# ILC investigation and in-field traceability using a high sensitivity & high mass geophone set

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# ILC investigation and in-field traceability using a high sensitivity & high mass geophone set

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ABSTRACT

Following and in relation to the recently finalized EMPIR-infra AUV project, and in attempt to accommodate a raising interest and need globally for high level metrology in both the very Low Frequency range (VLF) and the Ultra Low Frequency range (ULF), an Inter Laboratory Comparison (ILC) has been initiated among 4 different National Metrology Institutes (NMIs)/Designated Institutes (DIs). The participating metrology institutes already have measurement capability (CMC) in the frequency range relevant for providing traceability to in-field vibration monitoring using geophones.

## 1. Introduction

The specific task of the ILC is to measure the complex voltage sensitivity of a single axis of a specific geophone and amplifier set, configured to also simulate high sensitivity and weight of a seismometer (~2kV/(m/s), ~2.2kg) at specified frequencies, with primary means i.e. according to ISO 16063–1 and ISO 16063-11 method 3.

The aim of the ILC is to compare each participant's low frequency calibration method and setup in the frequency range from 0.5 Hz to 20 Hz. Optional points may be carried out as found possible during the exercise near the resonance frequency(ies) of the transducer.

The selected high mass transducer set will induce mechanical stress on the exciter during measurements and the influence on the results from non-desirable mechanical effects will be presented and discussed in this paper. The general outcome of results and conclusion will be used to evaluate participant measurement capabilities, as well as for discussion on topics found relevant when performing calibration of high mass and high sensitivity devices in the selected frequency range.

The responsible individual or the ILC pilot laboratory is Jacob Holm Winther (HBK-DPLA, Denmark) and the other participants are Ronaldo da Silva Dias (INMETRO, Brazil), Alessandro Schiavi (INRIM, Italy) and Adrien Canu (LNE, France). Mr Torben Rask Licht (expert consultant, Denmark) was involved in reporting of results and evaluation of data.

### *1.1. General geophone technology and applications*

Geophones are essential instruments in seismic surveys, geotechnical engineering and subsoil monitoring and investigation, by summarizing the basic concepts of geophones technology and their application from the recent book of J. M. Reynolds [1]. Geophones typically employ a moving-coil mechanism, where a coil suspended by a leaf-spring in a magnetic field generates voltage proportional to ground movement, and do not require power supply. They require damping to prevent ringing and ensure rapid response to subsequent seismic events. Geophones are designed with natural frequencies tailored to the survey's depth and resolution requirements, falling between 4 and 30 Hz for standard surveys, over 100 Hz for high-resolution reflection surveys, and below 5 Hz down to 0.5 Hz for seismology. Adjusting damping and natural frequency ensures optimal performance across different survey conditions. This mechanism allows detecting soil particle velocity or displacement.

Geophones, often distributed in networks and arrays [2–4], are deployed strategically based on their orientation to capture specific wave types efficiently. In practical applications, the geophone is implanted into the ground with a spike attached to the base of the casing (Fig. 1a) to ensure good ground coupling. Shear-wave geophones are slightly different in that they can have two spikes mounted side-by-side. A typical geophone construction is shown in Fig. 1b.

In the field of geophysical seismology, geophones are used for the measurement and analysis of seismic phenomena occurring within the Earth. These devices are designed to detect and record seismic waves generated by events such as earthquakes, volcanic eruptions, and other tectonic activity, converting mechanical waves into measurable electrical signals. These signals, proportional to the intensity of the movement, are then exploited to extract information on the terrain characteristics and seismicity of the area. From a systematic bibliographic worldwide survey, including very recent investigations (e.g., Refs. [5–10]), it results that geophones are used in a wide range of applications in seismology geophysics, including:

- Seismic Monitoring: to monitor seismic activity in seismically active regions, providing data fundamental to understanding the frequency, intensity and spatial distribution of earthquakes.
- Studies of the Earth's Internal Structure: to understand the Earth's internal structure and the processes that shape it. Using networks of geophones arranged in various configurations, geophysicists can analyse the propagation speeds of seismic waves through different

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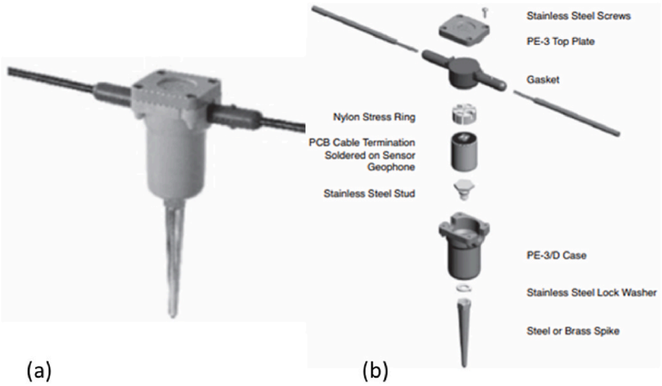


**Fig. 1.** Field geophone with spike (a); typical geophone construction (b) [1].

layers of the Earth, allowing them to delineate the composition and distribution of materials within it.

- Monitoring Volcanic Activity: to monitor seismic activity associated with magma growth and fluid movements in the volcanic system, and to predict imminent eruptions and warn local communities of the danger.

Moreover, based on a technique called "Seismic Exploration" is possible to map subsurface structure and identify potential reserves of oil, natural gas, other minerals, and new energy sources [11–13]. In geotechnical engineering, geophones are used to study rocks and soils to support civil engineering systems, providing information of soil composition and materials, with the aim to design foundations, retaining walls, and other structures (sometimes very sensitive ones [14]), in a safe and cost-effective way [15,16]. With a focus on environmental sustainability, the investigation of subsoil composition supports the strategies to protect groundwater, environments, and to manage landfills [17–21].

Monitoring leaks in water networks is a crucial aspect to ensure efficient and sustainable use of water resources. In this context, the use of geophones has proven to be a technologically advanced and effective option. These devices have been successfully adapted to locate leaks in water networks, allowing rapid and targeted intervention to reduce losses and optimize water use, by detecting vibrations generated by water leaks [22–24]. When a leak occurs, the flow of water through the pipe creates vibrations that travel through the ground. Data extracted from geophone survey, precisely identify the location and extent of leaks, allowing timely and targeted intervention.

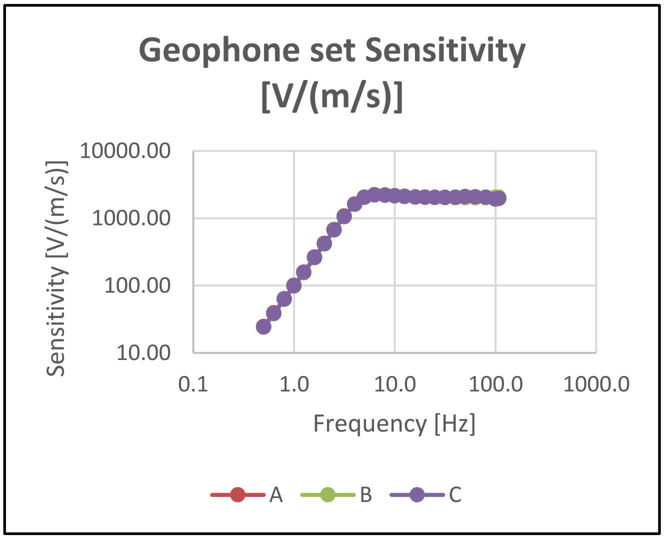


**Fig. 2.** Frequency responses from the 3 laboratories.

Like every measuring instrument, in particular if used for monitoring extremely important phenomena linked to the health, safety and well-being of people, geophones also need to be carefully calibrated and verified. At present, the traceability of geophone is provided by NMIs or by accreditation laboratory, by exploiting traditional methods used for accelerometers calibrations. Nevertheless, although many methods and systems have been developed during the last decades to calibrate geophones [25–32], according to pertinent Standards, such as ISO 16063 series, agreed protocols for calibration and systematic comparisons among NMIs, are not yet available. To avoid this lack, this preliminary ILC, at NMI/DI level was recently organized, with the aim to include within the calibration and measurement capabilities (CMCs) the low-frequency range suitable for geophone calibration, to provide the traceability to SI.

## 2. Low frequency ILC and devices

In an international comparison at low frequencies to support the measurement capability (CMC) of NMI's, the typical ILC devices used are high sensitivity accelerometers, due to its high-quality output signal level. This feature ensures better signal-to-noise ratio at lower frequencies where the level of acceleration and therefore the output signal of the transducers is limited due to the physical characteristics of the vibration exciters. However, these comparisons are only representative when we consider the calibration of typical accelerometers, geophones and other high sensitivity velocity transducers, whose mass and dimensions are small and do not produce significant stress of the vibration exciter.

### 2.1. Laboratory measurements and setup

Seismometers are currently used for low frequencies in-field measurements, and they must be calibrated in order to provide proper traceability. For this purpose, the geophone, or the seismometer itself, is mounted on the moving table of the vibration exciter. This is a transducer heavier and larger than any other accelerometer, and with a fixation system completely different. The effect of these differences in the calibration process were not completely evaluated in all details. However, a few main considerations discussed, when performing primary calibration according to ISO16063-11 method 3 calibrations, were:

- *Higher mass introduced to laboratory setup; >1,5* kg.
- *Higher sensitivity introduced to electrical laboratory equipment; >*2 kV/*(m/s)*
- *Different mechanical setup needed.*
- *Extended frequency range*, 100mHz -> 10mHz
- *Different influence on equipment used for calibration, bending, modes.*
- *Different influence from setup during calibration; curvature, modes …*
- *Several unknown parameters for uncertainty estimation*
- *Investigation needed on conditioning and output.*
- *Great care taken in system performance to avoid damaging devices.*
- *Great care taken to avoid damaging laboratory equipment.*
- *Critical transport of devices*
- *Comparable measurements and setups*
- *Limited/not much help from current primary standard, major amendment needed.*

As described the objective of this intercomparison was to evaluate these effects, so a geophone with amplifier set was circulated and calibrated by primary methods by different NMI's. The set consisted of a HBK type 8380 geophone, and a HBK type 2692 amplifier (NEXUS).

The results obtained support the suggestion of use of a real seismometer, or a set like the one used, to provide traceability to calibration laboratories. The set used, for example, showed good time-stability over the period of the ILC (approx. 1 year), and even after many trips being

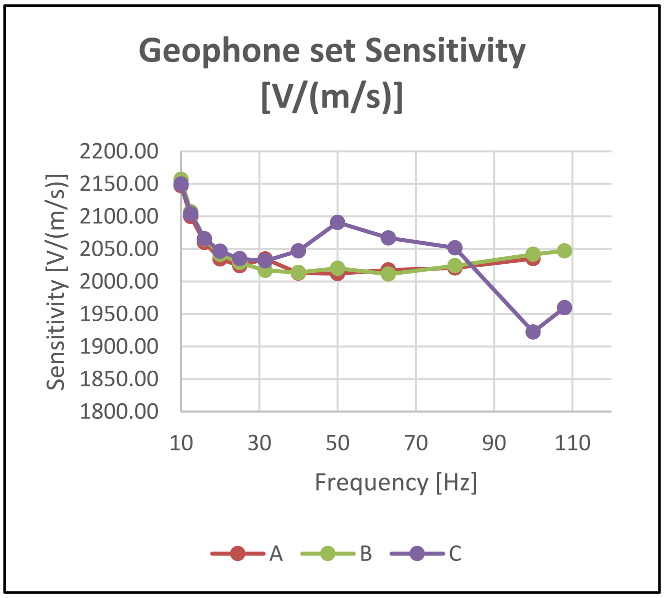


**Fig. 3.** Zoom-in on Fig. 2.

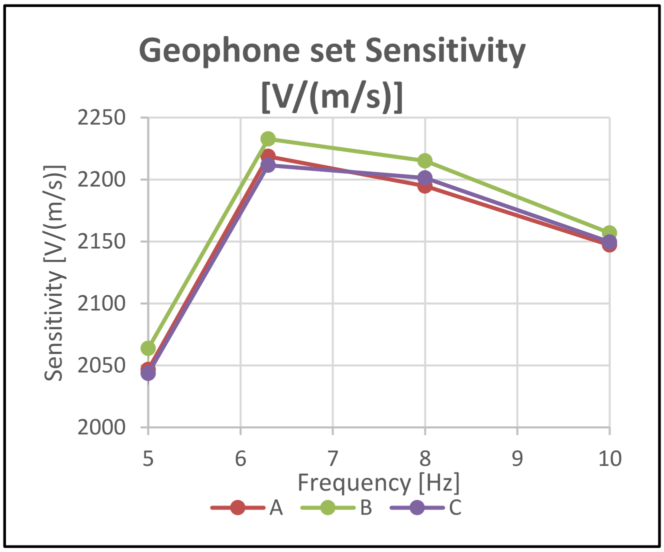


**Fig. 4.** Zoom-in on Fig. 2.

transported as cargo from one NMI to another.

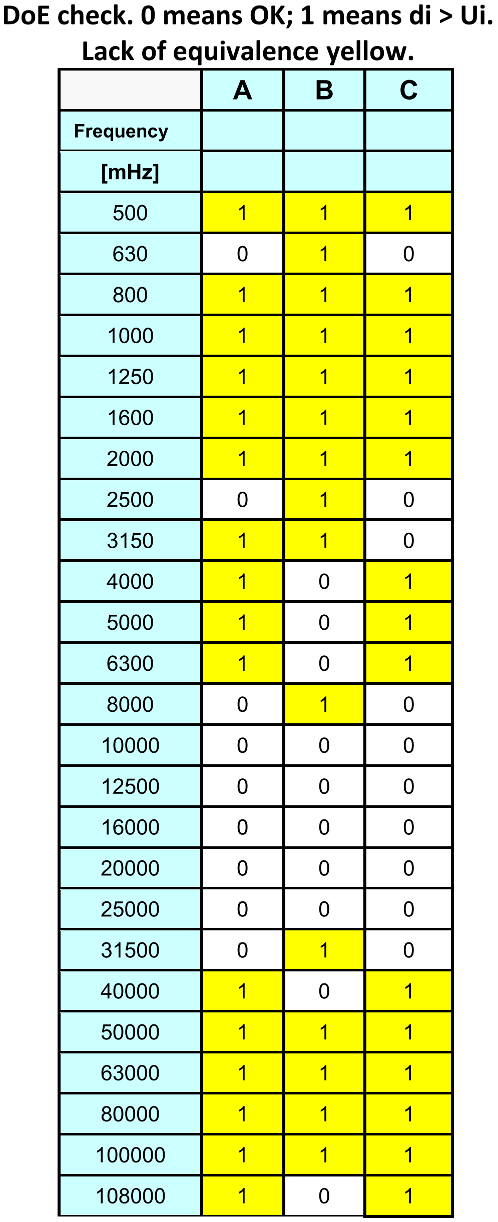
In Brazil, INMETRO intends to use two seismometers as traveling standards to carry out a proficiency comparison among accredited laboratories. The vibration and acoustics laboratories of INMETRO are now working together with these laboratories to establish a technical protocol, which should be representative of the calibration procedures used. The good results obtained at this ILC will be very important to increase and support the level of confidence in the proficiency comparison that will be carried out in Brazil.

## 3. Preliminary results

The results available from 3 of the laboratories are shown in Figs. 2–4. One laboratory is still performing the calibration and its results will be analysed later.

Table 1 is created by the same method as used for international key comparisons under the CIPM MRA to get a picture of the degree of equivalence (DoE) among several laboratories. It shows the DoE among the results from each laboratory and the reference value calculated. Values of DoE equal to zero or less than one means that the results showed good agreement.

**Table 1**
Degrees of equivalence among 3 laboratories from which data were available at the time of writing.



**DoE check. 0 means OK; 1 means di > Ui.**
**Lack of equivalence yellow.**

| | A | B | C |
|---|---|---|---|
| Frequency | | | |
| [mHz] | | | |
| 500 | 1 | 1 | 1 |
| 630 | 0 | 1 | 0 |
| 800 | 1 | 1 | 1 |
| 1000 | 1 | 1 | 1 |
| 1250 | 1 | 1 | 1 |
| 1600 | 1 | 1 | 1 |
| 2000 | 1 | 1 | 1 |
| 2500 | 0 | 1 | 0 |
| 3150 | 1 | 1 | 0 |
| 4000 | 1 | 0 | 1 |
| 5000 | 1 | 0 | 1 |
| 6300 | 1 | 0 | 1 |
| 8000 | 0 | 1 | 0 |
| 10000 | 0 | 0 | 0 |
| 12500 | 0 | 0 | 0 |
| 16000 | 0 | 0 | 0 |
| 20000 | 0 | 0 | 0 |
| 25000 | 0 | 0 | 0 |
| 31500 | 0 | 1 | 0 |
| 40000 | 1 | 0 | 1 |
| 50000 | 1 | 1 | 1 |
| 63000 | 1 | 1 | 1 |
| 80000 | 1 | 1 | 1 |
| 100000 | 1 | 1 | 1 |
| 108000 | 1 | 0 | 1 |

The results show good agreement in the mid frequency range. However, above 30 Hz one laboratory clearly deviates significantly.

Considering that this is a device used in seismology, its resonance falls around 5 Hz. Therefore, it is also expected that deviations will be found around the damped resonance of the geophone.

The phase shift was only available for 2 laboratories and the comparison can be seen in Figs. 5 and 6. The results follow the theoretical curves very well and are tracking each other within the uncertainties except around the damped resonance.

## 4. Monitoring and test

Before the circulation of the unit several tests were made to check

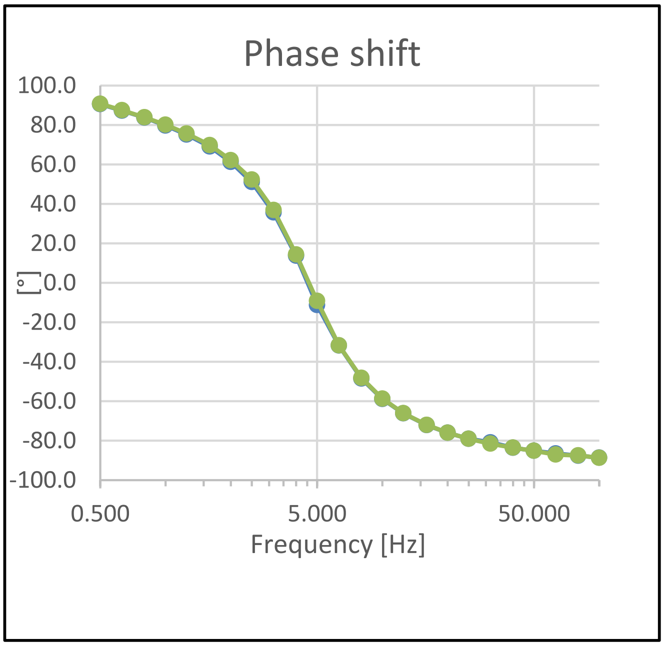


**Fig. 5.** Phase shift for two laboratories.

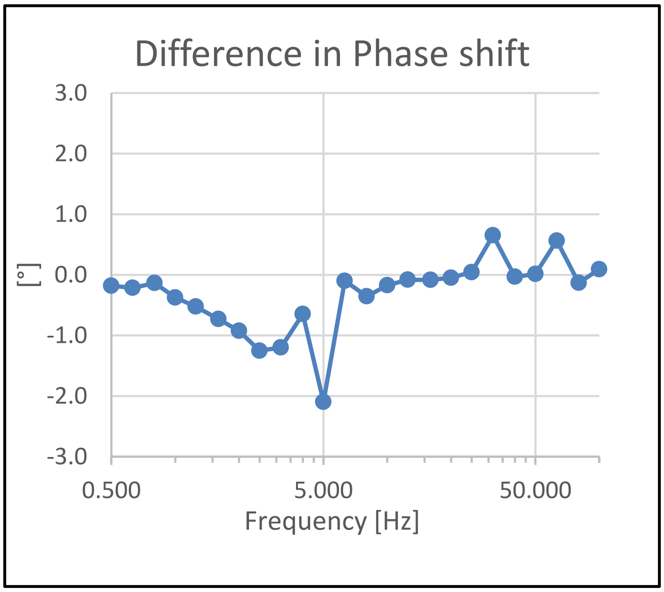


**Fig. 6.** Difference in Phase shift.

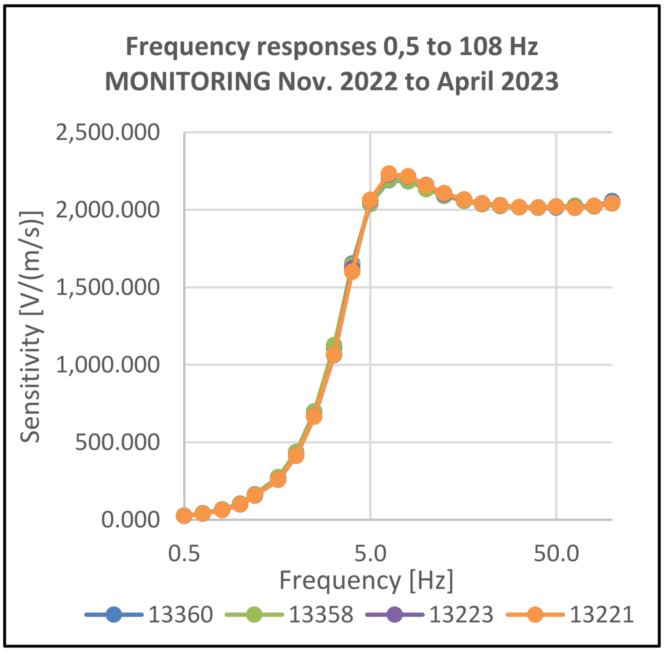


**Fig. 7.** Results during test and monitoring. Legend numbers are Test/Certificate numbers generated automatically by the system.

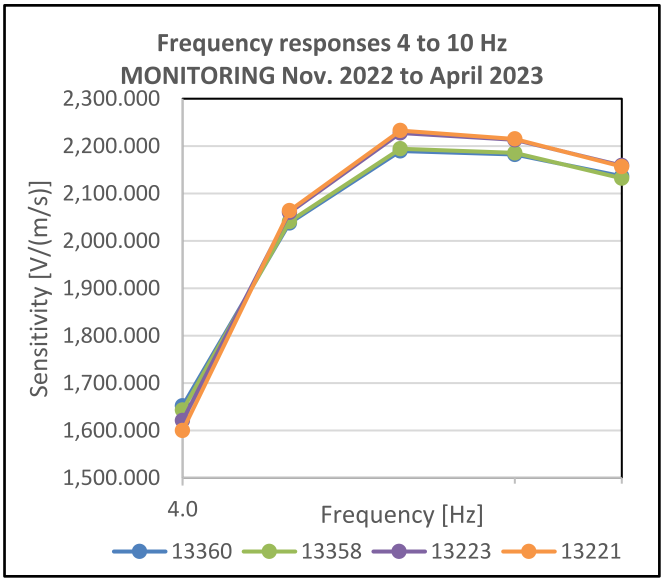


**Fig. 8.** Zoom of Fig. 7 Legend numbers are Test/Certificate numbers generated automatically by the system.

stability. The results are shown in Figs. 7–9.

The legends are Test/Certificate numbers generated by the system. 13221 is performed 2022-11-02, 13223 is performed 2022-11-04, 13358 is performed 2023-04-11, 13360 is performed 2023-04-11. The results show variations at high frequencies, probably due to mounting conditions, in the order of 0,7 %, much smaller than one of the results from the comparison.

The spread around the geophone damped resonance is about 1,7 % which is comparable to what was found during the comparison.

## 5. Conclusions

In the mid frequency range, the laboratories can fulfil the normally stated uncertainties and make precise measurements with the unusual transducer made challenging by weight and size.

One laboratory has apparently had some problems with resonances or bad fixturing above 30 Hz. This can probably be solved by simple means, allowing good traceable calibrations up to more than 100 Hz.

The deviations around the resonance in the 5–8 Hz range in **both the monitoring results and the comparison** are probably not reflecting lack of capability of the laboratories, but more likely effects coming from the transducer itself or from misalignment or levelling procedures. This needs further investigations.

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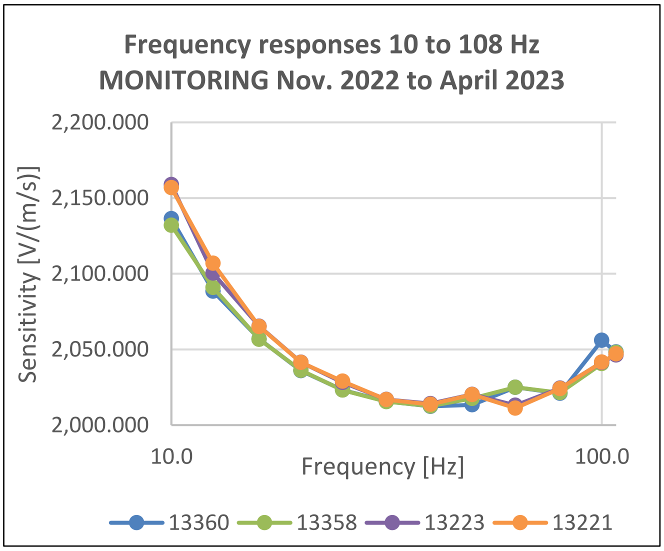

**Fig. 9.** Zoom of Fig. 7. Legend numbers are Test/Certificate numbers generated automatically by the system.

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