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GROUND VIBRATION MONITORING AT CERN AS PART OF THE INTERNATIONAL SEISMIC NETWORK

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Abstract

The civil engineering activities in the framework of the High Luminosity LHC project, the Geneva Geothermie 2020 [1] and the continuous monitoring of the LHC civil infrastructures triggered the need for the installation of a seismic network at CERN. A data acquisition system has been deployed in 3 places at CERN: ATLAS, CMS and the Prévessin site. The system is sending all the raw data to the Swiss Seismological Service (SED) [2] and performs FFT on the fly to be stored in the LHC database.

INTRODUCTION

In the future decades, the mechanical stability of high energy accelerator components, in particular of magnetic elements guiding and focusing the beam, will become crucial: high luminosity [3] typically requests smaller beam sizes, thus requiring an improved vibration stability of the structures and a better knowledge of the environmental mechanical noise to determine any detrimental effect on the accelerator performances and eventually correct for that. The vibration stability of the structures is linked to the dynamic behavior of the structure itself and the environmental conditions where the structure is installed. A seismic wave striking the LHC will induce beam position (orbit) changes all along the circumference. If the position change is too large and too fast, the resulting beam loss could lead to a beam abort. For small earthquakes (that do not induce mechanical damage to accelerator components) the LHC protection system is able to safely abort the beams without any risk of damaging the accelerator components. However, the repetition of beam aborts will affect the integrated luminosity, i.e. the availability for production of physics data, of the accelerator and generate extra operation costs.

In view of future sensitive projects such as the HL-LHC [3] civil engineering operation and the geo-thermal exploitation in the Geneva canton, CERN in collaboration with the Swiss Authorities decided to deploy a seismic network to evaluate their impact on the LHC machine operation. The goal of the network is to collect the seismic activity background level in 2017 as reference before the main activities described previously start and will continue over the next decade. A study mandated by the Geneva canton to evaluate the impact of the possible micro seismicity induced by geothermal exploitation on the CERN installation gave the following result; there is a probability of local earthquakes: Monthly, magnitudes may reach up to ~3, but most earthquakes are expected to be limited to magnitude ~2 with a weekly frequency. In the geothermal exploitation framework and following the Resonance SA study, the Service Industriel de Genève (SIG) [4] has decided to densify the local seismic network in the Geneva canton to optimize the predictive model and localize the best site for geothermal exploitation. Thanks to the new stations installed at CERN, more low magnitude seismic events should be recorded with a better spatial resolution. As an example, the LHC beam orbit oscillations on 13th November 2016 between 5am and 7pm GMT (UTC+1) are shown in Figure 1. The beam position is influenced by the moon gravity and by a series of earthquake waves which propagated through the Earth's crust from New Zealand. (with a maximum magnitude of Mw 7.9 at 12:03am GMT).

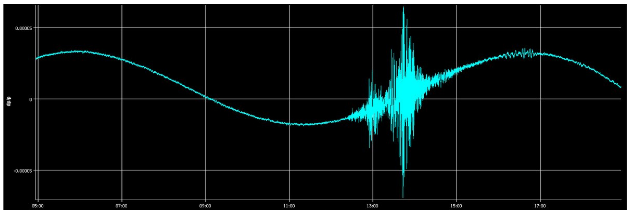

Figure 1: LHC beam horizontal orbit oscillations.

This paper presents the requirements, the design, the validation tests and the installation of the LHC seismic network deployed at CERN beginning of 2017 in collaboration with the Swiss Seismological Service (SED).

REQUIREMENTS

Seismic Wave on LHC

The impact of a ground wave travelling across the LHC depends on the wave amplitude and wavelength and its orientation in relation to the ring. The consequence of the passage of a seismic wave across the LHC while it is in operation may be divided into 3 categories:

- The amplitude is very small ($< 0.1 \mu m$), the passage may not even be detected.
- The amplitude is large enough to temporarily disturb the beam during the passage of the wave and will lead to a small loss of data for the experiments
- The combination of amplitude and wavelengths are strong enough for the beam movements to cause large particle losses, leading eventually to a beam abort by the Machine Protection System (MPS) [5]. In that case it will take a few hours to restore a quality of beam to a level suitable for the data acquisition for the LHC experiments. Such events should be extremely rare in order not to affect the LHC uptime and the data acquisition periods. A rate of one per week can already be considered to have a significant impact.

Frequency-amplitude Impact on LHC

The CERN seismic network should measure both the low amplitude vibrations of the LHC during its normal operation and the high amplitude vibrations due to, for example, HL-LHC related excavation works, near source earthquakes triggered by the geothermal project or teleseismic earthquakes. One has to decide the boundaries inside which ground motion will be measured. The upper limit was fixed

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to an acceleration of 2 g, which corresponds to a near source earthquake of magnitude M7.5. In terms of frequencies, the LHC is subject to industrial vibrations (frequencies >10 Hz), mainly due to the tunnel ventilations and cryogenic lines. To monitor such vibrations, the seismic sensors should be able to measure vibrations up to 100 Hz. On the other hand, the frequencies excited by regional earthquakes are comprised in between 30 s (0.033 Hz) and 10 Hz: a sensor measuring frequencies down to 30 s is a minimum requirement for monitoring earthquakes. Figure 2 shows the Power Spectral Density (PSD) of ground motion vibration as measured in point 1 and 5 of LHC tunnel. Because the LHC tunnel is at a depth of at least 80 meters underground, the vibration due to human activity is strongly attenuated.

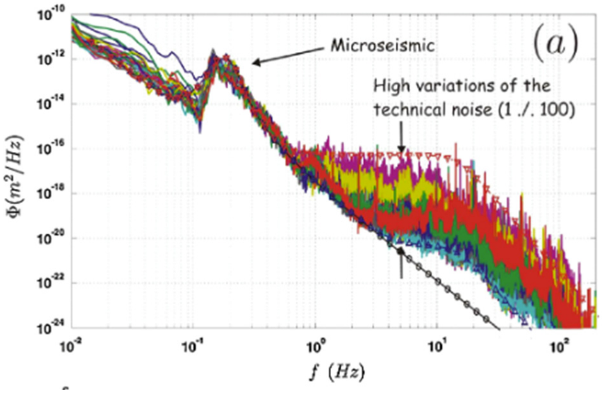

Figure 2: Ground motion measurements in different LHC tunnel locations.

Global Seismographic Network Connections

The Global Seismographic Network (GSN) (Figure 3) is composed of more than several thousand stations, globally distributed, with state-of-the-art digital seismic equipment that provides free, real-time, open access data. The Swiss Seismological Service at the ETH Zurich is the federal agency for earthquakes in Switzerland. Its activities are integrated in the federal action plan for earthquake precaution. The raw data must arrive to SED within 10 seconds, with a 1 ms accuracy. Switzerland needs a seismic network to monitor background seismicity and to understand the effects of rare, large-scale earthquakes that cause extensive damage. This is important even in a country such as Switzerland with a moderate seismic hazard. A dense, state-of-the-art network that monitors seismic activity in real time fulfils this role: it rapidly notifies the authorities, the media and the public about earthquakes in the wake of significant seismic events and provides high-quality data for hazard studies and fundamental earthquake research.

According to the geothermal exploitation project, and the consequent densification of the local seismic network around Geneva and the CERN needs, it was decided to connect the CERN seismic network to the Swiss and World-wide seismic network.

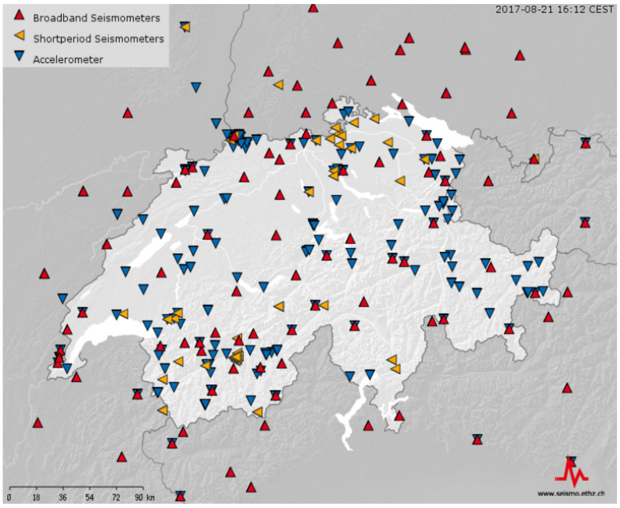

Figure 3: Swiss Seismic Network.

SEISMIC STATIONS OVERVIEW

Sensors

Due to the dynamic range of the data-loggers and the sensors' characteristics, it is not possible to cover the range of vibrations required for CERN seismic stations with only one sensor.

A high noise is inherent to strong motion sensors and do not permit to measure low amplitude vibrations, but they can measure high ranges and for example the 2 g accelerations needed for this network.

A broadband seismometer will be used for low amplitude vibrations. Broadband seismometers measuring at low frequencies (<30 s) are not necessarily designed to measure up to 100 Hz. A pre-selection of the sensors able to measure up to 100 Hz was performed. Moreover, the signal of broadband seismometers can be very sensitive to magnetic fields, so a selection of the most suitable references was performed.

In order to fulfil the requirements in terms of measured amplitudes, two sensors were chosen: a broadband seismometer and a strong motion sensor. The chosen broadband seismometers are the 6T series [6] from Guralp™ for the underground stations and the 40T series [7] at the surface, with a bandwidth extension up to 100 Hz. The strong motion sensor is the Episensor ES-T [8] from Kinemetrics™. They are supplied by a 12V switching mode power supply outputting 2 A with less than 50 mVpp ripple.

Stations Locations

It has been decided to start with three seismic stations. Two stations are installed underground, as close as possible to experiment points ATLAS and CMS. These locations have been chosen in order to measure the impact of the drilling of shaft for HL-LHC upgrade. During LHC run, these two stations are installed in a very quiet environment so every small vibration can be detected. However due to human activities during technical stop, long LHC shutdown in winter or civil engineering activities for HL-LHC these stations can have a lot of background noise during these periods. For that reason, it has been decided to have a third station on the surface, at the center of the LHC ring, as far as possible from any human activities in order to have a very good reference station (see figure 4).

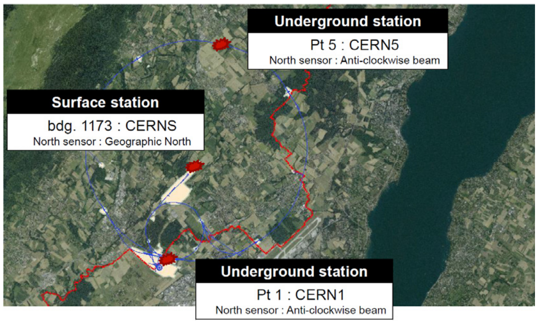

Figure 4: seismic stations locations.

SEED Format

Seismic data-loggers give the possibility to send data in the SEED format [9], used worldwide by seismologists. SED is adding directly on its server the additional metadata information and integrate CERN into the international seismic network. A real-time miniSEED data package contains 512 bytes divided in two parts: a header and the recorded data and should be delivered with a 10 seconds latency. The header is composed of a Network Code, a Channel Identifier, a Location Identifier, a Station Identifier, a Data Quality Indicator, a Sequence Number, a timestamp, the size of the record, the frequency of the record and some additional separators in the header. After the header, the record is composed of concatenated binary data. The time stamp and sequence number allow the server to discard data if they arrive in a non-coherent order.

Ground Vibration Acquisition System

The data acquisition system (DAQ) should be easy to implement in the LHC tunnel and robust to the harsh environment. The data should be easy to analyze and stored in the LHC logging database, so the DAQ has to able to communicate with the CERN infrastructure. There was no existing system fully satisfying the needs of measuring natural ground motion (broadband seismometer) and industrial vibration (strong motion sensor) related to HL-LHC civil engineering activities.

To satisfy the different requirements, the NI™ CompactRIO 9035 [10] has been chosen with two NI 9239 C-series modules [11]. A LabVIEW Real-Time application has been developed making use of the embedded FPGA. (see Figure 5).

Raw data is acquired, processed and shared in real time by the CompactRIO. It is sent to SED which redirects it towards the worldwide seismic databases. The Power spectral densities are available for CERN users and a more complete version of the data is only available for CERN experts. Each of these data is post-processed independently to fulfill the requirements of the users. If one module fails, the other modules can continue streaming. (see Figure 6)

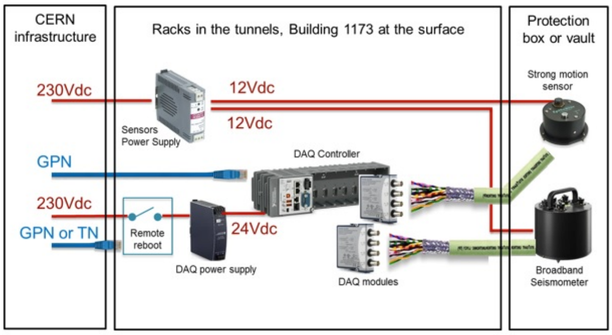

Figure 5: Acquisition system architecture.

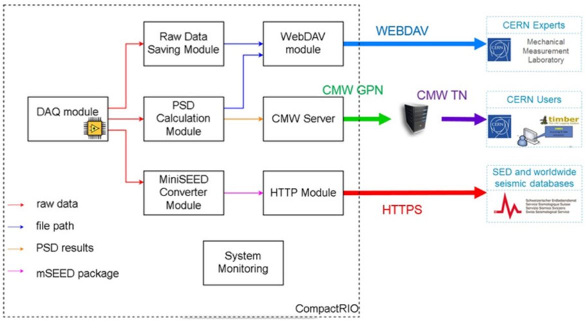

Figure 6: Software architecture.

Different communications protocols are used depending on the destination of the data. WebDAV protocol [12], which is natively supported in LabVIEW, is used to transfer data to the CERN file storage system. HTTPS [13] has been chosen as agreed with CERN and SED IT security service to stream miniSEED data. To communicate with the LHC database, an internal protocol, CMW [14], has been used. One of the challenge for this application was to fit the time accuracy required (1ms). The internal clock of a CompactRIO has an accuracy of 40 ppm at 25 degrees Celsius, which can lead to 3 s of drift per day: as for any seismic data-logger, an external synchronization is required. Although it is possible to use GPS synchronization with a CompactRIO, it requires an additional GPS module, an antenna, and to get the GPS signal underground for the sensors located close to the LHC. As NTP service [15] at CERN provides a time accuracy below 1 ms and does not require external hardware, this reference was chosen to develop the CERN seismic stations.

To be integrated in the international seismic network, it was also critical to have a very robust system and be notified in case of faults. In case of network failure with a station, data will be stored locally and resend later. Two independent Linux machines are also present to monitor the three DAQ systems and send a warning in case of problem. Two power supplies will be installed to have redundancy in case of failure. They will be monitored through the C-series modules and a warning will be sent if one fails. In case of a complete power failure, an independent machine will send a warning and the DAQ will restart automatically once power comes back again.

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CONCLUSION

The deployment of 3 seismic stations at CERN have been successfully performed and earthquakes have been caught from different places around the world (Figure 7).

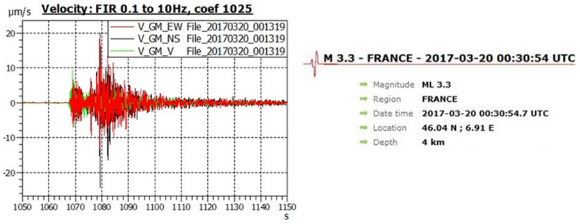

Figure 7: Recorded earthquake close to Chamonix.

The network was designed to be compatible with the LHC harsh environment and to track the ground motions in between 30 s and 100 Hz, with amplitudes ranging from LHC ground motion up to 2 g. This wide range of measurements allows to get an accurate feedback on the ground stability in the LHC tunnel.

Thanks to the valuable collaboration between CERN and SED, the data, made available at CERN and for worldwide seismic organizations, will be used for very diverse applications. The study of the impact of earthquakes on the LHC will be a guidance for the "Géothermie 2020" project, aiming at developing the use of geothermal energy in the Geneva canton without impacting CERN. The data is planned to be used in the HL-LHC framework, a project to upgrade the LHC. The vibration levels will be of particular interest during the excavation of the new LHC shafts. Finally, the network will be used as a valuable reference to monitor vibration levels in the LHC on a long-term basis.

The systems have been running 24/7 for several months and show to fulfill all requirements.

Future development may be done to get data at SED within 2 seconds instead to the actual 10 seconds and maybe more stations will be added later to increase the spatial accuracy.

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