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 com-

5 munication, 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

10 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)

15 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

20 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 which are covering a large
25 spectral domain, from a few Hz to several hundred kilohertz. 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
30 stations. 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
35 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). A similar relation was obtained by Bowman et al. (1998).

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

40 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
45 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
50 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

55 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). A specially dedicated software (UltraMSK) will lead the

60 recording of the detected transmitter signals and will deliver a daily data file.

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

65 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).

4 Example of VLF Observations

70 Figure 2 displays VLF observations recorded by the new system in Graz (Austria). We have selected the observation of 20 March 2019 where a solar flare has been detected. In the first panel of Figure 2 we show the variation of the amplitude (right-vertical axis) and the phase (left-vertical axis) versus the time (horizontal axis) for the GBZ transmitter localized in Skelton (Great Britain) and emitting at the frequency of 22.1 kHz. The second panel shows the solar X-ray flux versus the time as recorded by GOES satellite. The third panel displays the TBB transmitter signal emitted from Bafa (Turkey) at frequency of

75 26.7 kHz. It is important to note that both transmitter (GBZ and TBB) signals have been simultaneously disturbed at $\sim$ 1200 UT by the X-ray solar flare recorded by GOES satellite.

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

80 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 are mainly installed in Europe, we propose a new location with two antennas in the Indian Ocean: a first one in the southern hemisphere
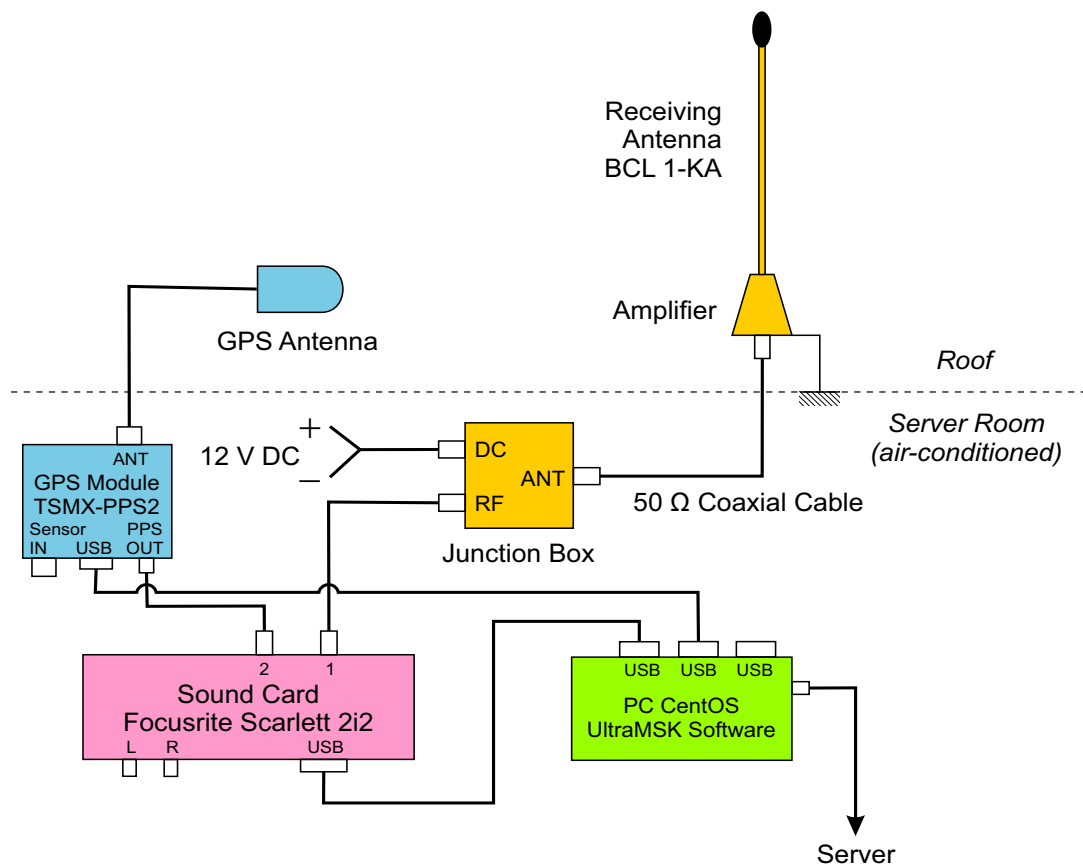
Figure 1. Block diagram of the reception system including the monopole antenna, the preamplifier, the GPS receiver and the sound card.

(Réunion Island) and another one near the equator (Sri Lanka). Figure 3 displays the location of the new receiving facilities

85 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

90 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 3. Due to its unique location, this island of Indian

95 Ocean captured the interest of many western nations in the history. Also its proximity to the equator provides accessibility to
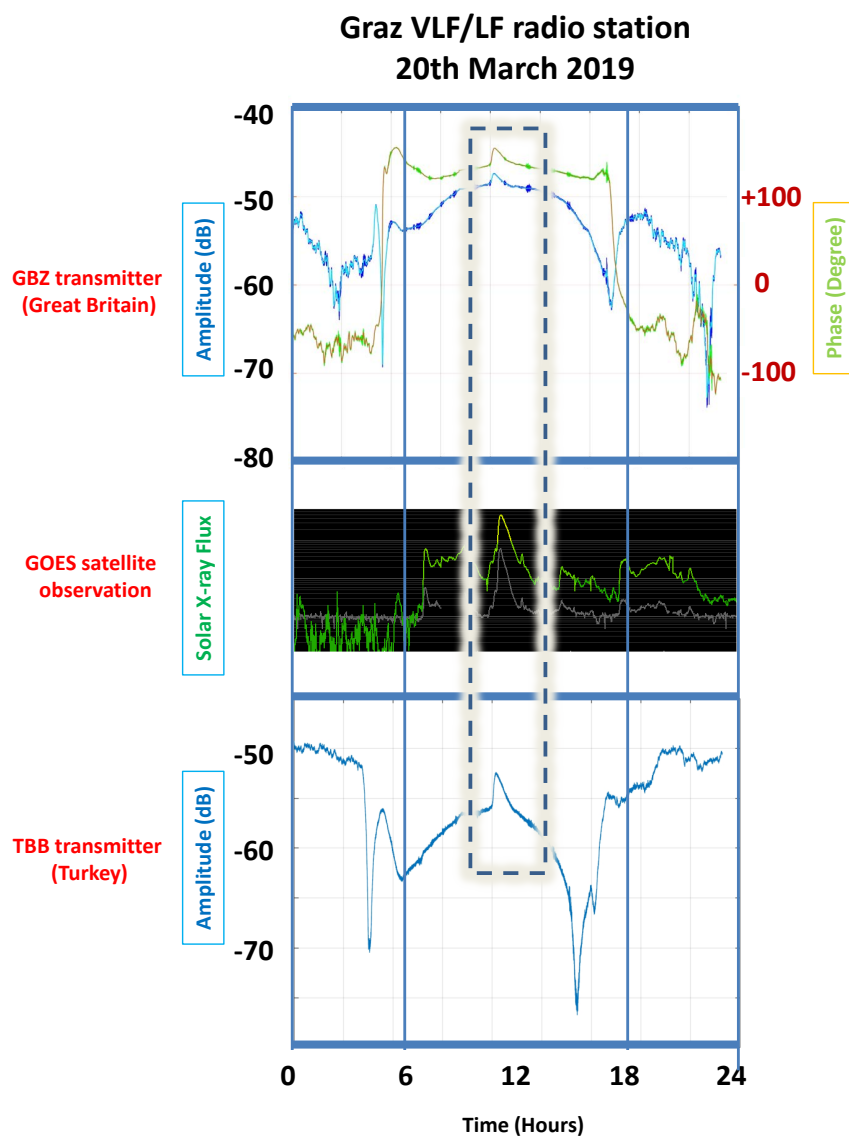
Figure 2. Example of VLF signal enhancements associated to X-ray solar flare recorded on 20 March 2019 around 1200 UT by the Graz VLF ground-based facility (first and third panels) and by the GOES satellite (second panel). The first panel displays the amplitude (blue curve) and the phase (green curve) variations of the GBZ transmitter signal (Great Britain) as detected by the new reception system (see Figure 1). The third panel shows the amplitude variation of the TBB transmitter signal (Turkey) as observed by the INFREP reception system (Biagi et al., 2019). The dashed rectangle indicates the starting and the ending times of the solar event on GOES satellite and the counterparts as recorded in radio signals of GBZ and TBB transmitters. The VLF signal enhancements around 1200 UT coincide with the maximum of the solar X-ray flux.

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 (Christian et al., 2003). 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 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 3) 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), the launch of which is scheduled for early 2023 on a Sun-synchronous orbit at a maximum altitude of ~ 600 km and a local time at descending node of 0930 LT. 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 brief communication, 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
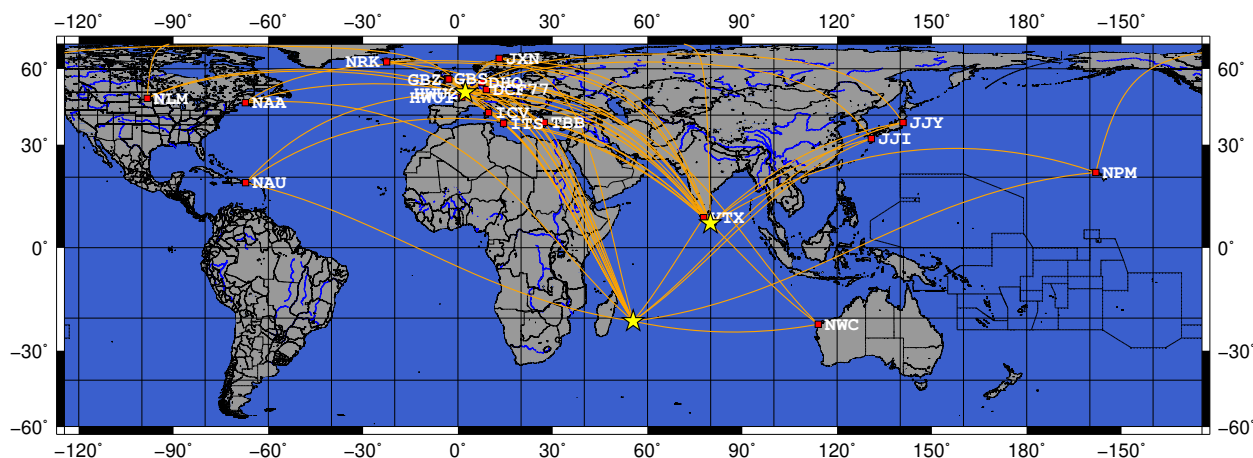
Figure 3. The map shows the location (yellow stars) of the new VLF/LF receiving facilities in Guyancourt, Réunion, and Sri Lanka together with important transmitter stations (red squares) and their corresponding great circle paths (orange lines). The Sri Lanka station is particularly useful to sample 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.

LF (30-300 kHz) frequency bands. Each individual facility consists of a monopole antenna, a preamplifier, a GPS receiver
130   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
135   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 et al., 2022) highlight the VLF/LF techniques and related methods in the frame of geophysical prospecting with
solid earth background.

Author contributions.   PG, AM, MB and HE have co-written the paper. PG is the coordinator of the new antennas network, and supervises
140   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 2, HE made the map showed in Figure 3. 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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