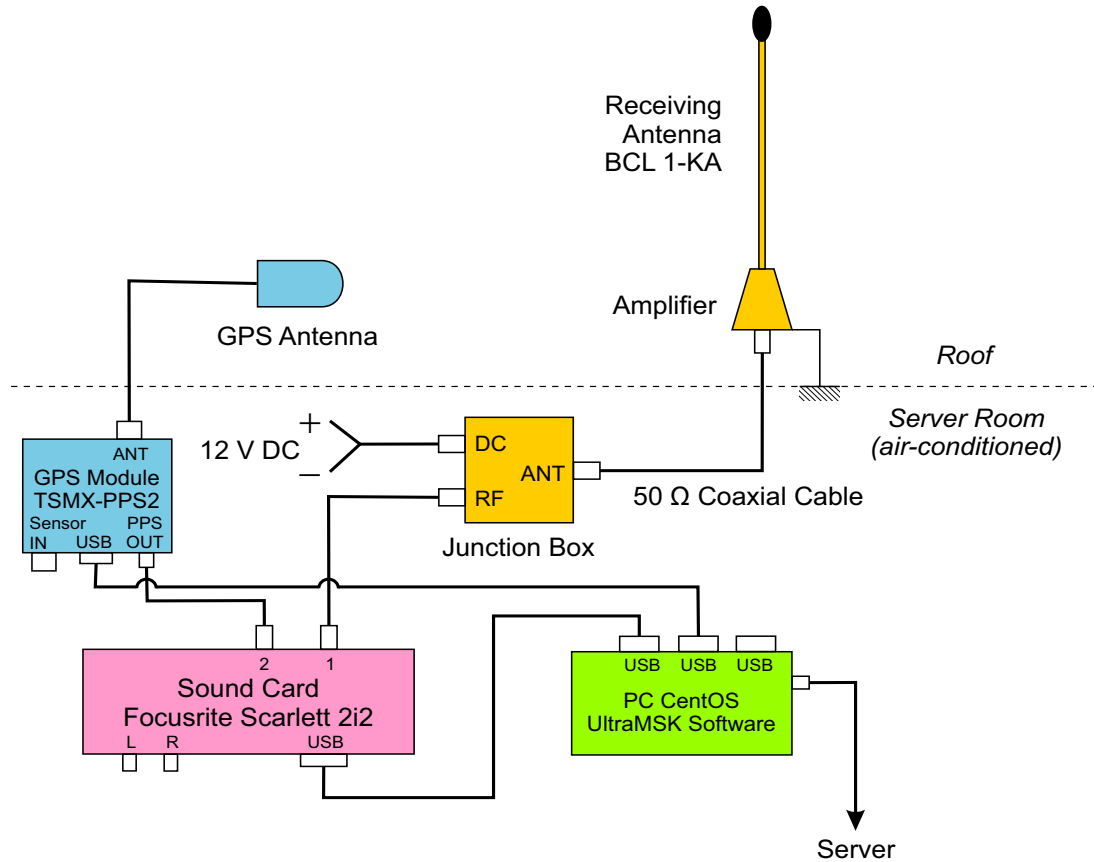
Figure 1. Block diagram of the reception system including the monopole antenna, the preamplifier, the GPS receiver and the sound card.

4 Example of VLF Observations

Figure 3 displays VLF observations recorded by the new system in Graz (Austria). We have selected the observation of 20
March 2019 where a solar flare C4.8 X-ray has been detected (see https://www.spaceweatherlive.com/en/solar-activity/top-50-
solar-flares/year/2019.html). In the top panel of Figure 3 we show the variation of the amplitude (right-vertical axis) and the
phase (left-vertical axis) versus the time in UT (horizontal axis) for the GBZ transmitter localized in Skelton (Great Britain)
and emitting at the frequency of 22.1 kHz. The middle panel shows the solar X-ray flux versus the time as recorded by GOES
satellite. The bottom panel displays the TBB transmitter signal emitted from Bafa (Turkey) at frequency of 26.7 kHz. The
intermittent noisy variations of the transmitter signals (amplitude and phase), during daytime, are local interferences because
of the site location in an urban area. The great circle paths are, respectively, in the order of 1540 km and 1445 km between Graz
facility and GBZ and TBB transmitters. It is important to note that the VLF signal enhancements of both transmitter (GBZ and
TBB) around 1200 UT coincide with the increase of the solar flare C4.8 X-ray recorded by GOES satellite. Since the operation

Figure 2. Photo of the new reception system in operation since 2019. The left and right panels display, respectively, the new antenna (i.e., Procom BCL 1-KA) rigidly fixed on a pole and installed on the roof of the building/institute, and the detected radio signal is processed/digitized by a sound card Focusrite Scarlett 2i2 which is connected to a PC running under a Linux operating system. The electronics boxes, power supply, and connecting cables are in an air-conditioned environment. The compact arrangement of devices still enables easy maintainability.

of the new system in 2019, preliminary results have been investigated particularly those related to the VLF/LF propagation in the Earth's waveguide (Eichelberger et al., 2021) and also case studies of seismo-electromagnetic events based on combined observations of CSES satellite (Zhang et al., 2020).

5 Deployment and Site Selection

Our study is based on the observation of the variability in amplitude and phase of the radio wave emitted by VLF/LF transmitters in order to determine a typical seismic signature. The wave properties of the transmitter signal will be affected during its propagation due to ionospheric disturbances above the EQ preparation zone (Hayakawa, 2015). The analysis of the received signal should allow to characterize and to define the "precursor signature" occurring on the ray path between the transmitter and the receiver stations. Then it is relevant to have the densest possible mesh of antennas. While the current networks is localized in Europe, the International Network for Frontier Research on Earthquake Precursors (INFREP, Biagi et al., 2019), we propose a new location with two antennas in the Indian Ocean: a first one in the southern hemisphere (Réunion Island) and another one near the equator (Sri Lanka). Figure 4 displays the location of the new receiving facilities and the geodesic paths towards some of the relevant transmitters, showing the importance of this new spreading. The Earth's seismic activity is mainly (but not exclusively) linked to the tectonic activity and, in particular, to subduction zones where the lithosphere sinks into the terrestrial mantle. Thus many EQs occur at the boundary of convergent plates. A map of the location of convergent plate margins on Earth was displayed by Stern (2002, Figure 1a).

The setting up of an antenna on Réunion Island, in addition to benefiting from the scientific and technical infrastructures already existing on site, will be particularly interesting for the study of seismicity and volcanism along the East Africa rift system, linked to the progression of the Somalia plate towards the Africa plate (see Bird, 2003, Figure 18). Let us also notice that the planned new VLF station in Réunion will lead to a larger space coverage of this region of the world and can be combined with other VLF networks in the southern hemisphere, like the SAVNET network in Brazil (Raulin et al., 2009).

Another VLF/LF facility shall be set up in Sri Lanka, as shown in Figure 4. Due to its unique location, this island of Indian Ocean captured the interest of many western nations in the history. Also its proximity to the equator provides accessibility to the equatorial region where occurs the so-called equatorial electrojet (Forbes, 1981). The intended location of the VLF receiver is the University of Moratuwa which is closer to the western edge of Sri Lanka.

It is important to note that Sri Lanka already hosts another low frequency receiver from the World Wide Lightning Location Network (Dowden et al., 2002; Lay et al., 2004). Hence the University of Peradeniya, localized in the center of the country, currently holds a VLF receiver with magnetic loop antennas. Both systems in Moratuwa and Peradeniya universities cover the same frequency range but present different hardware configurations. Our proposed system uses a monopole electric antenna for the signal receptions whereas the present VLF receiver at University of Peradeniya has two magnetic loop antennas oriented along magnetic north-south and east-west directions. Goals of the magnetic loop antenna system are to study the electron and ion compositions of equatorial ionosphere and lightning observations (Maxworth et al., 2021). The combine of both systems
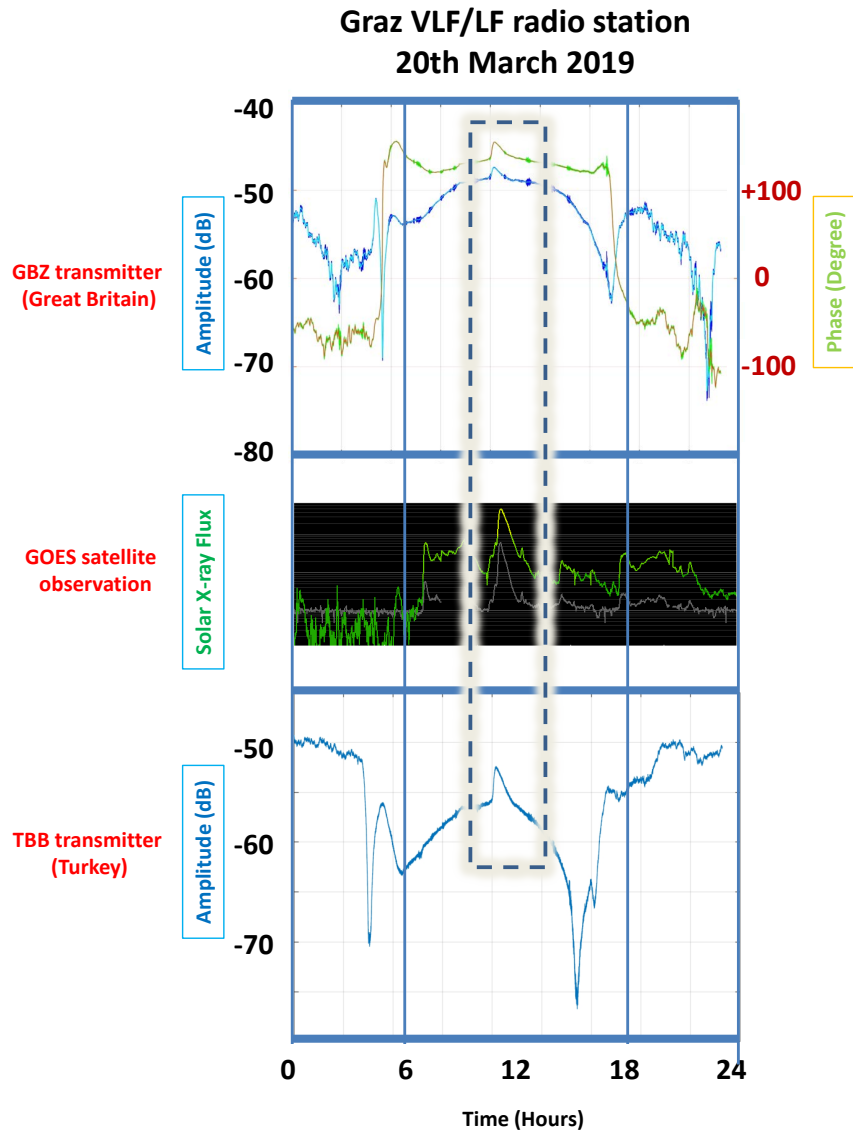
Figure 3. VLF observations recorded on 20 March 2019 by the reception system (see Figure 1). Top and bottom panels display, respectively, GBZ (Great Britain) and TBB (Turkey) transmitter signals detected by the Graz VLF/LF radio station. VLF signal enhancements of both transmitter (GBZ and TBB) around 1200 UT coincide with the increase of the solar flare C4.8 X-ray (middle panel). The dashed rectangle indicates the start and the end of this solar event and the corresponding observations on GBZ and TBB radio signals.

will help the calibration process and the possibility to cross-check natural and strong man-made signals. In addition to finding earthquake precursor signatures we will emphasize on the performance of the two VLF/LF antenna configurations.

The installation of the two receivers in Réunion and Sri Lanka will be preceded by the setting up (currently in progress) of an antenna and its reception system on the LATMOS site in Guyancourt (near Paris) in order to finalize the data acquisition, processing and storage chain. It will also allow to test and validate the right functioning of the equipment which will be the first node of this new VLF/LF network.

The data collected from our new network of VLF/LF receivers (in Guyancourt, Réunion, Sri Lanka) are intended to join the International Network for Frontier Research on Earthquake Precursors (INFREP, Biagi et al., 2019). In addition, for a better study of the wave propagation in the ionosphere, observations from ground-based VLF/LF stations will be complemented by space observations, especially those collected by the China Seismo-Electromagnetic Satellite (CSES). This mission is the first Chinese satellite devoted to the investigation of ionospheric disturbances in connection with EQs (Shen et al., 2018). It was launched on 2 February 2018, and orbits at an altitude of ~ 507 km at fixed local times 0200 LT and 1400 LT. Investigations have been done about magnetic field variations measured at low altitude by CSES and ESA's *Swarm* satellites in connection with EQs (Schirninger et al., 2021). Boudjada et al. (2021) have performed a wave spectral analysis of the intensity variations of a VLF signal emitted by the ground-base NWC transmitter radio station (localized at North West Cape, Australia, see Figure 4) and observed by the electric field experiment (EFD) onboard the CSES satellite. Additionally, the data collected by our new VLF/LF network will also be combined with those of the ionospheric sounding instrument IONO onboard the (CubeSat) nano-satellite INSPIRE-SAT 7 (Meftah et al., 2022) which was launched on 15 April 2023 on a Sun-synchronous orbit with descending node near 0930 LT. It orbits at an altitude between 490 km and 530 km. Magnetic field measurements along the orbit can also be used as well as those of the other CubeSat UVSQ-SAT, precursor nano-satellite of INSPIRE-SAT 7, launched on 24 January 2021 (Meftah et al., 2021).

6   Conclusions

In this paper, we present a new VLF/LF reception network for searching and studying earthquakes electromagnetic precursors. The proposed system will allow us a daily monitoring of transmitter signals in the VLF (3-30 kHz) and LF (30-300 kHz) frequency bands. Each individual facility consists of a monopole antenna, a preamplifier, a GPS receiver and a sound recorder card; it is identical to the UltraMSK system already in operation in Graz (Austria). At a first step, three antennas and their reception device will be deployed in Guyancourt (France), Réunion (France) and Moratuwa (Sri Lanka). The collected data are intended to join the INFREP network and will be completed by space observations performed by the CSES satellite and the INSPIRE-SAT 7 and UVSQ-SAT CubeSats, allowing the enhancement of the capability of earthquakes electromagnetic precursor detections. Of course additional observational approaches and observables can be considered (Meng et al., 2019), for an integrated perspective, in order to characterize atmospheric and ionospheric excitations related to natural hazard events. Actual status of seismo-electromagnetic investigations as evaluated and reviewed in recent papers (Eppelbaum, 2021; Chen
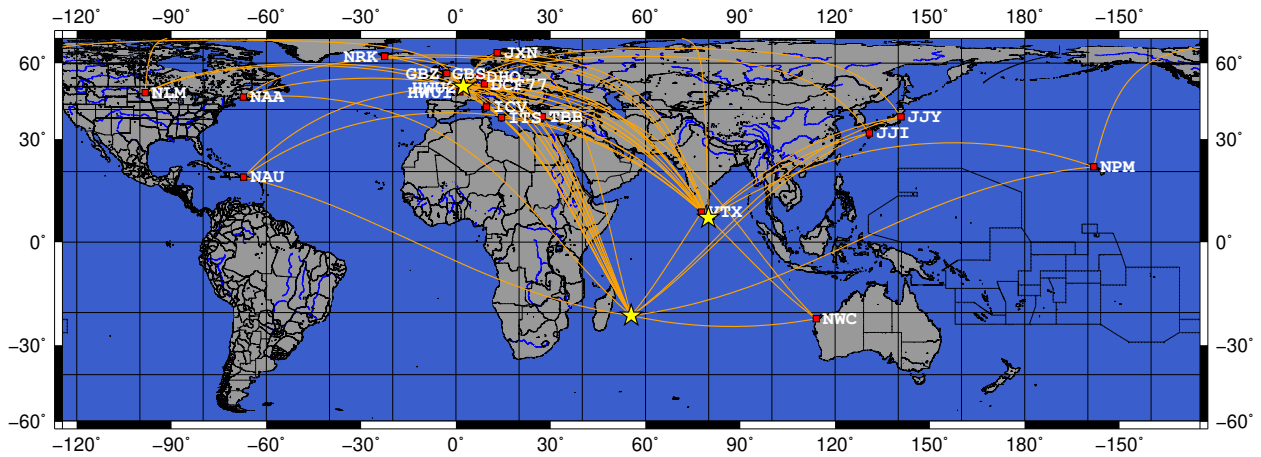
Figure 4. The map shows the location (yellow stars) of the new VLF/LF receiving facilities in Guyancourt, Réunion, and Sri Lanka together with important transmitter stations (red squares) and their corresponding great circle paths (orange lines). The Sri Lanka station is particularly useful to sample the area close to the Sunda subduction zone with large earthquakes via the path to the NWC transmitter (19.8 kHz), Western Australia. The facility in Réunion enables a broad range of paths over East Africa.

et al., 2022) highlight the VLF/LF techniques and related methods in the frame of geophysical prospecting with solid earth background.

165 *Author contributions.* PG, AM, MB and HE have co-written the paper. PG is the coordinator of the new antennas network, and supervises the installation of the new equipments. AM is involved in setting up the VLF antenna in Sri Lanka. MB, HE and KS have implemented the UltraMSK reception facility in Graz. MB carried out the study presented in Figure 3, HE made the map showed in Figure 4. MM participates in the installation of the VLF antennas in France. PB is the PI of the INFREP network. All co-authors reviewed the paper.

Competing interests. The authors declare that they have no conflict of interest.

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References

Biagi, P. F., Colella, R., Schiavulli, L., Ermini, A., Boudjada, M., Eichelberger, H., Schwingenschuh, K., Katzis, K., Contadakis, M. E., Skeberis, C., Moldovan, I. A., and Bezzeghoud, M.: The INFREP Network: Present Situation and Recent Results, Open Journal of Earthquake Research, 8, 101–115, https://doi.org/10.4236/ojer.2019.82007, 2019.

Bird, P.: An updated digital model of plate boundaries, Geochem. Geophys. Geosyst., 4, 1027, https://doi.org/10.1029/2001GC000252, 2003.

Boudjada, M. Y., Biagi, P. F., Al-Haddad, E., Galopeau, P. H. M., Besser, B., Wolbang, D., Prattes, G., Eichelberger, H., Stangle, G., Parrot, M., and Schwingenschuh, K.: Reception conditions of low frequency (LF) transmitter signals onboard DEMETER micro-satellite, Phys. Chem. Earth, 102, 70–79, https://doi.org/10.1016/j.pce.2016.07.006, 2017.

Boudjada, M. Y., Eichelberger, H. U., Zhang, X., Magnes, W., Denisenko, V., Pollinger, A., Galopeau, P. H. M., Schwingenschuh, K., and Besser, B.: Analysis of ground-based very low frequency signal recorded onboard CSES satellite, in: 2021 Kleinheubach Conference, pp. 1–3, https://doi.org/10.23919/IEEECONF54431.2021.9598373, 2021.

Bowman, D. D., Ouillon, G., Sammis, C. G., Sornette, A., and Sornette, D.: An observational test of the critical earthquake concept, J. Geophys. Res., 103, 24,359–24,372, https://doi.org/10.1029/98JB00792, 1998.

Chen, H., Han, P., and Hattori, K.: Recent advances and challenges in the seismo-electromagnetic study: A brief review, Remote Sens., 14, https://doi.org/10.3390/rs14225893, 2022.

Cicerone, R. D., Ebel, J. E., and Britton, J.: A systematic compilation of earthquake precursors, Tectonophysics, 476, 371 – 396, https://doi.org/10.1016/j.tecto.2009.06.008, 2009.

Clilverd, M. A., Rodger, C. J., Thomson, N. R., Brundell, J. B., Ulich, T., Lichtenberger, J., Cobbett, N., Collier, A. B., Menk, F. W., Seppälä, A., Verronen, P. T., and Turunen, E.: Remote sensing space weather events: Antarctic-Arctic Radiation-belt (Dynamic) Deposition-VLF Atmospheric Research Konsortium network, Space Weather, 7, S04 001, https://doi.org/10.1029/2008SW000412, 2009.

De Santis, A., Abbattista, C., Alfonsi, L., Amoruso, L., Campuzano, S. A., Carbone, M., Cesaroni, C., Cianchini, G., De Franceschi, G., De Santis, A., Di Giovambattista, R., Marchetti, D., Martino, L., Perrone, L., Piscini, A., Rainone, M. L., Soldani, M., Spogli, L., and Santoro, F.: Geosystemics view of earthquakes, Entropy, 21, 412, https://doi.org/10.3390/e21040412, 2019.

Dobrovolsky, I. P., Zubkov, S. I., and Myachkin, V. I.: Estimation of the size of earthquake preparation zones, Pure Appl. Geophys., 117, 1025–1044, https://doi.org/10.1007/BF00876083, 1979.

Dowden, R. L., Brundell, J. B., and Rodger, C. J.: VLF lightning location by time of group arrival (TOGA) at multiple sites, J. Atmos. Solar-Terr. Phys., 64, 817–830, https://doi.org/10.1016/S1364-6826(02)00085-8, 2002.

Eichelberger, H., Schwingenschuh, K., Boudjada, M. Y., Besser, B. P., Wolbang, D., Rozhnoi, A., Solovieva, M., Biagi, P. F., Stachel, M., Aydogar, Ö., Muck, C., Grill, C., and Jernej, I.: Characterization of sub-ionospheric VLF/LF waveguides for seismic event studies during solar minimum, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-15760, https://doi.org/10.5194/egusphere-egu2020-15760, 2020.

Eichelberger, H., Boudjada, M. Y., Schwingenschuh, K., Galopeau, P., Rozhnoi, A., Solovieva, M., Biagi, P., Fedun, V., and Besser, B. P.: Sub-ionospheric VLF/LF waveguide anomalies over Europe, in: Proceedings of the XXXIVth URSI General Assembly in Rome, pp. Fr–GHE–AM1–1, https://www.ursi.org/proceedings/procGA21/papers/URSIGASS2021-Fr-GHE-AM1-1.pdf, 2021.

Eppelbaum, L. V.: VLF-method of geophysical prospecting: A non-conventional system of processing and interpretation (implementation in the Caucasian ore deposits), ANAS Transactions, Earth Sciences, 2/2021, 16–38, https://doi.org/10.33677/ggianas20210200060, 2021.

Forbes, J. M.: The Equatorial Electrojet, Rev. Geophys. Space Phys., 19, 469–504, https://doi.org/10.1029/RG019i003p00469, 1981.

Hayakawa, M.: VLF/LF Techniques, chap. 5, pp. 139–197, John Wiley & Sons, Ltd, https://doi.org/10.1002/9781118770368.ch5, 2015.

210   Hayakawa, M. and Hobara, Y.: Current status of seismo-electromagnetics for short-term earthquake prediction, Geomatics, Natural Hazards and Risk, 1, 115–155, https://doi.org/10.1080/19475705.2010.486933, 2010.

Hayakawa, M., Molchanov, O. A., Ondoh, T., and Kawai, E.: The precursory signature effect of the Kobe earthquake on VLF subionospheric signals, J. Comm. Res. Lab., Tokyo, 43, 169–180, 1996.

Hayakawa, M., Raulin, J. P., Kasahara, Y., Bertoni, F. C. P., Hobara, Y., and Guevara-Day, W.: Ionospheric perturbations in possible associ-
215   ation with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF propagation data, Nat. Hazards Earth Syst. Sci., 11, 513–518, https://doi.org/10.5194/nhess-11-513-2011, 2011.

Keilis-Borok, V.: Earthquake prediction: State-of-the-art and emerging possibilities, Annu. Rev. Earth Planet. Sci., 30, 1–33, https://doi.org/10.1146/annurev.earth.30.100301.083856, 2002.

Lay, E. H., Holzworth, R. H., Rodger, C. J., Thomas, J. N., Pinto, O., and Dowden, R. L.: WWLL global lightning detection system: Regional
220   validation study in Brazil, Geophys. Res. Lett., 31, L03102, https://doi.org/10.1029/2003GL018882, 2004.

Maxworth, A., Lichtenberger, J., Liyanage, P., and Gołkowski, M.: First results from the ELF/VLF receiver in Sri Lanka, in: Proceed-
ings of the XXXIVth URSI General Assembly in Rome, pp. Fr–H01–AM2–3, https://www.ursi.org/proceedings/procGA21/papers/URSIGASS2021-Fr-H01-AM2-3.pdf, 2021.

Maxworth, A. S., Gołkowski, M., Cohen, M. B., Moore, R. C., Chorsi, H. T., Gedney, S. D., and Jacobs, R.: Multistation observations of
225   the azimuth, polarization, and frequency dependence of ELF/VLF waves generated by electrojet modulation, Radio Sci., 50, 1008–1026, https://doi.org/10.1002/2015RS005683, 2015.

Meftah, M., Boutéraon, T., Dufour, C., Hauchecorne, A., Keckhut, P., Finance, A., Bekki, S., Abbaki, S., Bertran, E., Damé, L., Engler, J.-L., Galopeau, P., Gilbert, P., Lapauw, L., Sarkissian, A., Vieau, A.-J., Lacroix, P., Caignard, N., Arrateig, X., Hembise Fanton d'Andon, O., Mangin, A., Carta, J.-P., Boust, F., Mahé, M., and Mercier, C.: The UVSQ-SAT/INSPIRESat-5 CubeSat mission: First in-orbit measure-
230   ments of the Earth's outgoing radiation, Remote Sens., 13, 1449, https://doi.org/10.3390/rs13081449, 2021.

Meftah, M., Boust, F., Keckhut, P., Sarkissian, A., Boutéraon, T., Bekki, S., Damé, L., Galopeau, P., Hauchecorne, A., Dufour, C., Finance, A., Vieau, A.-J., Bertran, E., Gilbert, P., Caignard, N., Dias, C., Engler, J.-L., Lacroix, P., Grossel, K., Rannou, V., Saillant, S., Avelino, Y., Azoulay, B., Brand, C., Dominguez, C., Haasz, A., Paskeviciute, A., Segura, K., Maso, P., Ancelin, S., Mercier, C., Stee, V., Mangin, A., Bolsée, D., and Billard, C.: INSPIRE-SAT 7, a second CubeSat to measure the Earth's energy budget and to probe the ionosphere,
235   Remote Sens., 14, 186, https://doi.org/10.3390/rs14010186, 2022.

Meng, X., Vergados, P., Komjathy, A., and Verkhoglyadova, O.: Upper atmospheric responses to surface disturbances: An observational perspective, Radio Sci., 54, 1076–1098, https://doi.org/10.1029/2019RS006858, 2019.

Molchanov, O., Rozhnoi, A., Solovieva, M., Akentieva, O., Berthelier, J. J., Parrot, M., Lefeuvre, F., Biagi, P. F., Castellana, L., and Hayakawa, M.: Global diagnostics of the ionospheric perturbations related to the seismic activity using the VLF radio signals collected
240   on the DEMETER satellite, Nat. Hazards Earth Syst. Sci., 6, 745–753, https://doi.org/10.5194/nhess-6-745-2006, 2006.

Nina, A., Biagi, P. F., Mitrović, S. T., Pulinets, S., Nico, G., Radovanović, M., and Popović, L. Č.: Reduction of the VLF signal phase noise before earthquakes, Atmosphere, 12, 444, https://doi.org/10.3390/atmos12040444, 2021.

Parrot, M.: DEMETER Satellite and Detection of Earthquake Signals, chap. 6, pp. 115–138, CRC Press, Boca Raton, https://doi.org/10.1201/9781315166841, 2018.

245   Raulin, J.-P., Correia de Matos David, P., Hadano, R., Saraiva, A. C. V., Correia, E., and Kaufmann, P.: The South America VLF NETwork (SAVNET), Earth, Moon and Planets, 104, 247–261, https://doi.org/10.1007/s11038-008-9269-4, 2009.

Samanes, J. E., Raulin, J.-P., Macotela, E. L., and Guevara Day, W. R.: Estimating the VLF modal interference distance using the South America VLF Network (SAVNET), Radio Sci., 50, 122–129, https://doi.org/10.1002/2014RS005582, 2015.

Schirninger, C., Eichelberger, H. U., Magnes, W., Boudjada, M. Y., Schwingenschuh, K., Pollinger, A., Besser, B. P., Biagi, P. F., Solovieva, M., Wang, J., Cheng, B., Zhou, B., Shen, X., Delva, M., and Lammegger, R.: Satellite measured ionospheric magnetic field variations over natural hazards sites, Remote Sens., 13, 2360, https://doi.org/10.3390/rs13122360, 2021.

Schwingenschuh, K., Prattes, G., Besser, B. P., Močnik, K., Stachel, M., Aydogar, O., Jernej, I., Boudjada, M. Y., Stangl, G., Rozhnoi, A., Solovieva, M., Biagi, P. F., Hayakawa, M., and Eichelberger, H. U.: The Graz seismo-electromagnetic VLF facility, Nat. Hazards Earth Syst. Sci., 11, 1121–1127, https://doi.org/10.5194/nhess-11-1121-2011, 2011.

Shen, X., Zhang, X., Yuan, S., Wang, L., Cao, J., Huang, J., Zhu, X., Piergiorgio, P., and Dai, J.: The state-of-the-art of the China Seismo-Electromagnetic Satellite mission, Sci. China Technol. Sci., 61, 634–642, https://doi.org/10.1007/s11431-018-9242-0, 2018.

Stern, R. J.: Subduction zones, Rev. Geophys., 40, 1012, https://doi.org/10.1029/2001RG000108, 2002.

Yoshida, M., Yamauchi, T., Horie, T., and Hayakawa, M.: On the generation mechanism of terminator times in subionospheric VLF/LF propagation and its possible application to seismogenic effects, Nat. Hazards Earth Syst. Sci., 8, 129–134, https://doi.org/10.5194/nhess-8-129-2008, 2008.

Zhang, X., Wang, Y., Boudjada, M. Y., Liu, J., Magnes, W., Zhou, Y., and Du, X.: Multi-experiment observations of ionospheric disturbances as precursory effects of the Indonesian Ms6.9 earthquake on August 05, 2018, Remote Sens., 12, https://doi.org/10.3390/rs12244050, 2020.