STRENGTHENING PRIORITY FSI COMPONENTS

INTO KEY ESFRI RESEARCH INFRASTRUCTURES

ONESHOT CALL

EPOS-BE

UPGRADE OF BELGIAN FEDERAL RESEARCH INFRASTRUCTURE FOR EPOS

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Royal Observatory of Belgium

EPOS-BE

Upgrade of Belgian federal research infrastructure for EPOS

Contract - FSIRI/33/EP1

FINAL REPORT

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ABSTRACT

The “European Plate Observing System” (EPOS), part of the ESFRI roadmap, provides open access to multidisciplinary data in support of solid Earth science. To ensure the participation of the Royal Observatory of Belgium (ROB) to EPOS, the EPOS-BE project adapted ROB’s existing pan-European GNSS services to EPOS’ workflows so that they could become pre-operational EPOS services. Secondly, EPOS-BE upgraded ROB’s GNSS stations and some key seismic stations in the Belgian seismic network with the goal to offer high-quality data to EPOS. In addition, EPOS-BE performed the site characterization of ROB’s seismic and accelerometric network using geological information and geophysical field array techniques.

Thanks to the EPOS-BE project, the ROB became a key partner in EPOS. EPOS now has access to ROB’s upgraded observation infrastructure and services while ROB benefits from the novel technologies that EPOS is developing as a brand-new e-infrastructure.

Keywords EPOS, GNSS, seismic network, array seismology, services, multidisciplinary data, site characterization

1. INTRODUCTION

The **“European Plate Observing System” (EPOS)** is the unique research infrastructure supporting solid Earth science in Europe and aiming at improving our understanding of the complex dynamic Earth system. EPOS provides, through one integrated system, access to the data and services offered by solid Earth science infrastructures (**National Research Infrastructures** - NRI) distributed all over Europe. EPOS gathers input from different disciplines such as geodesy (GNSS), geology, seismology, volcanology, or geomagnetism. To deal efficiently with these multidisciplinary data, EPOS is organized in **Thematic Core Services** (TCS). In each TCS, selected **Service Providers** (SP) ensure the data from the underlying NRI are standardized and quality-checked and the SP also ensure the NRI data become discoverable from EPOS’ central data portal which provides access to EPOS’ **Integrated Core Services** (ICS).

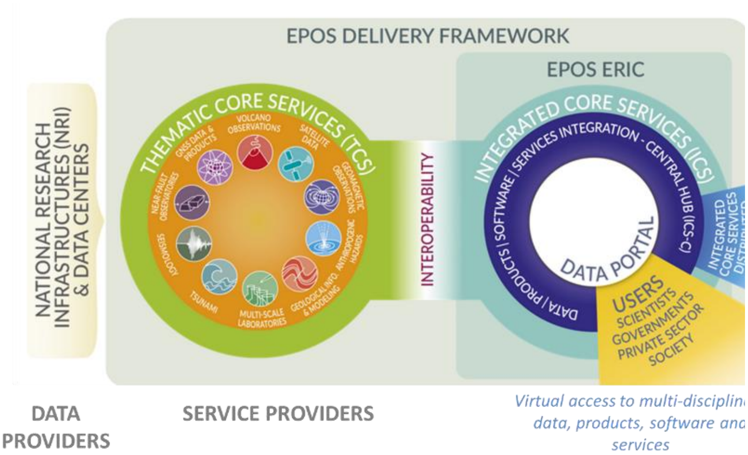


Figure 1: *EPOS architecture*

When BELSPO issued the oneshot call for proposals to “*Upgrade federal research infrastructures already existing in the FSIs to become, in the medium term, key actors in the ESFRI RI or in the Belgian node*” at the end of 2018, EPOS was in its implementation phase (EPOS-IP) and the BELSPO call came just at the right moment for ROB. Firstly, ROB’s existing seismic, accelerometric and GNSS observation infrastructure was planned to be included in EPOS for scientists to get direct access to ROB’s observations in an open access philosophy. Secondly, ROB’s existing pan-European GNSS services offered the potential for ROB to become a key Service Provider in EPOS.

Following BELSPO’s call for proposals, ROB’s GNSS and seismological teams joined forces to propose the EPOS-BE project, which focused primarily on the GNSS and Seismological TCS of EPOS. The EPOS-BE proposal was accepted for funding and the project ran from 15/12/2018 to 15/06/2023.

2. STATE OF THE ART AND OBJECTIVES

2.1 GNSS

EPOS' Thematic Core Service "GNSS data and products" (EPOS-GNSS) aims to gradually provide access to GNSS data, metadata and products from minimum 3000 continuously operating GNSS stations (GNSS= Global Navigation Satellite Systems, such as GPS, GLONASS, Galileo, Beidou, ...). To achieve this goal, EPOS decided to build upon the experiences gathered within the EUREF permanent GNSS network (EPN) which is a European network of about 400 continuously operating GNSS stations. ROB, who hosts the EPN Central Bureau (https://www.epncb.oma.be), manages the EPN in collaboration with several EPN coordinators. ROB and EUREF have been working together for many years to develop the EPN towards a GNSS network providing open access to standardized GNSS data, metadata, and products. As part of its EPN Central Bureau activities, ROB monitors the daily quality of the GNSS network data and metadata. This expertise in managing and monitoring a European-scale GNSS network enabled ROB to play a key role in EPOS and become one of its Service Providers in the TCS "GNSS data and Products". However, to allow so, ROB's EUREF services had to be adapted to EPOS needs and workflows. Therefore, a first objective of EPOS-BE was to

> ***upgrade ROB's existing EUREF infrastructure and services to become a key Service Provider in EPOS' GNSS TCS.***

Additionally, ROB has been managing a network of high-quality GNSS stations in Belgium since the 1990s. The GNSS data of these stations enable monitoring small ground movements (sub-mm to mm/yr). However, in Belgium ground movements are close to, or below, the detection limit of GNSS. By integrating the GNSS data in EPOS, it will be possible to compare the GNSS results with those from other disciplines, increase trust in the results, and improve the measurement and understanding of these small movements. However, before being able to integrate ROB's GNSS data in EPOS, the outdated hardware at the GNSS stations had to be replaced. Therefore, a second objective of EPOS-BE was to

> ***upgrade the infrastructure at ROB's GNSS stations to prepare it for integration in EPOS.***

2.2 Seismology

The TCS "Seismology" builds on three existing European infrastructures to provide services for seismic waveform data, earthquake parametric data and earthquake hazard data. These three institutes at the origin of EPOS are ORFEUS (Observatories & Research Facilities for European Seismology), EMSC (European-Mediterranean Seismological Centre) and EFEHR (European Facilities for Earthquake Hazard and Risk), respectively. The TCS "Seismology" integrates data from ORFEUS that coordinates digital seismology in Europe. The ROB is a founder of ORFEUS and is a member of its board of directors. Since 2002, ROB has been a member of the VEBSN (European Virtual Broadband Seismic Network) project coordinated by ORFEUS. The VESBN project spearheaded the pan-European exchange of high-quality broadband seismological data between national research institutes and ORFEUS. For many years ROB and ORFEUS have been collaborating to provide open access to seismic waveform data from the Belgian seismic network to the seismological research community through the ORFEUS Data Centre (ODC), one of the nodes within the European Integrated Data Archive (EIDA) in ORFEUS. Early 2019, ROB signed a Data Management Agreement between Seismic Network BE and ORFEUS EIDA-node ODC. Together with its membership in the board of directors of ORFEUS, the ROB thus is deeply involved in EPOS seismology.

The ROB has maintained a modern seismic network since 1985 and is the only Belgian agency that provides seismic data to ORFEUS (BE network, code 1980). Currently, BE data is streamed to ORFEUS from the Eben-Emael (BEBN), Oostende borehole (BOST), Membach (MEM), Opitter borehole (OPTB), Rochefort cave (RCHB), and Uccle (UCC) stations. These high-precision data are used for seismological studies at local, regional and world scales. However, to be able to provide high quality, continuous data streams of the entire BE network, a third EPOS-BE objective was to

> ***upgrade the seismic infrastructure of the Belgian seismic network and to improve seismic data streaming.***

This includes upgrading outdated short-period seismographs, containing sometimes only vertical components, to fully broadband sensors. In addition, the data storage and station communication are improved by renewing the acquisition systems of many stations.

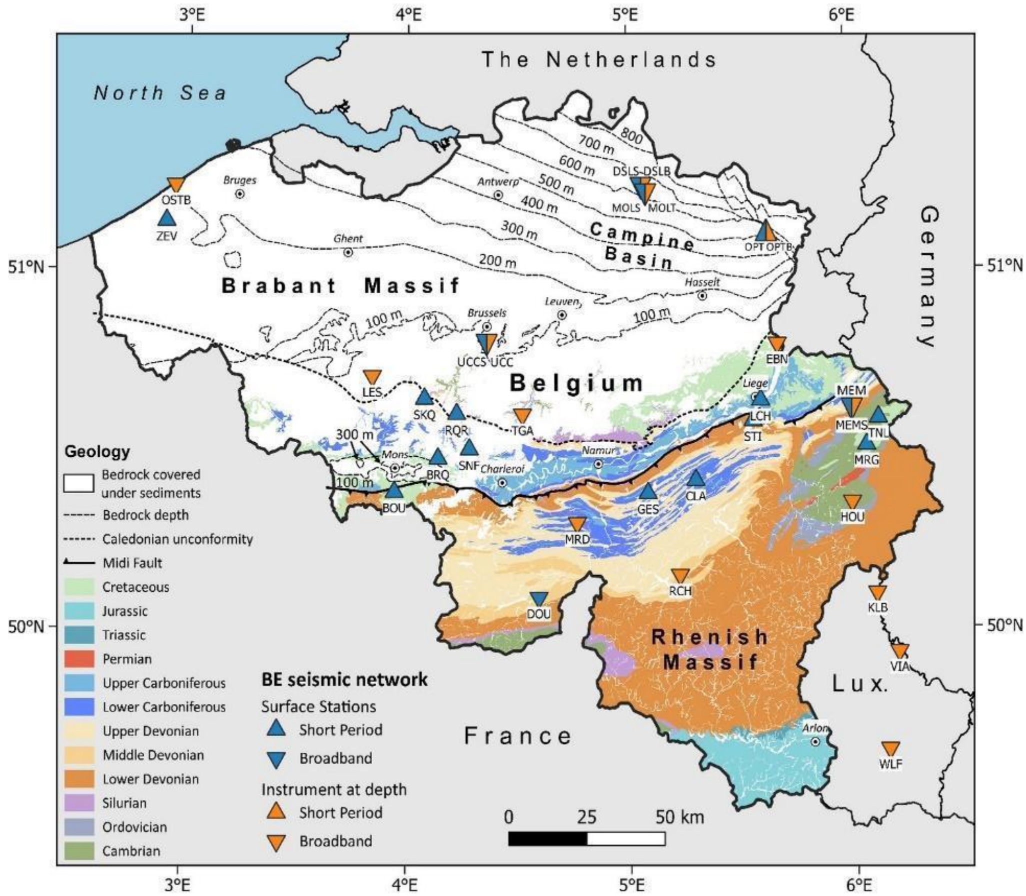


Figure 2: *The UCC Belgian Seismic network in relation to local geology, prior to the station renewal during EPOS-BE. Note up- and downwards symbols for station types.*

During the last 40 years, only a few studies have characterized the subsurface below the Belgian stations, e.g., site characterization of the Dessel surface, tunnel, and borehole stations (Verbeeck, 2019), the BRAIN.be pioneering LARGE-MEM project (Lecocq *et al.,* 2020), site characterization of the CSE station (Van Noten *et al.*, 2015), and the SESAME project. However, a systematic analysis of all stations using modern, non-invasive methods was still completely lacking. A last objective of EPOS-BE was to

> ***characterize the seismic station sites of the entire Belgian seismic network.***

This information is needed to assign soil classes to the sites and to evaluate seismic site response. Site conditions can be obtained to understand amplification of earthquake ground motion, linked to instrumental and macroseismic shaking intensities. This site characterization is also needed to better correct instrumental records and to select appropriate GMPEs (ground motion prediction equations) which will improve seismic hazard maps and generation of shakemaps after an earthquake. This site information needs to be implemented in the station metadata at ORFEUS.

3. METHODOLOGY

3.1 GNSS methodology

3.1.1 Upgrade of ROB's existing EUREF infrastructure and services to become a key Service Provider (SP) in the EPOS GNSS TCS

The methodology used for upgrading ROB's EUREF services was agreed with EPOS' GNSS TCS and was based on the future role that some of upgraded services could play within EPOS.

As a first step, the services, which had the most potential to become future EPOS services, were selected. These are:

1) M^3G "Metadata Management and Distribution System for Multiple GNSS Networks": this service collects, validates, and distributes the metadata of the EPN stations. Agencies operating EPN stations have an M^3G login account to upload/update the metadata (equipment type, station owner …) of their GNSS stations. M^3G validates the content of the GNSS station metadata and distributes it to EUREF.
2) ROB-EUREF data repository: it is a publicly open data repository including all the daily GNSS data of the EPN stations since 1996. The data are provided to ROB by more than 100 different agencies (data owners) all over Europe with the goal of making these data publicly available. The repository contains more than 2 million data files of 400+ GNSS stations.
3) DQMS "Data Quality Monitoring Service": this service monitors and validates the GNSS data quality of the EPN stations.
4) Ground deformation monitoring service that regularly computes the positions, velocities, and position time series of the EPN stations.

In a second step, it was necessary to investigate, in consultation with EPOS, how these services could be integrated in the workflows of the GNSS TCS and consequently which updates would be required for each of the services. It was agreed that (see also Figure 3):

- The application of ROB's M^3G would be mandatory for all EPOS-GNSS stations that desire to make the data of their GNSS station discoverable through EPOS. This means that during the EPOS-BE project, M^3G had to be adapted to 1) accommodate the expected increase of the number of GNSS stations and 2) respond to EPOS-specific requirements (access through Application Program Interface, inclusion of additional station metadata, …).
- To make the content of the ROB-EUREF repository visible to EPOS, the ROB would need to create an EPOS-GNSS data node on top of the ROB-EUREF data repository. This consists of installing the open-source Geodetic Linkage Advance Software System (GLASS) to set up a virtualization level on top of the data repository. GLASS indexes the GNSS data files, validates the data with respect to station metadata in M^3G, performs data quality checks, and stores all information in the local

node database. GLASS subsequently ensures the synchronization of this local database with the EPOS-GNSS Data Gateway (DGW) where all EPOS' GNSS data are accessible through an Application Program Interface (API) and a web portal. By installing GLASS, making sure its database is populated by historical data as well as new incoming GNSS data, and then synchronizing it with the DGW, the ROB-EUREF repository will become a suitable EPOS-GNSS data node and its data will be integrated in EPOS.

In addition, EPOS requires that each agency operating an EPN station formally gives EPOS the permission (through the signature of an EPOS-GNSS data supplier letter) to redistribute their data. Therefore, during EPOS-BE, EPOS-GNSS data supplier letters must be collected from more than hundred agencies.

- EUREF's DQMS would be used as a basis for a new EPOS-GNSS data quality monitoring service that should monitor the GNSS data quality of the EPOS-GNSS stations on a daily basis and provide feedback to station operators and data analysts. This will require that during EPOS-BE, EUREF's DQMS has to be adapted to retrieve these metrics from the 10 EPOS-GNSS data nodes, instead of computing the data quality metrics ourselves (as done for EUREF). In addition, the new DQMS must be able to handle the increased amount of GNSS stations (3000+ expected for EPOS, compared to 400+ for EUREF). Hence, the upgraded system to detect stations with degraded data quality must require fewer manual interactions than currently in EUREF's DQMS.
- EUREF's ground deformation monitoring service computes the positions/velocities/coordinate time series of the EUREF stations each 15 weeks. This computation has been designed for reference frame applications, which is the primary mission of EUREF. However, to be useful for EPOS, the EUREF computation needed to be upgraded to better assess the precision of the estimated velocities (which is important information for geophysicists) and also to provide velocities for a higher number of stations. At the start of EPOS-BE, the station velocities were only published for so-called EUREF Class A stations. This EUREF classification was too rigid for EPOS and needed to be revised during EPOS-BE, including a better assessment of the precision of the estimated station velocities.

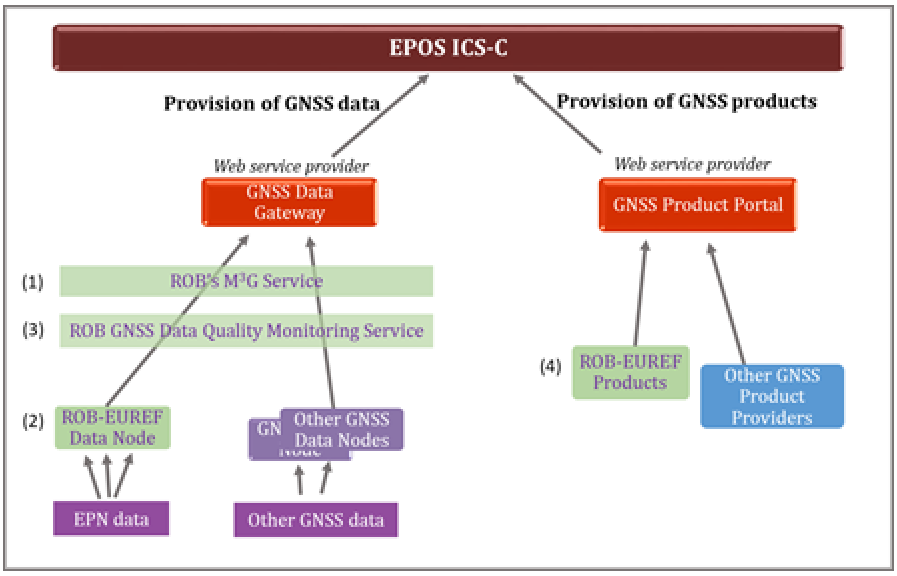


Figure 3: *Schematic overview of ROB's upgraded EUREF services within the workflows of the GNSS TCS of EPOS.*

3.1.2 Upgrade ROB's GNSS stations to prepare ROB to become a NRI providing data to EPOS

ROB's network of GNSS stations consisted of GNSS instruments (GNSS antennas and receivers) that were purchased in 2011 and tracked the GPS, GLONASS, and Galileo satellite signals. The lifetime of the GNSS receivers was estimated to be 10 years and this was confirmed by the fact that ROB's GNSS receivers were considered in 2020 by the manufacturer as end-of-life without possibility for repairs or firmware. Hence, the equipment was unsuitable for integration in EPOS and therefore, ROB needed to purchase new state-of-the-art GNSS instruments, which would also track all new satellite constellations, such as BeiDou and IRNSS. By doing this upgrade, the GNSS stations of ROB would be of sufficiently high quality to integrate their data in EPOS. ROB had already informed EPOS of its intentions to provide GNSS data to EPOS by signing the EPOS-GNSS data supplier letter.

The different steps to upgrade the equipment are:

- Ordering (public procurement), testing and installing the GNSS instruments in ROB's EPN stations.
- Set up the data flow from the new instruments to the central facility at ROB.
- Upgrade the existing web-based network management system to operate with the new instruments.

3.2 Seismology methodology

3.2.1 Upgrade of permanent and non-stationary seismic infrastructure

Because of the limited lifetime of seismometers (20 years) and acquisition systems (10 years) in the BE network, the strategy in renewing the permanent seismic infrastructure consisted of

- Ordering new seismographs and acquisition systems using public procurement.
- Testing seismographs in the UCC lab and comparing probabilistic power spectral density (PPSD) with the fixed UCC sensor.
- Building and soldering acquisition systems cabins in the UCC lab.
- Drilling new boreholes on site for installation of posthole sensors (if needed).
- Installing sensors, power connection (if needed), and devices for remote management and data collection.
- Data comparison of old and renewed stations.

To perform the site characterization of the Belgian network, due to budget reasons (availability of only 24K€) it was decided to move away from classic and expensive seismograph systems and focus on nodal systems. In classic methods, usually more expensive seismographs (e.g., Lennartz 3D-5s) are cabled to high performance acquisition systems (e.g., Datacube, Cityshark, Warran). Nodal systems (i.e. nodes) are lightweight and wholistic instruments that are faster to deploy and easier to handle than classic seismographs. Nodal systems are autonomous geophone-based instruments and although this equipment entered the field of Seismology only recently, these lightweight solutions have already revolutionized seismological fieldwork. However, because of this new approach and the fact that nodes, to our knowledge, are not yet used in site characterization, their performance and usage, both in the lab and in the field, needed to be studied in detail during EPOS-BE.

3.2.2 Site characterization methods

Array seismological techniques were introduced originally to increase the signal-to-noise ratios for teleseismic monitoring of intermediate magnitude earthquakes and nuclear tests. Later analysis of the wavefield propagation showed that array seismology also can resolve the dispersive behavior of body and surface waves, opening the field to resolving the geological structure and its velocities below the surface. Here below we give an overview of the most relevant techniques used for site characterization in EPOS-BE.

a) Parameterization of site characteristics

The ORFEUS Station Book provides station information from every station included in EIDA. Information on station's metadata from the EIDA database is fixed and limited, but additional site information, such as owner data, morphology data, housing, geology, as well as site photos, can be added manually. Within the morphology data, following site characteristics are listed and need to be updated or acquired during the EPOS-BE project for the entire BE network:

- **Geological Unit**: formal and descriptive stratigraphic information of the subsurface
- **Morphology Class**: Topographic amplification factors (T1 -> T4) as prescribed by the Italian seismic code (NTC08, Italian technical construction norm) with

Topographic Class	Description	Amplification factor
T1	Flat surface, isolated slopes and cliffs with average slope angle i ≤ 15 ◦	1
T2	Slopes with average slope angle i > 15 ◦	1.2
T3	Relief with ridge width much smaller than the base and average slope angle 15 ◦ < i ≤ 30 ◦	1.2
T4	Relief with ridge width much smaller than the base and average slope angle i > 30 ◦	1.4

- **Ground Type EC8**: Eurocode 8 (EC8) defines five typical ground types (A, B, C, D, E) and 2 special ground types (S1, S2) that may be used to account for the influence of local ground conditions on the seismic action. These five ground types are explained in the table below.

Ground type and description	$V_{s,30}$ [m/s]
A: Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	>800
B: Deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth.	360-800
C: Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.	180-360
D: Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180
E: A soil profile consisting of a surface alluvium layer with *v*s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with *v*s > 800 m/s.	

- **Groundwater Depth [m]**: depth to local groundwater level. Here, we give the difference between the elevation of the seismic sensor and the interpolated top of the groundwater body in the area.
- **Vs 30 [m/s]**: The time-averaged shear wave velocity in the top 30 m from the surface, obtained by borehole measurements, array techniques or derived from lab tests.
- **f_0 [Hz]**: resonance frequency of the ground obtained by Horizontal-over-Vertical spectral ratio analysis (H/V). f_0 correlates with the depths to the impedance contrast between soft sediments and hard rock layers and is therefore a good indicator for the frequency at which a seismically stimulated soil layer or basin may resonate.
- **Amp (f_0)**: Amplitude of the H/V spectral peak at the resonance frequency. Recent studies however have shown that the amplitude of the ambient noise f_0 does not correspond with the site's amplification factor during an earthquake and caution should be taken to interpret this value.

- **Basin Flag**: flagged when deep basin amplification effects can be expected at the site.
- **Bedrock Depth [m]**: Depth to the seismic bedrock, i.e., depth to the geological unit that, because of the impedance contrast with the upper layers, controls the lowest (fundamental) resonance frequency peak. Do not confuse this parameter with the "Engineering" bedrock, which corresponds to the unit where a conventional Vs value (in Belgium a value 800 m/s) is first exceeded.

Within ORFEUS, reliability quality factors of site parameters are lacking although recent SERA consortium efforts clearly indicated the importance of adding quality factors to site characteristics. As much as possible, parameter uncertainties are given in the results.

b) Array techniques and configurations

To perform the site characterization and attain relevant site parameters, both conventional passive seismic array techniques and home-made methods needed to be developed and applied during EPOS-BE. The list below briefly describes existing and newly developed methods.

Array configurations and dGPS positioning

Creating a proper array installation geometry requires an iterative process between the array configuration and forward modeling of the resulting dispersion curve and whether the predicted dispersion curve (see F-K method) can resolve the estimated Vs value. With prior knowledge of the geological subsurface (from geological maps, boreholes, Vs literature values, single station methods applied on the permanent station), best array apertures can be estimated. The different applied ambient noise methods for array seismology might even require different array geometries to achieve their best results. For the FK analysis, it is preferred to have irregularly placed sensors with a high variety of interstation distances. This will avoid aliasing effects in the array transfer function and ensures a very wide frequency range in the dispersion curve. In contrast, for the application of the MSPAC method groups of similar interstation distances are required.

Although the SmartSolo seismic nodes have an internal GPS, the use of a differential GPS (dGPS) was preferred for accurately measuring the node positions. The coordinate of each node was computed in

QGIS by averaging the position of two-minute dGPS recordings with 1s interval. Positioning results were considerably improved over internal GPS positioning.

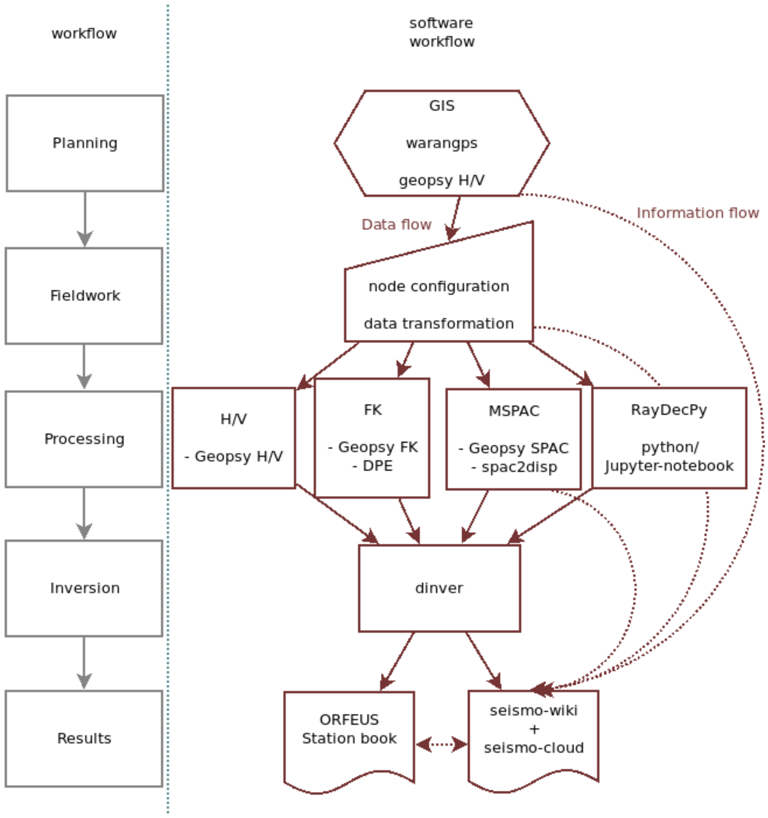


Figure 4: *Workflow for seismic site-characterization of a single station, starting from planning, fieldwork, data processing, model inversion and storage of the results.*

Frequency-Wavenumber (FK) analysis

In our case, the FK method performs an analysis of the propagation of the ambient noise seismic wavefield recorded by the array. By applying a multidimensional Fourier transform (in space and time), we obtain the frequency-wavenumber spectrum. For each station in the array, the obtained seismic waveforms are delayed based on arbitrarily chosen horizontal wavenumber vectors. The time delays of a harmonic plane wave propagating along the horizontal plane in direction of the wavenumber *k* and the apparent propagation velocity are related to the absolute length of the wavenumber vector. Using the semblance or the beampower then allows to measure the coherence of the delayed waveforms for all stations for that chosen wavenumber. By testing many wavenumber vectors in the wavenumber plane, one tries to find those wavenumber vectors that maximize the array output. The wavenumber found corresponds to **a plane wave along the surface crossing the seismometer array**.

Surface waves have a dispersive behavior and can be represented by a superposition of sine waves. Each wave has a distinct frequency and corresponding phase velocity, defining its wavelength. So, one can imagine the propagation of a single/monochromatic wave of a fixed frequency with a certain wavelength, that is defined by the integrated shear-wave velocity of the subsurface “seen” by this wave. With the help of a velocity/slowness - frequency plot, this dispersive behavior can then be visualized and later used for inversion.

In the opposite way, the subsurface elasticity parameters defined by the local geology and site-conditions will correspond to a unique dispersion curve at this special location. Through forward models and inversion software we then can estimate the subsurface geology of a site that best explains the observed dispersion curve.

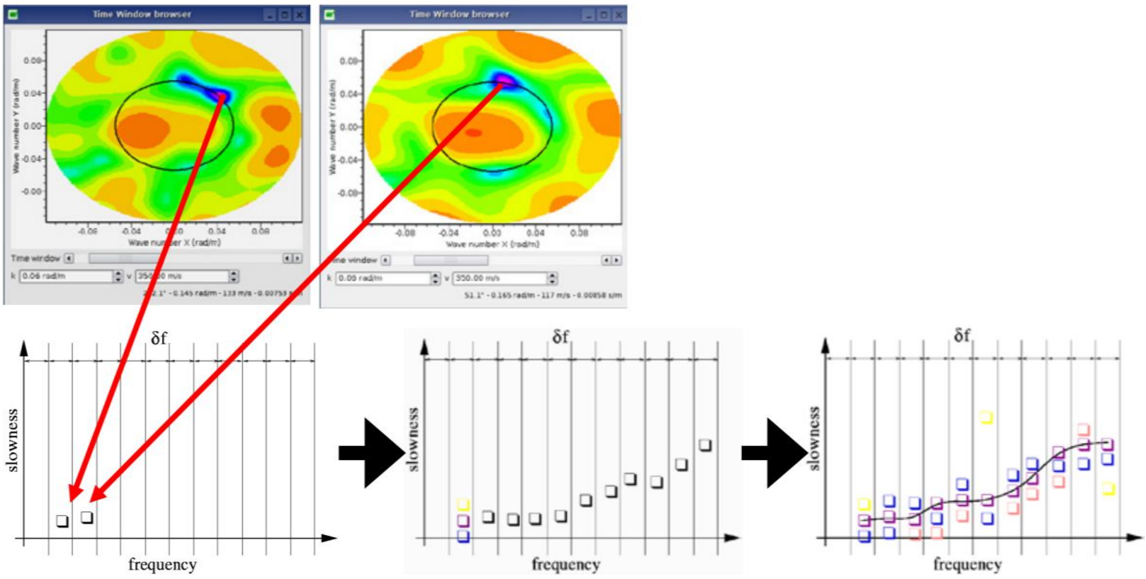


Figure 5: *The construction of a dispersion curve with the F-K-method. On top, the obtained coherence (high values blue) in the wavenumber plane for a certain frequency value, that then translates to a corresponding phase velocity of the seismic waves in the plot below. This step is repeated for various frequency values until the full dispersion curve is obtained. [NMSOP-2, Ch. 9]*

Modified Spatial Autocorrelation method (MSPAC)

The spatial autocorrelation function describes the similarity between seismograms recorded by station pairs with similar interstation distance. Under the assumption of a stationary wavefield (stable in space and time), noise represents the sum of plane waves propagating without attenuation in a horizontal plane in different directions with different powers. The spatial autocorrelation function is then only dependent on the phase velocity of the wavefield for each frequency and can be solved by a Bessel function.

The classical SPAC method requires very regular interstation distances/array geometries. With the introduction of the **M**odified **SP**atial **A**uto**C**orrelation method (MSPAC), station pairs of broadly similar intersensor distances can be grouped together. The average of the grouped autocorrelation coefficients then corresponds to a radial integration for each group of station pairs.

Active seismic methods

In the methods above, an indefinite number of sources is assumed. In active seismology, single sources are assumed, which, although physically easier to understand, only gives a limited insight into the subsurface structure and lithological framework at depth. At short source-receiver distance, a single source has a high energy content, high frequencies, but low waveform coherence with varying ray lengths. Despite these shortcomings, with large distances, we can make use of the plane-wavefield approximation and neglect the geometrical spreading of the waves (in ray geometries and spectral appearance). For the array geometry, regular array configurations were preferred over randomly installed configurations (as needed for array processing).

Quarry blasts

In many stone exploitation quarries in southern part of Belgium explosives are used to fracture rock. These explosions are often visible with the seismic network and in the temporary array installations. As we know the source and because long distance between source and receiver (array), we assume a plane wavefield crossing the array. Explosions have high energy in the surface waves. By cross-correlation of the surface waves crossing the array, we can precisely estimate the time delay of a wave package for all station combinations. With the high precision dGPS positions of the seismometers and known backazimuth of the raypath, we can estimate the phase velocities of the waves. Applying a narrow bandpass filter in the frequency domain allows the estimation of the phase velocity for each frequency bin. From this, over a wide frequency range, the dispersion curve can be constructed.

Jumping and hammering

Seismic waves also can be generated within the array by either hammering on an impact plate or jumping of a strong seismologist. From the manual picking of the first motion arrival at each sensor within the array, the p-wave velocity of the subsurface can be calculated either through averaging all velocity estimations for each sensor-source distance and the corresponding time residual, or by linear regression in the time-distance plots. The required s-wave velocity might be estimated the same way, but their onsets in the wave train are often hard to identify due to their emergent onsets. Also, they might be confused with other wave types, e.g., surface or acoustic waves. Then we just convert the Vs values from literature Vp/Vs ratios using the square root of 3. For the interpretation of the velocity, the raypath of the p-wave needs to be considered. This can be either a direct body wave through the uppermost (thick) layer or the p-wave travels critically refracted on the interface between soil and rock layer, with the faster speed of the lower layer. This method gives us a second order velocity of the subsurface.

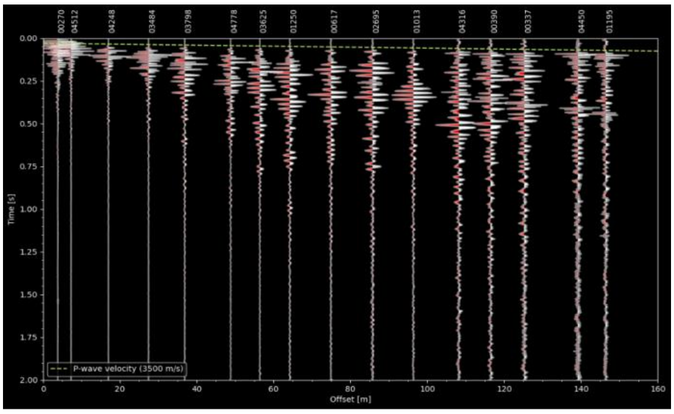


Figure 6: *Example of hammershot arrivals on 16 SmartSolo seismic nodes placed in a linear array next to the permanent station of Tangissart (TGA). Heylen (2023).*

MASW

A more sophisticated approach is the use of the so-called MASW technique (**M**ultichannel **A**nalysis of **S**urface **W**aves). This method uses linear arrays with regular and tight sensor spacing to record the surface waves emitted by hammer shots at each end of the array. The data is recorded in the time-space domain and using the FK method can be translated into the frequency-wavenumber domain, by applying a two-dimensional Fourier Transform defined as:

$$\mathrm{F}(f,k) = \iint_{-\infty}^{+\infty} \mathrm{U}(x,t)\, e^{-2\pi i(ft+kx)}\, dx\, dt$$

From this, a dispersion map can be extracted that composes the maximum energy for all theoretical slowness (phase velocity) values in all frequency bins. In the final step, the high-frequency dispersion curve can be picked manually.

c) Single station methods

In addition to seismic array methods, single station methods were used for (i) resolving the lateral extension of the geological structure of a site, and (ii) obtaining site-parameters for stations where array installation was not possible, either due to logistic problems or because of a lack of project time.

H/V Spectral Ratio analysis

The HVSR method (Nakamura, 1989) divides the spectrum of the ambient noise recordings (usually 30 - 60 min) of the horizontal component of a station by the spectrum of the vertical component. In the case a subsurface impedance contrast (i.e., soft sediment – rock) is present, the HVSR spectrum shows a distinct pea representative of lithological transitions with distinct different velocity. The frequency of this HVSR peak is called the fundamental frequency f_0. f_0 correlates with the depth to the impedance contrast (the lower the frequency, the deeper the contrast), and, with known subsurface velocity, can be used as the first proxy for estimating the bedrock depth. HVSR helps to identify if a station is located on bedrock or if a velocity contrast can be expected. That is why it is listed in the Orfeus station book. When expanding this method to the arrays, it gives a first order approximation of the lateral extension of the impedance contrast at depth below the array; we can judge how well the point approximation for the velocity inversion over an array of up to 400 m is valid. HVSR is applied on all soft-sediment sites (see Annex 1).

In some regions (Brussels, Brabant Wallon, Mons), the f_0 - bedrock depth relation has already been calibrated on boreholes, so from the f_0 value, the bedrock depth can be directly obtained (Van Noten *et al.*, 2022).

RayDec(Py)

The name RayDec stands for "*Rayleigh wave ellipticity estimation using the random decrement technique*", developed by Hobiger *et al*. (2009). It is a single-station technique that generates an ellipticity curve that helps a lot in the velocity inversion of hard rock sites. The random decrement technique eliminates all wave types except Rayleigh waves in ambient noise recordings, and Love and body waves contributions are suppressed. This is the main advantage over HVSR, that might overestimate the ellipticity curve amplitudes as all wave types contribute to the spectral noise content.

Hobiger's original Matlab code has been translated to Python under the name RayDecPy, which can be accessed as a jupyter-notebook together with sample data. This example dataset has also been executed with the original Matlab RayDec code, assuring that the results are similar. RayDec has been applied on all seismometer sites for which continuous data was available to evaluate a first order velocity estimation (see Annex 1).

d) Creating the velocity profiles

All the previously created intermediate data sets (dispersion curves, ellipticity curves, correlation curves, fundamental frequency) can be used to invert a subsurface model of the elastic parameters at depths. Based on a priori geological information and some testing, outer boundaries of the parameters, depths and layer thicknesses were defined to limit the inversion to realistic values. During the inversion process, the required station parameters were sampled from a pseudo-random generator, with which a forward computation for the given input data type (e.g., synthetic dispersion curve) is compared. The misfit between the forward model and input data then quantified how well a certain set of model parameters explains the given input data. Based on the resulting misfits, a new (weighted) set of model parameters was drawn to reperform the forward computation and misfit calculation. Through many iterations of the inversion, the generation of new model parameters should converge and draw more and more similar values. With such a stabilization, we expect the final values to represent the most likely subsurface model to explain the obtained processed data set.

An inversion is highly non-unique and many different tries need to be performed, with different seeding parameters in order to avoid getting stuck in local minima of the parameter-misfit space. Although the inversion approach implemented in the *Dinver* software of *Geopsy* is a global algorithm that should prevent this, badly chosen model limits can enforce certain overfitting of the data and present false results. For the different seismometer sites, we have not all input data available (i.e., no dispersion curve in the FK analysis could be identified) and the different sites are characterized by strongly dissimilar geological subsurface conditions. To derive stable inversion results, a lot of testing is necessary; sometimes only the single input data must be used to generate a better understanding of its sensitivity towards certain depth ranges or parameters.

During the interpretation of the results of the inversion, we needed to keep in mind that we obtain data from an array with a spatial extent and that the final velocity model is a point source approximation. In addition, we might not have been able to install the array directly around a seismic station, while several seismometers are also installed at depth, compared to the temporary array sensors directly at the surface.

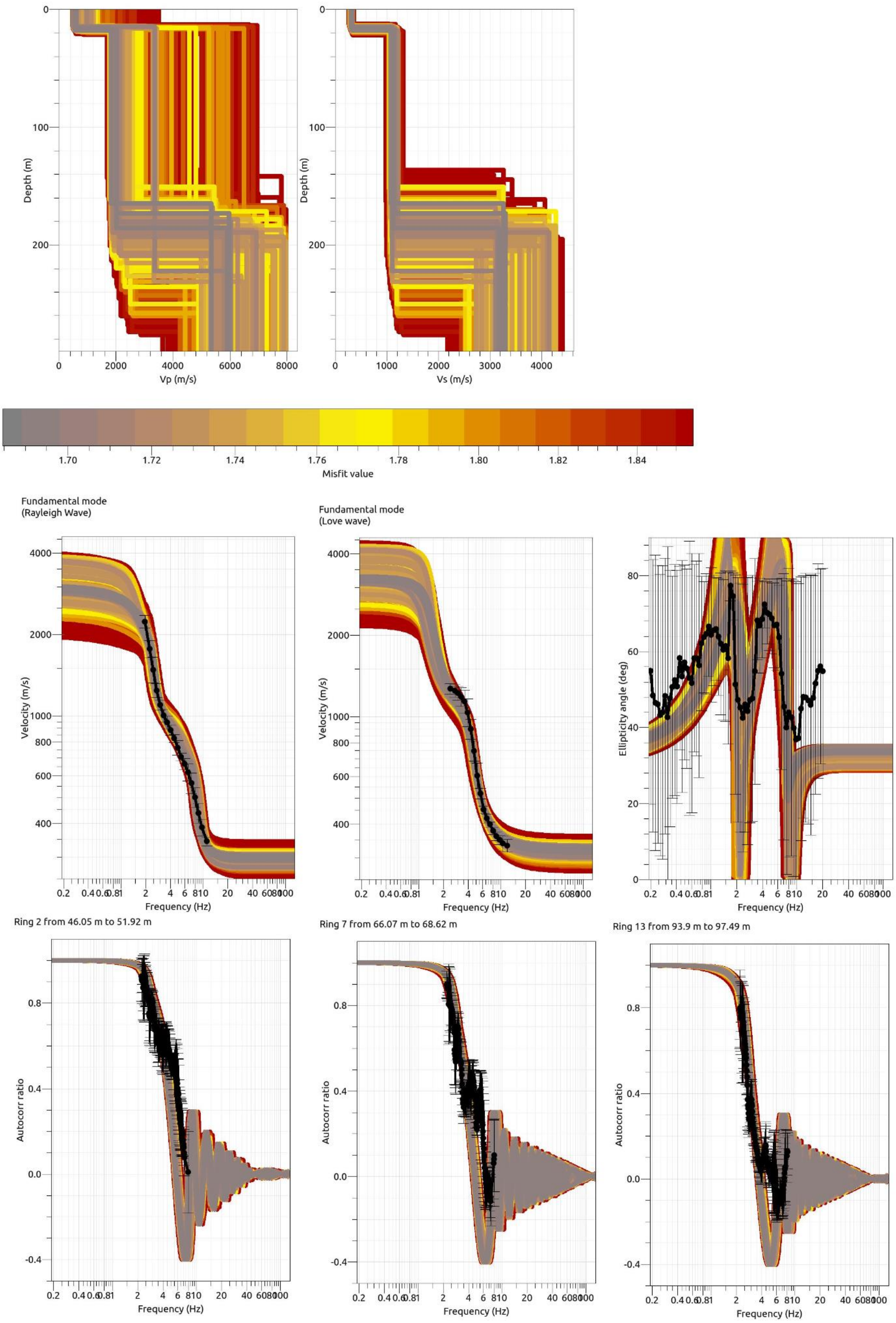


Figure 7: *Example for the BEBN station, showing the inverted final velocity profiles and forward models color-coded by misfit, together with the input data (black points with uncertainty bars).*

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1 GNSS

4.1.1 M^{3}G "Metadata Management and Distribution System for Multiple GNSS Networks"

During EPOS-BE, the M^{3}G portal was upgraded from V3.0 to V5.0 and the API was set up and advanced from V1.0 to V1.3. To enable collecting, validating and distributing the metadata of the large number of expected EPOS stations and handle the expected new users, we

- Increased M^{3}G's user-friendliness: a FAQ, quick start, and on-line tutorials were added to M^{3}G. In addition, some web forms and functionalities were simplified because they were unclear to the users.
- Increased M^{3}G's responsiveness by redesigning and optimizing its database and using a new database server, funded by EPOS-BE.
- Improved the management of personal data in order to fully comply with GDPR, such as stimulating usage of central contact information instead of personal contact information and the requirement to get explicit agreements to publish personal data.

In addition, the following EPOS-specific functionalities were implemented in M^{3}G (non-exhaustive list):

- Acceptance of additional station metadata, such as station pictures, EPOS node information, station's data set DOI (Digital Object Identifier);
- Usage of EPOS-specific, less rigid, metadata validation rules to attract as much as possible GNSS data providers;
- Ensure relevant GNSS station metadata collected by M^{3}G flows to EPOS using the workflows requested by EPOS;
- New API interface to facilitate the analysis of an EPOS-GNSS station lifecycle for the EPOS-GNSS Data Gateway;
- New API functions to export GNSS station metadata in the EPOS-specific GNSS Json format. This format helps in setting up and testing new EPOS GNSS data nodes and also allows to provide metadata about non-EPOS stations in an EPOS-compatible format, which is required to properly document the EPOS GNSS data products;
- Introduction of new virtual networks to ingest the GNSS metadata of the EPOS TCS Near-Fault Observatories and Volcanology.

Finally, administrator tools were developed to help with the management of the EPOS-GNSS network e.g., tool to store the information in the EPOS-GNSS data supplier letters and the EPOS-GNSS data node where a station intends to make its data available.

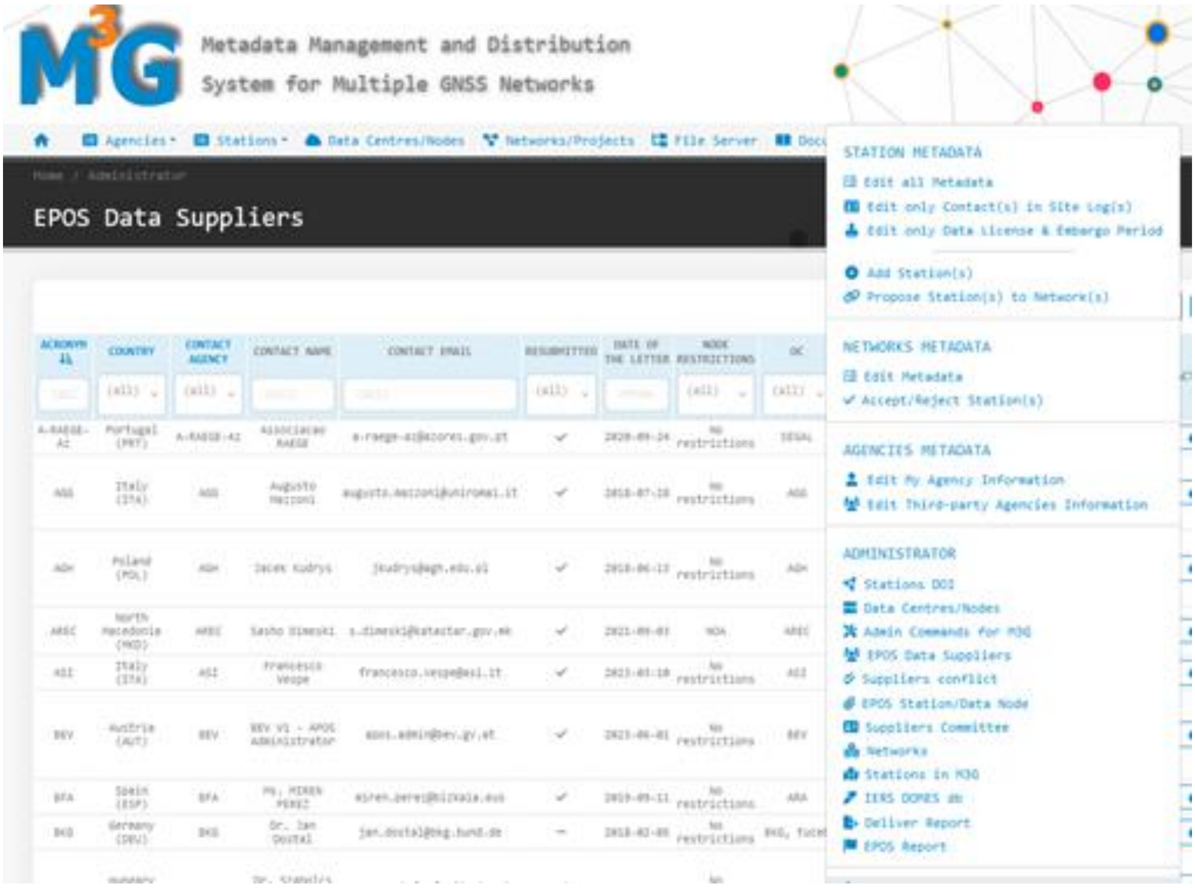


Figure 8: *Screenshot of M³G with overview of EPOS data providers as well as user and administrator tools (https://gnss-metadata.eu)*

While doing the developments indicated above, in 2021, M³G was included in EPOS Pilot Operational Testing (EPOS POT). As part of the EPOS POT, a user survey was conducted to get feedback on M3G's "Usefulness for purpose" and its "Integrated functionality". We decided to additionally include questions about its easy-of-use, documentation, and the support provided by the M³G team. The overall user score received by M³G was 9/10 and M³G was accepted as a pre-operational EPOS service. Hence, **the main EPOS-BE objective for M³G has been reached.**

The M³G service has been opened in the meantime to all agencies, also agencies not involved in EUREF or EPOS. As a result, M³G is now including the metadata of 3000 permanently tracking GNSS stations and is used by almost 150 European agencies (mapping agencies, universities, research agencies …) to manage the metadata of their GNSS stations and provide publicly access to these metadata.

4.1.2 ROB-EUREF data repository

Figure 9: *EPN stations agreeing to share their data with EPOS (in green)*

To prepare the ROB-EUREF data repository for integration in EPOS, it had to become an EPOS-GNSS data node and to do so, the following results were obtained:

- To increase the reliability of the GNSS data included in the ROB-EUREF repository, we set up a new flagging system for GNSS data with formatting errors and reprocessed the complete data set since 1996 to prepare the data for long-term preservation on the BELSPO LTP platform. However, due to an ongoing re-organization of the LTP, the data have not yet been sent to the LTP. This will be done after the end of the project.
- EPOS-BE convinced 82% of the EPN stations (see Figure 9) to share their data with EPOS. The majority of them formally signed the EPOS-GNSS data supplier letter, while the others gave their permission by email due to the complicated management structure in their agency (e.g., ESA). During this process, the ownership of the data sets of all EPN stations was clarified and a data license was attributed to the data sets as required by EPOS.
- The GLASS software has been installed on top of the ROB-EUREF data repository. The initial testing of the GLASS software already demonstrated that the software was not easy to use and still partly under development. However, the GLASS software was applied on the 2+ million EPN data files to index the files and generate data quality metrics, which were both stored on a newly installed database server (funded by EPOS-BE). This database was then synchronized with the EPOS-GNSS data gateway (https://gnssdata-epos.oca.eu) from where the data of the EPN stations are made discoverable and can be downloaded using a GUI or API.
- In addition to the installation and population of the ROB-EUREF node, new software was developed to automatically add the daily new incoming GNSS data of the EPN stations to the node and make them discoverable to EPOS.

In 2021, the ROB-EUREF node was evaluated by EPOS and it was accepted as a pre-operational EPOS service. Hence**, the main EPOS-BE objective for the ROB-EUREF data repository has been achieved.**

Although successfully validated by EPOS, the daily operation of the ROB-EUREF node revealed that in its present form it was unsuitable for a long-term service. Indeed, following EPOS recommendations, it has been installed on a virtual machine from an image containing all GLASS components, including the GLASS database. However, such a system cannot be adapted to handle the necessary modernizations in the software code. In addition, its database security is poor. These problems are mainly caused by the original set up of the node and the GLASS software itself. A new project proposal “SERVE” in response to BELSPO’s ESFRI-FED call was submitted in order to improve the node software. This proposal was selected for funding.

4.1.3 DQMS “Data Quality Monitoring Service”

During EPOS-BE, EUREF’s DQMS was upgraded to allow also validating the quality of EPOS’ GNSS data. The upgrade consisted of

- Development of the software to download the data quality metrics (DQM) from the EPOS-GNSS nodes using the node’s GLASS API. During the testing phase of the software, several problems arose. A first problem was that the retrieval of the DQM from the EPOS-GNSS data nodes was (extremely) slow. Then we noticed that there were GNSS data with missing DQM and finally we retrieved in some cases incorrect DQM. All these problems were caused by bugs in the GLASS software or by the node managers who lacked detailed knowledge of the functioning of the GLASS software. The development of alarms to detect degraded data quality started anyway, but required first a monitoring of data availability and reliability of the DQM at the EPOS GNSS data nodes. The software to do this monitoring were developed and are running: weekly & monthly emails are now sent to the EPOS GNSS data nodes who use this information to find problems at their data node.
- We also organized several meetings with the node managers to improve their understanding of the GLASS software and ensure they used it in a correct way. Slowly, we increased the reliability of the retrieved DQM, but the GLASS software bugs remained problematic. Therefore the developed DQMS should be considered as a prototype until the most critical GLASS software bugs are corrected.
- Development of a method and implementation of the software to automatically trigger station data quality alarms based on different anomaly detection techniques, so that the system is able to manage the large amount of expected EPOS stations. The new alarm system reduced the number of false alarms to a minimum.

Since 2022, the software to retrieve the DQM is running daily and storing the results in a local database. The data quality alarms running on these DQM are used to notify station operators when degraded data quality is detected in one of their stations. Using (prototype) web pages we also display the results of the node monitoring and data quality monitoring on a web site so that they can be consulted by node managers and station operators.

EPOS accepted the upgraded (prototype) DQMS in 2022 as a pre-operational EPOS service. The service will be refined in the SERVE project, but **the objective of EPOS-BE for the DQMS has been reached.**

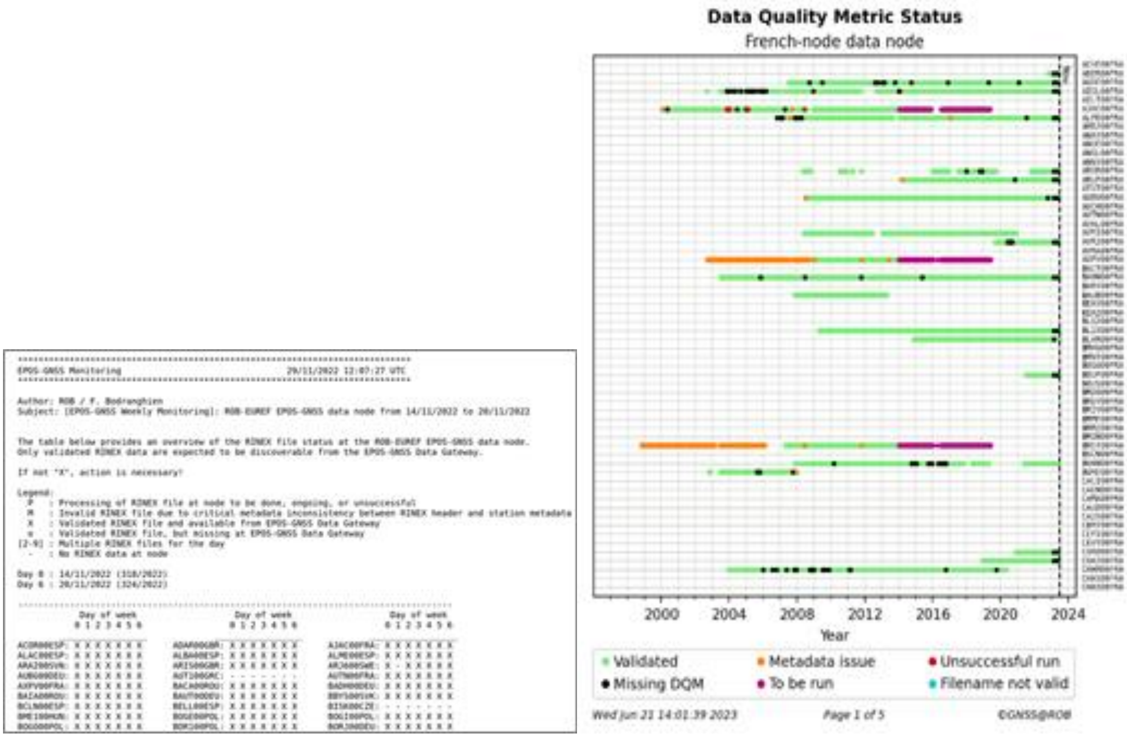


Figure 10: *Example of node monitoring output provided by prototype DQMS.*

4.1.4 Ground deformation monitoring service

EPOS-BE developed new criteria which allow to assess if the velocity that is estimated for an EPN station is of sufficient quality to enable measuring ground deformations with the highest precision (EPOS). The selected criteria have been divided in three classes:

1) Criteria related to the position time series
2) Criteria related to the reliability of the velocity estimation
3) Criteria related to the velocity variability

Based on these criteria, a refined station classification (with 8 classes instead of 2) was developed and velocities for 151 additional EPN stations could be provided to EPOS. The results are provided online at https://epncb.oma.be/_productsservices/ReferenceFrame/Station_Classification.php.

During this process, an enhanced outlier rejection of position time series was implemented by exploiting possible correlations with the results of the GNSS data quality monitoring and external solutions. To prepare the upgraded positions, velocities, and time series for integration in EPOS, the output format was also adapted to EPOS requirements and a Digital Object Identifier was associated with each newly issued solution.

Finally, in the background, to improve the reliability of each daily estimated position, the GNSS data analysis was upgraded to also integrate observations from Galileo observations (in addition to GPS and GLONASS observations).

In 2021, the upgraded ground deformation monitoring service was included in the EPOS POT and accepted as a pre-operational EPOS service. Hence, **the EPOS-BE objective for the ground deformation monitoring service has been reached.**

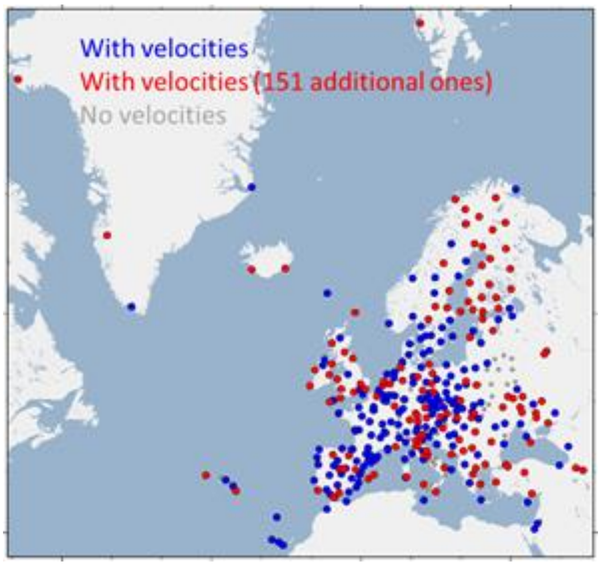


Figure 11: *In blue: EPN stations for which velocities were computed before the start of EPOS-BE. In red: additional EPN stations for which velocities are now reliably computed thanks to the new station classification developed in EPOS-BE*

4.1.5 GNSS network

In 2020, a public tender for purchasing six new GNSS receivers was issued, and the supplier was selected. The equipment was delivered early 2021, tested and installed in ROB's EUREF stations. By doing so, the stations tracked in addition the Galileo and BeiDou satellite constellations. The data flow to ROB was set up and the data were then integrated in EPOS through the pre-operational ROB-EUREF data node. Hence, **the EPOS-BE objective for the upgrade of the GNSS network was reached** and even exceeded the EPOS-BE ambition as the GNSS data are already integrated in EPOS.

4.1.6 GNSS conclusions & recommendations

Thanks to EPOS-BE, ROB was able to upgrade four of its pan-European GNSS services and include them in EPOS as pre-operational services. In addition, the equipment of ROB's GNSS stations was upgraded and their data were integrated in EPOS. EPOS-BE can therefore be considered as very successful.

Moreover, the impact of EPOS-BE exceeded the expectations. Thanks to the stimulus of EPOS-BE, ROB was able to push itself forward as a provider of future EPOS services, claiming a key position in EPOS. Consequently, at the end of 2019, ROB was one of the 10 agencies signing the Consortium Agreement of the TCS "GNSS data and products". By doing so, ROB expressed its willingness to provide the future EPOS-GNSS services and became a key agency in the governance of the GNSS TCS. ROB also received a seat on the EPOS-GNSS Consortium Board and the coordinator of EPOS-BE, C. Bruyninx, was elected chair of the EPOS-GNSS Executive Board. In 2020, C. Bruyninx was elected to represent the GNSS TCS within the EPOS ERIC Service Coordination Committee (SCC). The SCC, representing all the EPOS TCSs and the Integrated Core Services Central hub (ICS-C), provides support and advice to the EPOS Executive Director in formulating and executing the EPOS ERIC Annual Work Program. In November 2022, C. Bruyninx, was elected chair of the SCC and member of the Executive Board of EPOS ERIC.

Thanks to the active role of ROB's GNSS team in EPOS, ROB was the first in-line to participate in EPOS-related projects. This resulted in the participation to the EPOS Sustainability Phase EU project (2020-2023, https://cordis.europa.eu/project/id/871121), the Geo-INQUIRE project (2022-2026, https://cordis.europa.eu/project/id/101058518), and the EPOS-ON proposal submitted in reply to HORIZON-INFRA-2023-DEV-01 call.

While the collection and distribution of GNSS data to EPOS (or other instances) are an intrinsic part of ROB's core tasks, the operation of ROB's EPOS-GNSS services puts additional pressure on ROB's core tasks. Although, as explained in this report, ROB was the obvious agency to operate these services, their operation requires long-term staff and infrastructure. The improvement or evolution of the services to the evolving scientific landscape can mostly be covered by project-type funding, but there is presently no federal mechanism that allows to support operation itself of these.

4.2 Seismology

4.2.1 Renewal of the Belgian seismic network and non-stationary seismic infrastructure

a) The BE network

In 2019, a new station was installed at Tangissart (TGA, 50.6046°, 4.5223°) in the Walloon Brabant Province. The station is installed directly on the bedrock (Mousty Formation, shaley unit) of the Brabant Massif. ROB provided in-kind contributions for the seismic station (Güralp, CMG-40T, 30s) and station installation (technician and scientist, 6 days of preparation and installation). The material costs to install TGA were budgeted on EPOS-BE. The seismic noise test shows that this station already performs significantly better than UCCS in the higher frequency band and performs equally good as the UCCB borehole seismometer installed in Uccle (Brussels).

At the end of 2020, the call for tender was finished. Six new broadband seismometers were bought early 2021 after a long administrative public purchase procedure. The selected seismometer is the Nanometrics Trillium Compact Posthole 20 s combined with the Centaur datalogger. The Nanometrics company ensures excellent cost effectiveness and the sales representative in Germany prevented us from performing time-consuming customs procedures. This instrument can be installed in a borehole down to 300 m. We did not ask for a longer period sensor as the sensitivity to tilts increases, which is an issue for borehole installation. Even though it was not implemented in the EPOS-BE project proposal, we also renewed the Belgian accelerometric network as a dedicated budget has been allowed to renew 16 old, outdated Kinemetric-ETNA accelerometers by Nanometric Titan strong motion accelerometers.

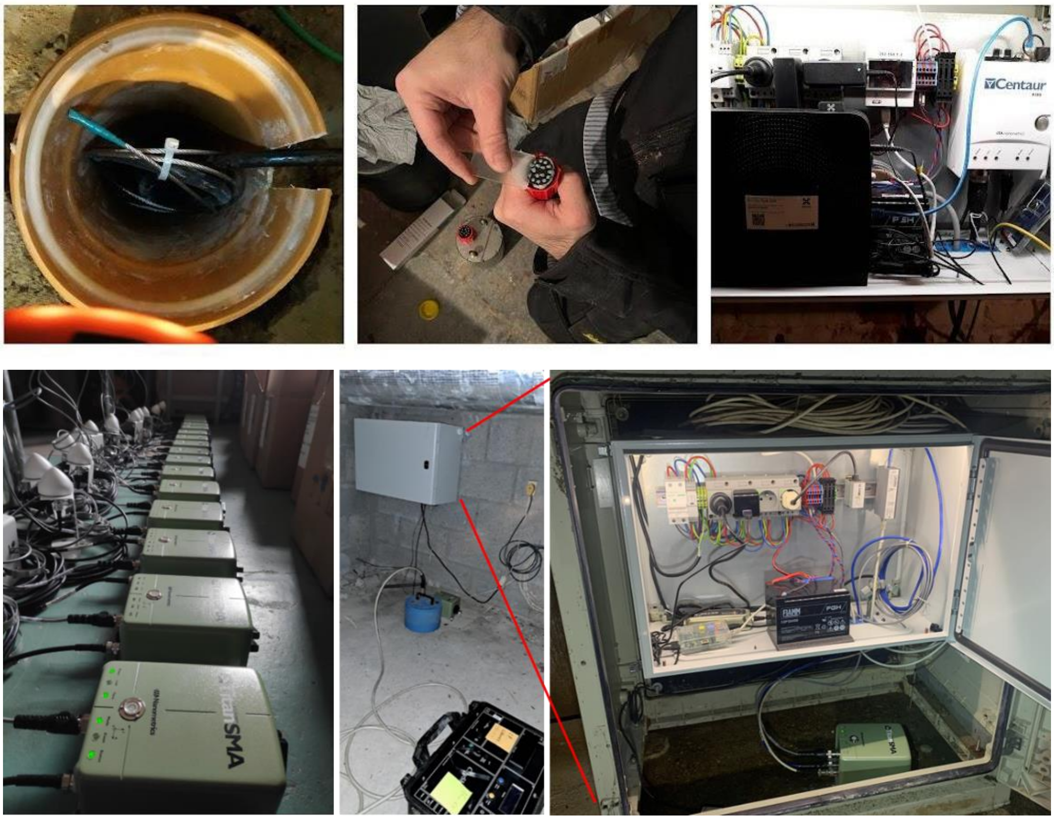


Figure 12: *Upper row: installation of a shallow borehole during the EPOS-BE station renewal. Lower row: Renewal of the BE accelerometric network using Nanometrics Titan Accelerometers. Left) Labo tests. Center) Accelerometer installation of the MASA accelerometer in Maaseik (BE). Right) Zoom of an accelerometer installation.*

Table 1 shows an overview of the renewal of the Belgian seismic network thanks to BELSPO's EPOS-BE funding. Five new Nanometrics Trillium Compact Posthole 20s seismometers were installed in Gesves (GES), Seneffe (SNF), Clavier (CLA), La Chartreuse (LCH) and Steenkerque (SKQ). The sixth station was bought for Bougnies (BOU), but due to ownership problems, the BOU site was not available anymore after 2021. To replace BOU (Hainaut province), we performed a geological investigation to find a good replacement site. The region of Hainaut has been a source of (induced and triggered) seismicity for more than a decade, starting at the end of the 19th century up to 1985, at the end of coal mining (see Camelbeeck *et al.,* 2022). Because of this historical seismicity, it was important to find a site close to the Mons graben. We tried to stay as close as possible to the bedrock and tried to stay away from air navigation obstacles (windmills, antenna's, transmission lines) and train and highway roads. A new site was found at Blaregnies (code BLRG) where the new seismometer is dug in a shallow hole in the thin Quaternary deposits of the Bly River, which are deposited above the Lower Devonian Burnot sandstone Formation. This geological configuration is broadly similar to the one at BOU. All of the other novel seismometers were installed at the same place as the previous station location, except for SKQ, where a shallow borehole was made closer to the house.

After the installation of all stations, the seismic waveform data was directly streamed to the ROB and incorporated into the routine processing tasks. For each of the new installed stations, there is a clear data quality improvement as seen in the PPSDs of the stations (Fig. 13). Hence, **the main EPOS-BE objective for the upgrade of the current Belgian seismic network is reached.** As a last step, we will extend the data streaming of the entire BE network to the Eida node of ORFEUS as soon as ORFEUS opens the station books of the new stations in the BE network (expected by the end of 2023).

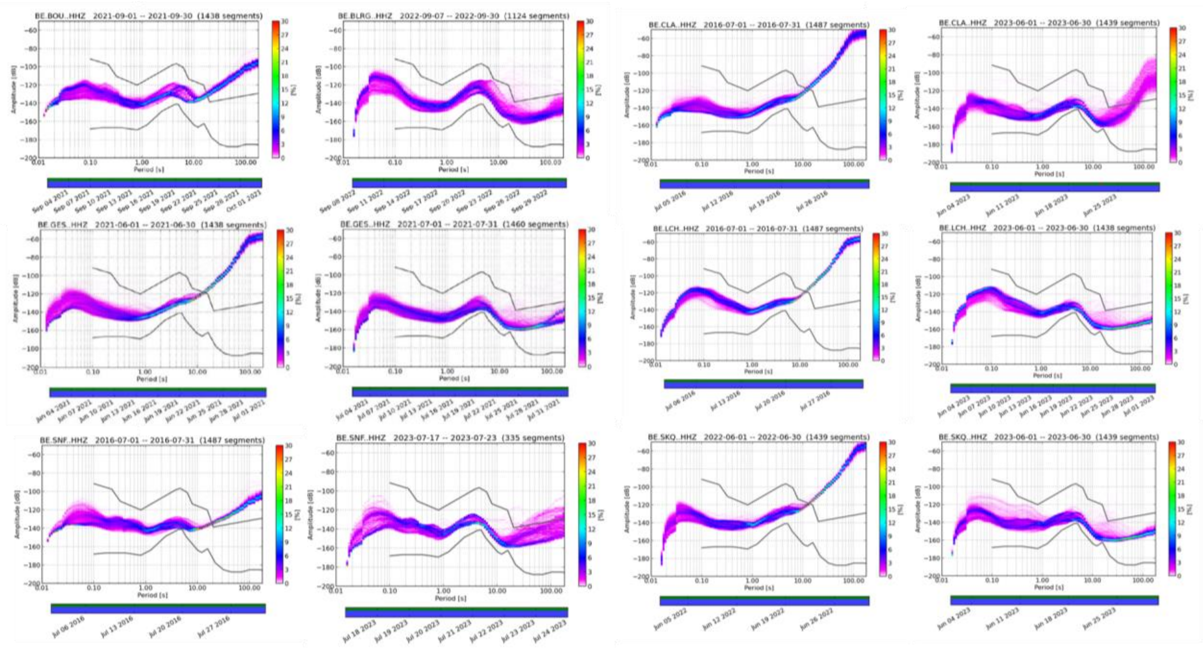


Figure 13: *Comparison of the data quality before (1st and 3rd column) and after (2nd and 4th column) the installation of the new sensors during EPOS-BE. Comparison is done using PPSDs (probabilistic power spectral densities) of one month of data each covering the same period of year. There is a clear improvement at periods longer than 3 s and slight increase in the anthropogenic frequency range (0.1 - 1s).*

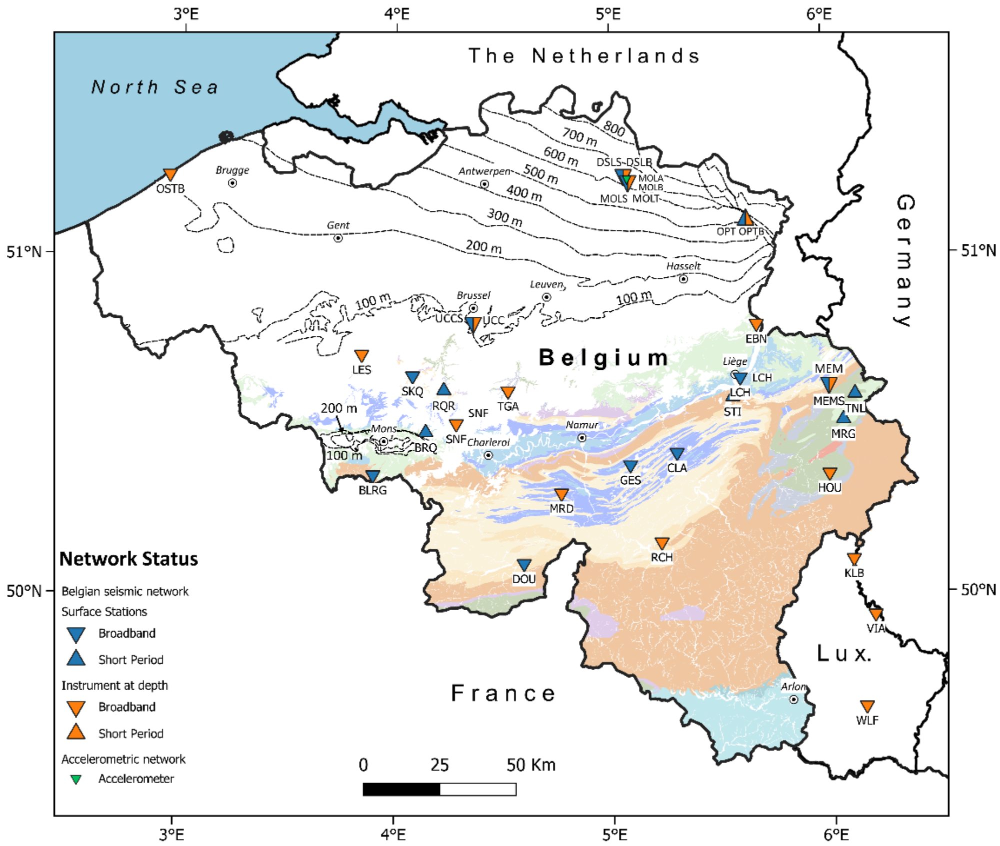


Figure 14: *Renewed Belgian seismic network after station updates in EPOS-BE.*

Table 1: *Renewed stations in the Belgian Seismic Network due to EPOS-BE funding.*

Code	Site	Renewal date	EPOS-BE Funded instruments (~111 k€)
DOU	Dourbes	17.06.2021	Nanometrics Centaur datalogger
GES	Gesves	01.07.2021	Nanometrics Trillium Compact Posthole
SNF	Seneffe	05.08.2021	Nanometrics Trillium Compact Posthole + Nanometrics Centaur datalogger
CLA	Clavier	13.08.2021	Nanometrics Trillium Compact Posthole
MEM	Membach	09.09.2021	Nanometrics Centaur datalogger
LCH	La Chartreuse (Liège)	24.02.2022	Nanometrics Trillium Compact Posthole + Nanometrics Centaur datalogger
BOU →BLRG	Bougnies → Blaregnies	07.09.2022/23.11.2022	Nanometrics Trillium Compact Posthole + Nanometrics Centaur datalogger
SKQ	Steenkerque	10.05.2023	Nanometrics Trillium Compact Posthole + Nanometrics Centaur datalogger
RQR	Ronquières	23.05.2023	Nanometrics Centaur datalogger
BRQ	Bracquegnies	14.06.2023	Nanometrics Centaur datalogger

b) Sensor reliability of SmartSolo nodes

After careful reviewing of different nodal systems, the decision was made to buy 21 new IGU-16HR SmartSolo® 3-component (3C) 5 Hz geophones for conducting array measurements. With these 21 new instruments we performed a set of lab- and field-based comparison tests. As such, we aimed to ensure the reliability of these new sensors for site characterization purposes and highlight their sensitivity in the use of ambient seismic noise towards the seismological community.

In the first so-called huddle test, all instruments were installed next to each other within a 1m x 1m square to assure the coherent recording of the ground shaking. These coherencies of obtained waveforms were further ensured by limiting the time record to the observation of a teleseismic earthquake originating from Japan (Magnitude Mw 7.3). By correlating the obtained spectra of all sensor combinations, we could invert (seismological expression for optimization) the data for the transfer function of the instruments expressed through complex poles and zeros (for details see Zeckra *et al.*, 2022). This information is crucial as the seismic sensor acts as a filter when translating the recorded ground shaking into electric voltages as an output signal. The transfer function then allows us to remove this filtering artifact and we can correctly reconstruct the actual ground shaking. Here, we could reproduce the poles and zeros given by the manufacturer. This means, we can reliably reconstruct the ground shaking when using the SmartSolo nodal sensors. In addition, we identified that the conversion parameters given in a dedicated seismological online database are incomplete and do not consider a gain factor introduced during the digitization process of the data recordings.

Further data processing revealed the missing gain value, which has been confirmed by the technical support of SmartSolo.

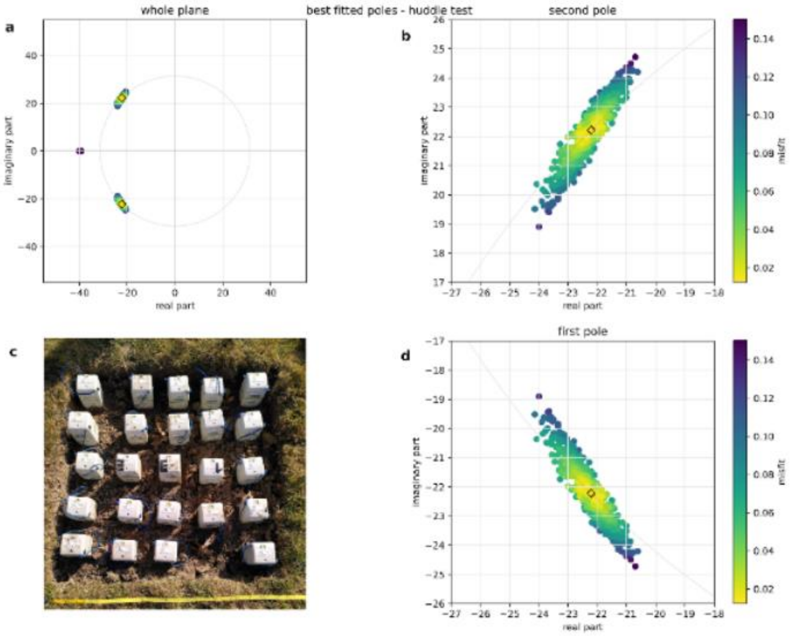


Figure 15: *The resulting poles of the SmartSolo nodes huddle test, color-coded by misfit from the manufacturer's values, shown by the diamond marker. a) result shown over the whole complex plane that has been defined as the solution space in the inversion. b) and d) close-up view of the two poles. c) 24 nodes co-located during the huddle test. Note the slightly imperfect installation, contributing negatively to the misfit values.*

The same experiment set-up allowed us to identify the sensor's self-noise levels by correlating the recorded spectras of three sensors at a time. The self-noise is a crucial parameter defining the instrument's absolute sensitivity. For the frequency range above 1 Hz, which is most crucial for the ambient noise analyses in the EPOS-BE project, the self-noise level is constant, and for the vertical component, it lies around the natural noise levels obtained at the quietest stations of the Belgian seismic network. For lower frequencies, the self-noise is lowering relatively to the ambient noise levels in Belgium and even reaching the lowermost noise levels observed on a global scale.

Under controlled recording conditions in the basement of the observatory we performed a comparison test of the new nodal sensor, with a Lennartz 3D/5s instrument that is classically used for decades for ambient noise studies, and the permanent surface station (Güralp 3ESP) as an absolute benchmark. The waveform similarity expressed through the coherence function and the spectral division revealed that the waveforms obtained with the new nodal instruments show higher similarity over a wider frequency range compared to the benchmark instrument, in comparison with the traditional sensor. This result is reproduced independently of the installation type of the nodal sensor, which either is coupled to the ground by a spike or stands on a tripod mounted to its base.

To evaluate the previous excellent performance of the new nodal instruments for practical application we analyze their performance based on processed data by using the Horizontal-to-Vertical spectral ratio (HVSR). This passive method using ambient seismic noise has been proven reliable for estimating the sedimentary thickness underneath Brussels (Van Noten *et al.*, 2022) and in Fig. 16 we present three example locations with various sensor combinations. The frequency of the main peak can be identified very well within the method’s uncertainties, independent of the sensor in use. The amplitude varies by 10% between the different sensors. The overall curve, which replicates the whole S-wave velocity profile, is congruent from 20 Hz until 0.2 Hz under very good recording conditions in the ROB’s basement; the latter is a great surprise, as this is way below the sensor’s natural frequency and usually sensors are not supposed to show reliable HVSR values in this frequency range. Under real-world, more realistic measurement conditions, the HVSR curve diverges stronger for the frequency range below the peak as is expected from theory. However, the peak frequency and amplitude as the most important parameters for earthquake engineering can still be identified reliably within the method's uncertainty.

Even though this **sensor reliability study was not a deliverable in the EPOS-BE project**, it is a clear improvement to fully explore the functionality of the sensors used in site characterization studies.

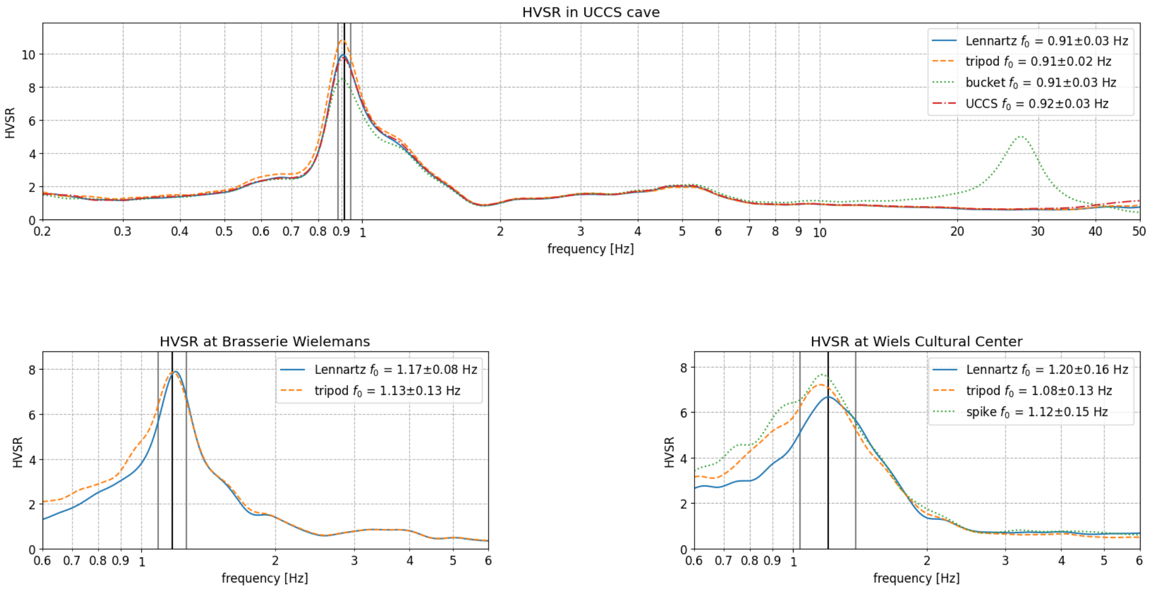


Figure 16: *Comparison of HVSR curves obtained with various sensors at three different locations in Brussels. Upper: HVSR curve at the Royal Observatory of the permanent station (UCCS), the Lennartz instrument and two SmartSolos with either a spike base in a sand-filled bucket or mounted on a tripod. Lower left: HVSR curve using a Lennartz and SmartSolo node on a tripod co-located in Forest. Lower right: HVSR of co-locating Lennartz and two SmartSolos either on a tripod or coupled into the ground with a mounted spike. Zeckra et al. (in review).*

4.2.2 Site Characterization of Belgian seismic network

a) In-depth array investigations of key seismic stations

A detailed site characterization was performed for nine seismic stations that have a long performance history in the BE seismic network and that are installed on a typical geological subsurface that is widespread in Belgium. These stations are GES, CLA, OPT(B), EBN, SNF, RQR, SKQ, UCC(B) and TGA. For each of these stations, dedicated fieldwork was performed with seismology staff during which arrays were installed close to the seismic stations.

Figure 17: *Site characterization next to seismic stations of Belgian seismic network*

We chose to present the results of the data analysis in factsheets, with one factsheet per station. This graphical representation is more attractive and explicative than describing the results of each station separately. Raw data such as array configurations, arrival times of active experiments, dispersion curves (.max extension) and inversion results can be requested by contacting the authors (seismo.info[at]oma.be). In the future, these results will be provided through the website Seismology.be. For stations available in ORFEUS, station information was already updated in the station book with data similar as shown in Table 2.

Each factsheet contains:

- a geological map and explanation of the subsurface geology below the station
- information on the fieldwork array configuration used for site characterization
- overview of the obtained dispersion curves and velocity inversion(s)
- summary of the site characterization results and methods used
- overview of obtained ORFEUS station book parameters
- summary of station characteristics

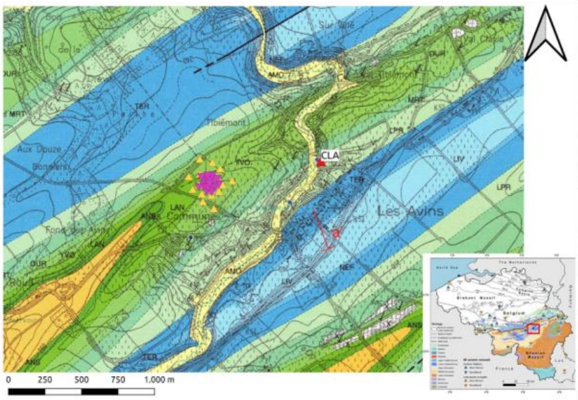
With the provision of these detailed key station parameters **the site characterization of the Belgian network objective is reached.**

Table 2 (next page): *Site characterization results for nine key stations in the Belgian seismic network as result of array seismology during EPOS-BE*

Orfeus Stationbook parameters	CLA	EBN	GES	OPT	OPTB	RQR	SKQ	SNF	TGA	UCC	UCCB
Geological Unit	Limestone (Longpré formation)	Chalk (Upper Cretaceous, Maastrichtian)	Sandstone (Famennian, Ciney formation)	Fine sands (Mol formation)	Marine clays (Heers formation)	Slates (Brutia formation)	Mudstone - Siltstone (Steenkerque formation)	Limestone (Lives formation)	Shale (Mousty Formation)	Sands (Lede formation)	Quartzite/Slate (Tubize formation)
Morphology Class	T2	n/a	T1	T1	n/a	T1	T1	T1	T2	T1	n/a
Ground Type EC8	A (hard rock)	A (hard rock)	A (hard rock)	C (sedimentary deposits of hundreds of meters)	A (hard rock)	A (hard rock)	A (hard rock)	A (hard rock)	A (hard rock)	B (sedimentary deposits of tens of meters)	A (hard rock)
Groundwater Depth [m]	25 - 30	~ 20	~ 10		n/a	n/a	< 10	< 2	7	n.n.b.	n/a
$v_{S_{30}}$ [m/s]	2900	1100	982 +/- 32	362	846	> 800	1492 +/- 28	> 800	1188 +/- 170	280	1800
f_0 [Hz]	n/a	n/a	~ 50	0.28	n/a	n/a	n/a	n/a	n/a	0.90	n/a
Amp(f_0)	n/a	n/a	10	3.8	n/a		n/a		n/a	14	n/a
Basin Flag	False	False	False	True	n/a	False	False	False	False	True	n/a
Bedrock Depth [m]	0	0	0.3	356	0	0	0	0	0	115	0

CLA – Clavier

Geology



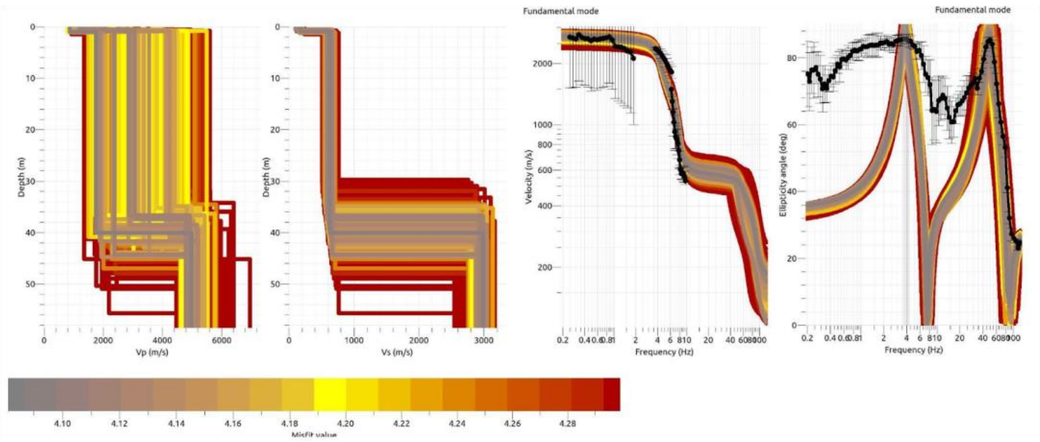
Fieldwork

Geology & lithology:

- sensor on concrete block on outcropping limestone (Longpré formation)
- Carboniferous thickness ~250 m

Array information:

- 21 sensors in 2 consecutive Arrays
- Apertures: 350 m and 140 m respectively
- passive registrations (noise + qb active)



Site characterization results

- input: array dispersion curves, quarry blast dispersion curve
- inversion of 3 layer model for array (soil, weathered layer, bedrock)
- using the bedrock layer vs for inferring the CLA stations V_{s30} value

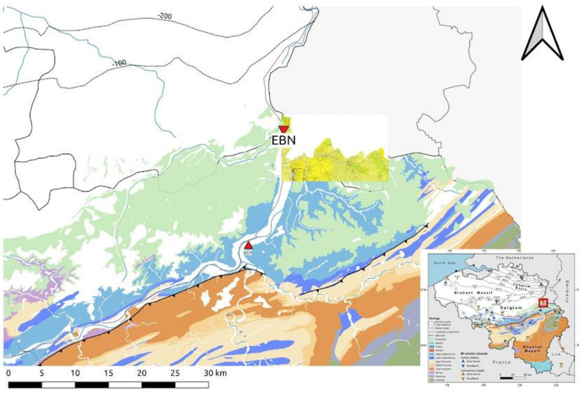
Orfeus Stationbook parameters	
Geological Unit	Limestone (Longpré formation)
Morphology Class	T2
Ground Type EC8	A (hard rock)
Groundwater Depth [m]	25 - 30 m
v_S30 [m/s]	2900 m/s
f_0 [Hz]	n/a
Amp(f_0)	n/a
Basin Flag	False
Bedrock Depth [m]	0
Description	

Summary:

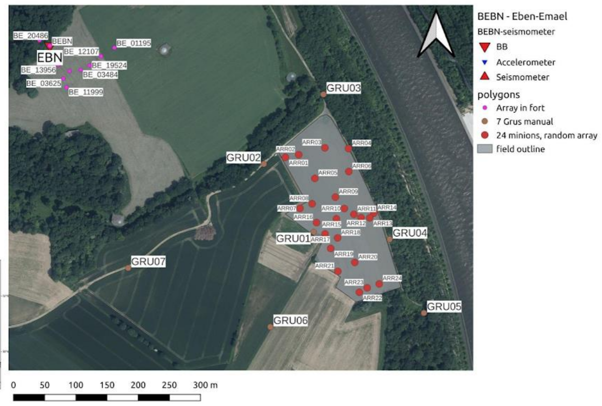
CLA is a bedrock station with v_{s30} of 2900 m/s, located directly on the outcropping Carboniferous bedrock, on the top of a steep slope.

(B)EBN – Eben-Emael

Geology



Fieldwork

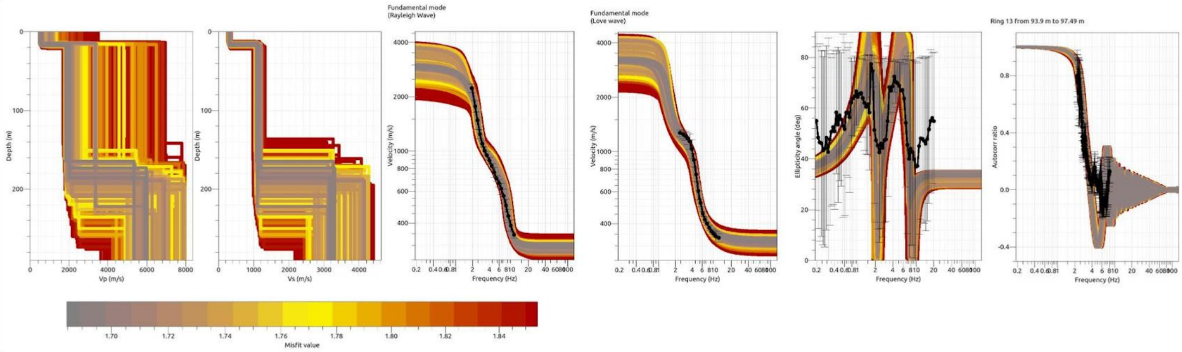


Geology & lithology:

- inside fort carved in massive chalk layer
- Upper Cretaceous/Maastrichian

Array information:

- L-shaped array inside fortress (10 minions on tripod)
- 24 minions + (6+1) Grus for surface array
- 1 Gru on top of BEBN sensor



Site characterization results

- input: Rayleigh and Love wave dispersion curves from minion array (IGU-16HR 3C), MSPAC, Rayleigh wave ellipticity of a single IGU-BD3C-5 SmartSolo node
- inversion of 3 layer model for array: soil(field), chalk, bedrock
- using the stable chalk layer Vs for inferring the BEBN stations V_{s30} value

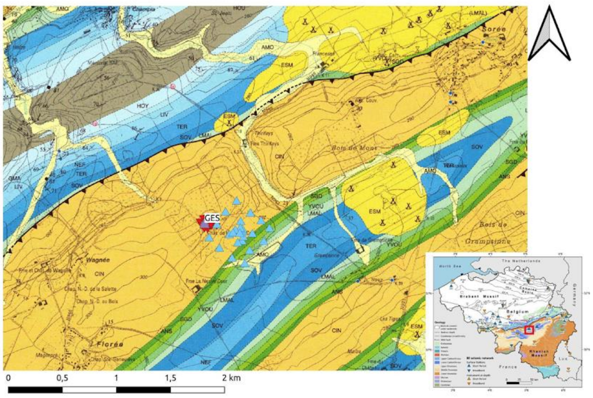
Orfeus Stationbook parameters	
Geological Unit	Chalc (Upper Cretaceous, Maastrichian)
Morphology Class	n/a (inside a tunnel, 46 m under the surface)
Ground Type EC8	A
Groundwater Depth [m]	~20 m
v_S30 [m/s]	1100
f_0 [Hz]	n/a
Amp(f_0)	n/a
Basin Flag	f
Bedrock Depth [m]	0
Description	

Summary:

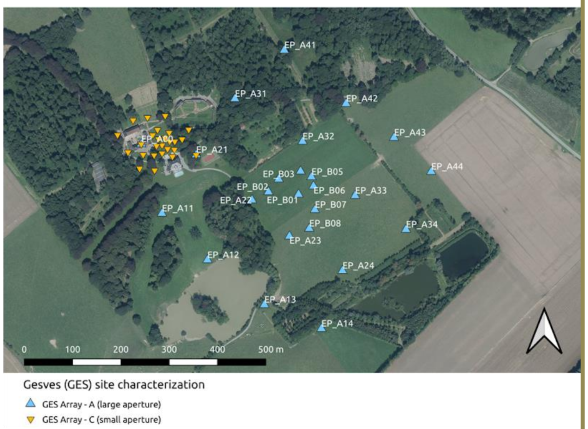
(B)EBN is a bedrock station with v_{s30} of 1100 m/s, located in a fort inside the Cretaceous chalk layer. Overall chalk thickness ~160 m.

GES – Gesves

Geology



Fieldwork

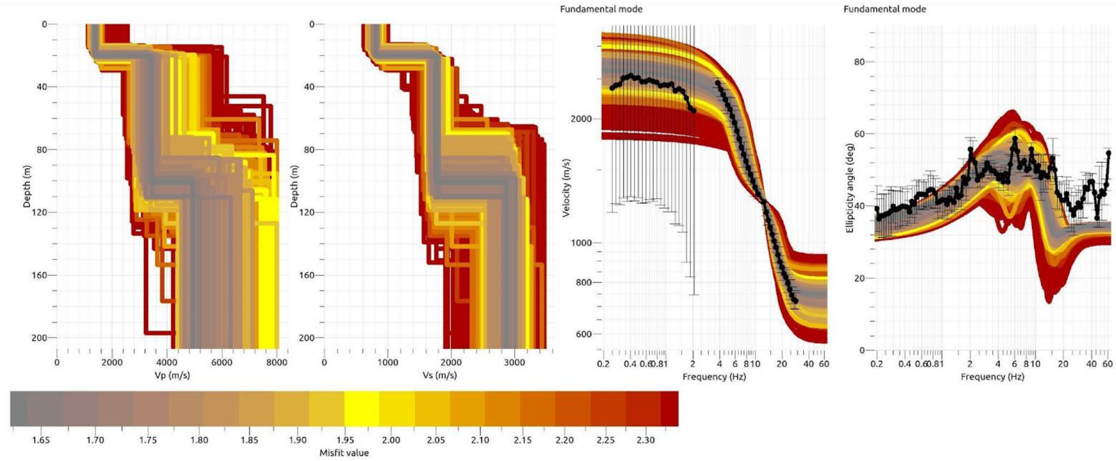


Geology & lithology:

- Devonian Ciney Sandstone
- on top of an anticlinal structure with an NE - SW oriented fold axis

Array information:

- 2 arrays of 24 minions with 400 m and 160 m aperture
- ambient noise, active through jumping (small array) + qb dispersion (big array)



Site characterization results

- input: array and quarry blast dispersion curve, MSPAC, rayleigh wave ellipticity
- inversion of 3 layer model for array (soil, weathered layer, bedrock)
- v_{s30} derived from averaging gpprofile outputs (geopsy software)

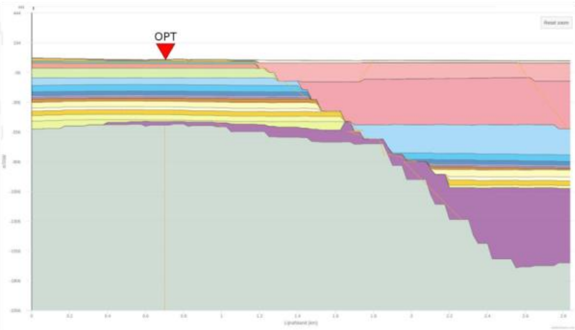
Morphology Data	
Geological Unit	Sandstone (Ciney formation)
Morphology Class	T1
Ground Type EC8	A (hard rock)
Groundwater Depth [m]	~10
v_S30 [m/s]	982 +/- 32
f_0 [Hz]	~50
Amp(f_0)	10
Basin Flag	False
Bedrock Depth [m]	0.3
Description	n/a

Summary:

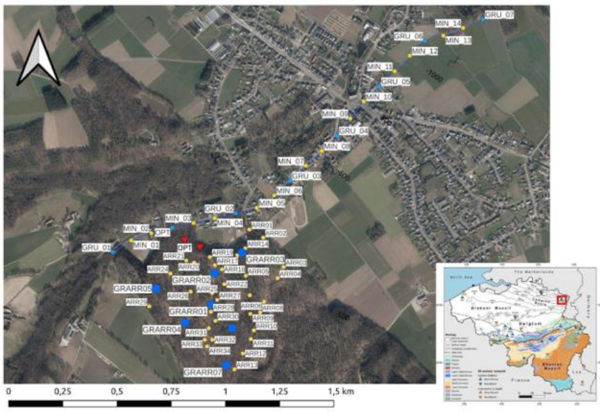
GES is a bedrock station with v_{s30} of 982 +/- 32m/s, located in the basement of a building, maybe leading to a higher V_{s30} value.

OPT(B) – Opitter

Geology



Fieldwork

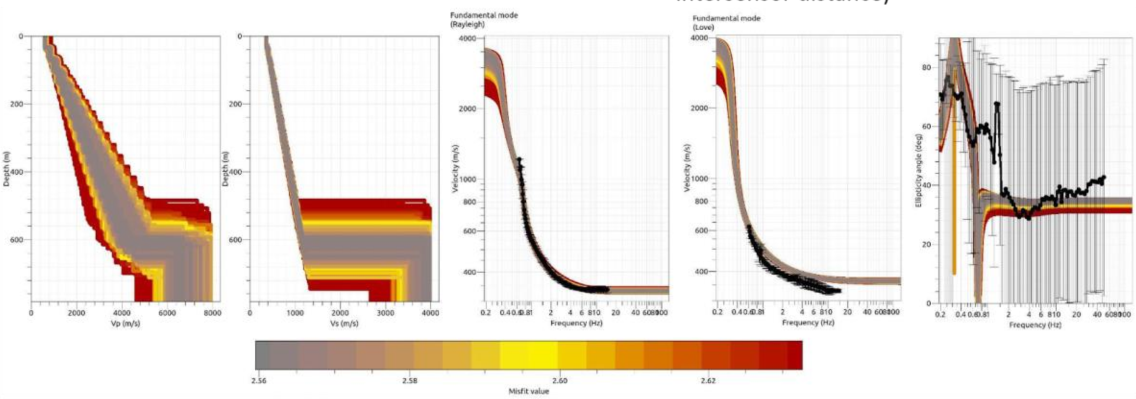


Geology & lithology:

- on the footwall of the Bree fault (southwestern border fault of the Roer Valley graben)
- thick sediments (~350m until engineering bedrock)

Array information:

- combined array (34 minions + 7 Grus) south of the station
- HV profile crossing Bree fault (100m intersensor distance)



Site characterization results

- input: array Rayleigh and Love dispersion curves, rayleigh wave ellipticity of single Gru
- inversion with linearly increasing velocity model (18 sub-layers) over bedrock half-space
- OPTS: v_{s30} derived from averaging gpprofile outputs (geopsy software)
- OPTB: v_{s30} derived from averaging velocities given for sensor depth below surface

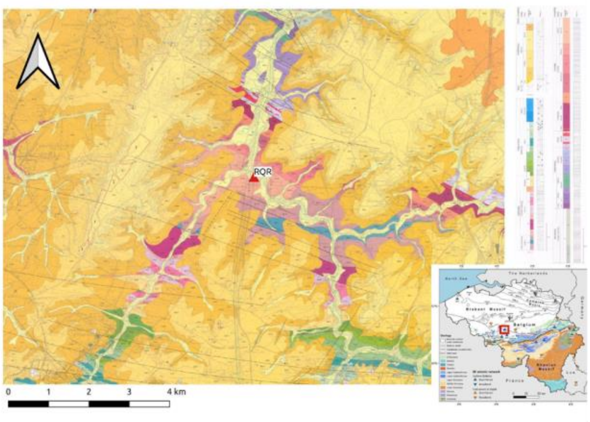
Orfeus Stationbook parameters	OPT surface station	OPTB borehole station
Geological Unit	Mol Formation (Pliocene Sediments)	Heers Formation (Paleocene marine clays)
Morphology Class	T1	n/a
Ground Type EC8	C	A
Groundwater Depth [m]		
v_S30 [m/s]	362.15	845.83
f_0 [Hz]	0.28	n/a
Amp(f_0)	3.8	n/a
Basin Flag	True	n/a
Bedrock Depth [m]	355.81	0
Description		

Summary:

OPT is the surface station with a low V_{s30} (362 m/s) value and gradually increasing velocities. **OPTB** is the borehole station placed in the Heers Formation that is considered to be part of the engineering bedrock (V_{s30} = 845 m/s).

RQR – Ronquières

Geology



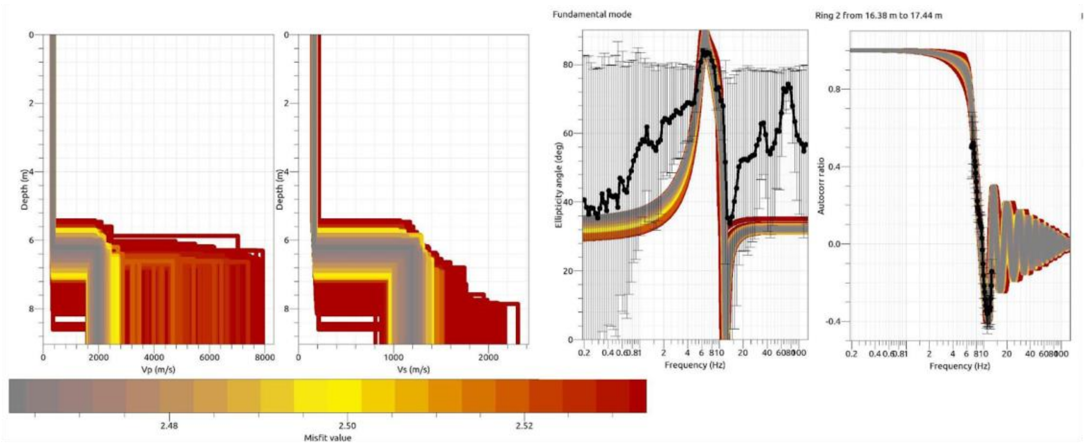
Fieldwork

Geology & lithology:

- array on anthropogenic infill
- sensor on bedrock, upper Silurian Ronquières formation (slates)

Array information:

- 21 minions in random set-up
- passive ambient noise and hammer shots



Site characterization results

- input: array MSPAC, rayleigh wave ellipticity
- inversion of 2 layers, as lack of control at greater depths (infill, bedrock)
- V_{s30} derived from bedrock velocity as sensor is in shallow borehole

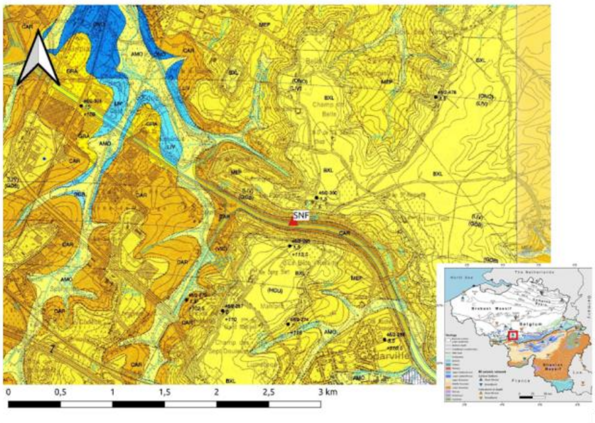
Orfeus Stationbook parameters	
Geological Unit	Ronquière Formation (Silurian Slates)
Morphology Class	T1
Ground Type EC8	A
Groundwater Depth [m]	n/a
v_S30 [m/s]	1200 +/- 60
f_0 [Hz]	n/a
Amp(f_0)	n/a
Basin Flag	false
Bedrock Depth [m]	0
Description	

Summary:

RQR is a bedrock station with V_{s30} of 1200 +/- 60 m/s, inside a 12m-deep borehole inside the bedrock.

SNF – Seneffe

Geology



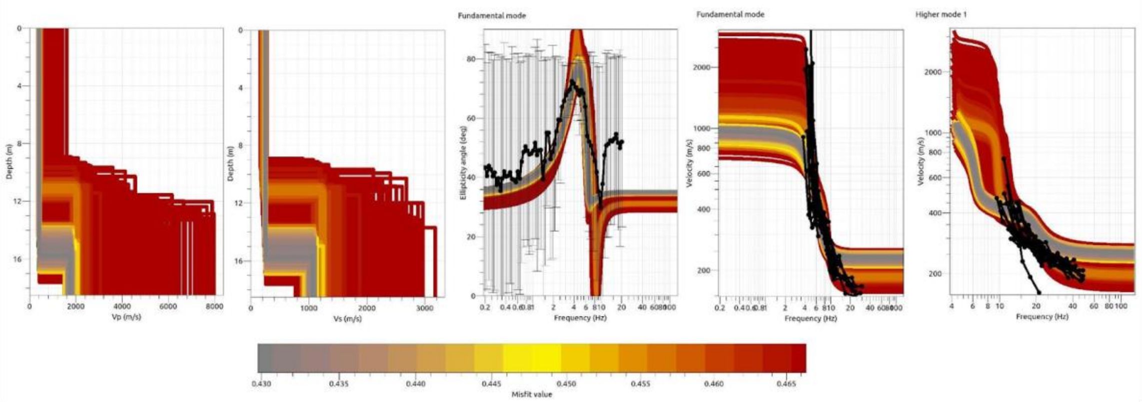
Fieldwork

Geology & lithology:

- Lives Formation (under the paleogene) as part of 700m of Carboniferous
- Limestone bedrock

Array information:

- linear arrays for active hammer shots
- 20 fixed & 1 mobile sensors, 2.5 m and 5 m spacing



Site characterization results

- input: active refraction, MASW and rayleigh wave ellipticity
- inversion of 2 layers, as lack of control at greater depths (soft soil over bedrock)
- v_{s30} derived from bedrock velocity as sensor is in shallow borehole

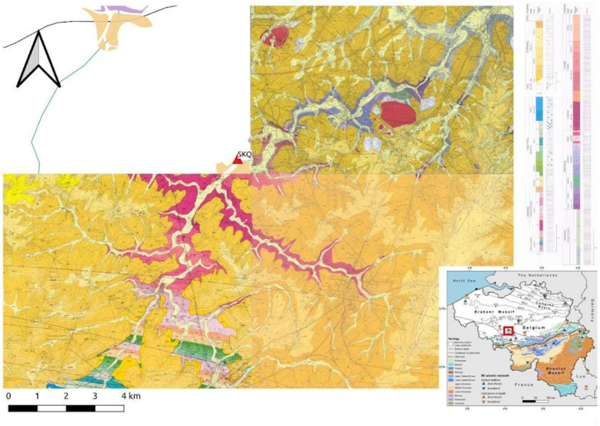
Orfeus Stationbook parameters	
Geological Unit	Limestone (Lives formation)
Morphology Class	T1
Ground Type EC8	A (hard rock)
Groundwater Depth [m]	13 m from surface, < 2 m from seismometer
v_S30 [m/s]	1200
f_0 [Hz]	n/a
Amp(f_0)	n/a
Basin Flag	False
Bedrock Depth [m]	0
Description	

Summary:

SNF is a bedrock station with v_{s30} of ~1200 m/s, inside a shallow borehole reaching the bedrock.

SKQ – Steenkerque

<u>Geology</u>



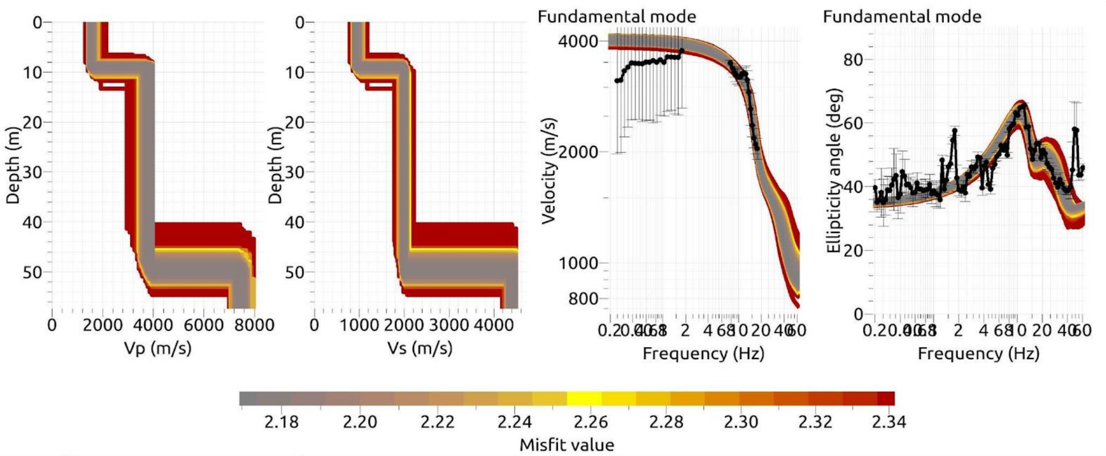
<u>Fieldwork</u>

Geology & lithology:

- Silurian Steenkerque formation (cleaved mud- and siltstone)
- sensor directly on/now in bedrock

Array information:

- 2 arrays of 21 minions with 250 m and 150 m aperture
- ambient noise, active through qb dispersion



Site characterization results

- input: array and quarry blast dispersion curve, rayleigh wave ellipticity
- inversion of 3 layer model for array (soil, weathered layer, bedrock)
- V_{s30} derived from averaging gpprofile outputs (geopsy software), misfit < 2.5

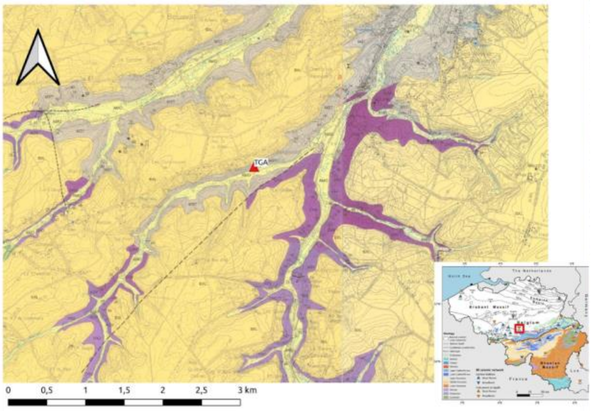
Orfeus Stationbook parameters	
Geological Unit	Mud- to Siltstone (Steenkerque formation)
Morphology Class	T1
Ground Type EC8	A (hard rock)
Groundwater Depth [m]	< 10 m
v_S30 [m/s]	1492 +/- 28 m/s
f_0 [Hz]	n/a
Amp(f_0)	n/a
Basin Flag	False
Bedrock Depth [m]	0 (borehole sensor in (altered) bedrock)
Description	

<u>**Summary:**</u>

SKQ is a bedrock station with v_{s30} of 1492 +/- 28 m/s, located on top of (station upgrade to posthole in) bedrock, likely leading to a higher V_{s30} value for the sensor.

TGA – Tangissart

Geology



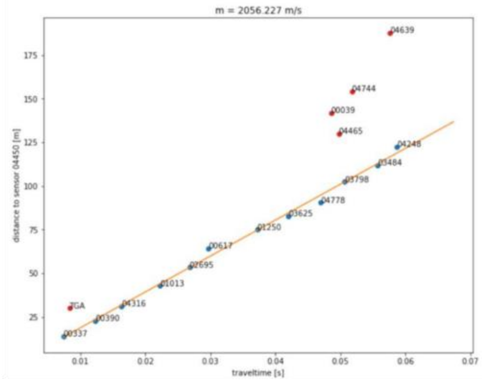
Fieldwork

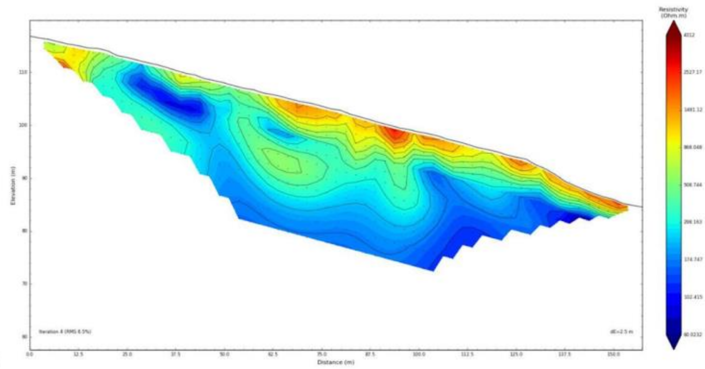
Geology & lithology:

- station (+ lower half of line installation) in Mousty formation (Cambrian bedrock)
- upper installation on Bruxelles Sands

Array information:

- line installation for active hammer shots
- parallel ERT profile
- 6 sensors out of profile





Site characterization results

- ERT and HVSR analysis for understanding subsurface geometries
- refracted p-wave onset picking for v_P estimation
- V_S estimation from literature v_P/v_S values (√3)

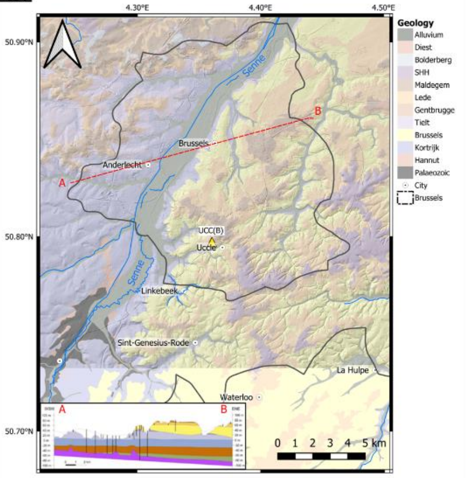
Orfeus Stationbook parameters	
Geological Unit	Shale (Mousty Formation)
Morphology Class	T2
Ground Type EC8	A (hard rock)
Groundwater Depth [m]	7 m
v_S30	1188 +/- 170 m/s
f_0	n/a
Amp(f_0)	n/a
Basin Flag	False
Bedrock Depth	< 0.1 m
Description	

Summary:

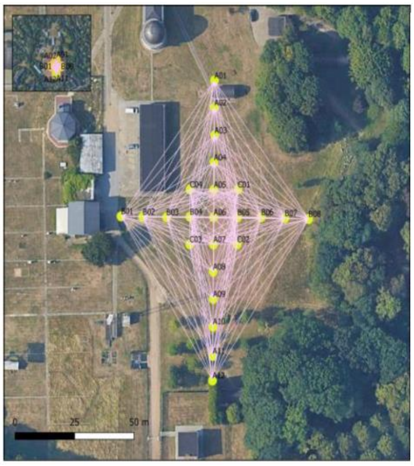
TGA is a bedrock station with v_{s30} of 1188 +/- 170 m/s, located on top of bedrock; the local cambrian Mousty formation, as part of the Cambro-Silurian Brabant Massif.

UCC(A/B) – Uccle

Geology



Fieldwork

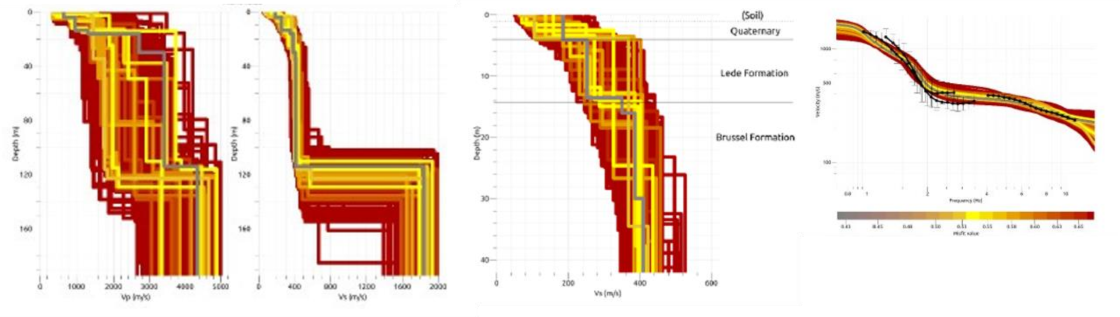


Geology & lithology:

- 114 m soft sediment geology above Brabant Massif. Top: Lede Formation
- Tubize Formation as bedrock

Array information:

- Regular cross installation
- One month or array installation
- First EPOS-BE array installation



Site characterization results

- input: fk dispersion curve, rayleigh wave ellipticity
- inversion of 4 layers with prior borehole knowledge (soft soil over bedrock)
- V_{s30} derived from soft sediment/bedrock velocity profile, Vp soft sediment profile less resolved

Orfeus Stationbook parameters	
Geological Unit	Sand (UCC: Lede Fm) and slate/quartzite (UCCB: Tubize Fm)
Morphology Class	T1
Ground Type EC8	B
Groundwater Depth [m]	unknown
v_S30 [m/s]	280 (UCC) - 1800 (UCCB)
f_0 [Hz]	0.9
Amp(f_0)	14
Basin Flag	True
Bedrock Depth [m]	115
Description	

Summary:

UCC is a soft sediment surface station with a low V_{s30} (280 m/s). Vs of the Brussels sands predominate the Vs in the first 115 m

UCCB is the borehole station placed in the Tubize Formation of the Brabant Massif with a fast bedrock velocity (V_{s30} = 1800 m/s).

b) Site characterization of current, temporary, abandoned and accelerometric seismic stations

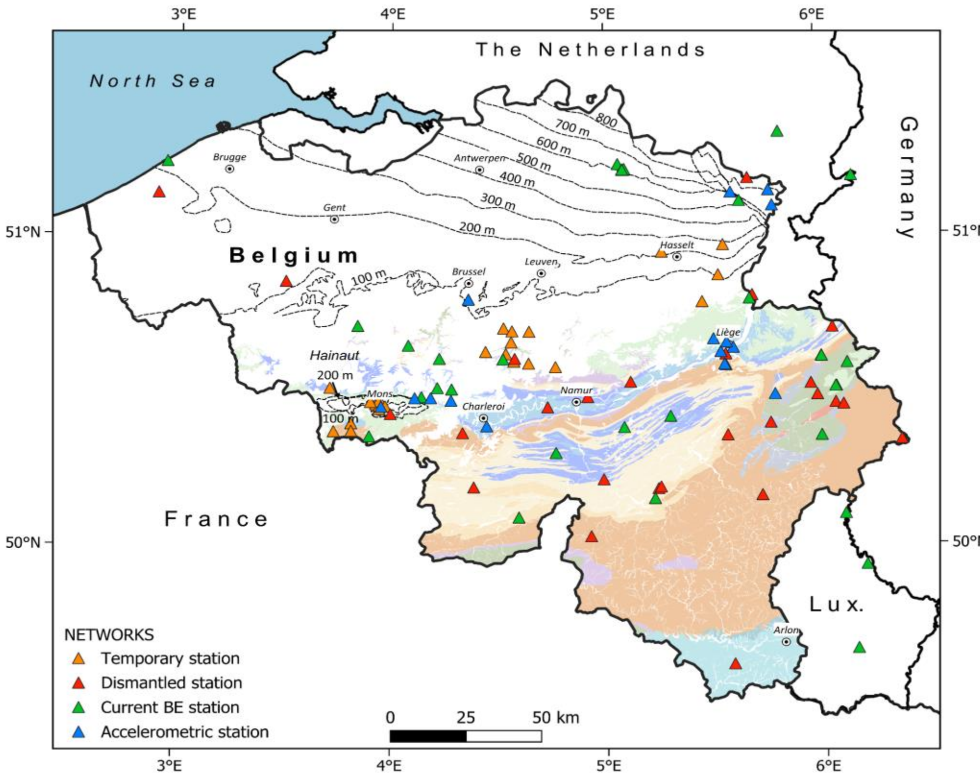


***Figure 18:** Overview of the accelerometric network and current stations, temporary arrays and dismantled stations in the Belgian seismic network. For each station the EC8 soil class was determined using geological information.*

Thanks to the site characterization of the key stations, we can extrapolate their information to all seismic (109) and accelerometric (16) stations in the Belgian seismic network. Seismic stations include all stations in the current network (46), in temporary arrays during seismic crises or swarms (34), or stations dismantled (29) because of logistic reasons or when the research project finished. Our aim was to provide the EC8 soil class for the entire network, and if possible the V_{s30}. In a first step, all geological information below these dismantled, temporary and active stations was derived using Belgian geological models. From the site characterization of the key stations, it is clear that a prior geological investigation already can solve the EC8 soil classification. For bedrock stations, when the geological substratum is similar to one of the key stations, site conditions were copied. Additional RayDec analyses on 1h of data were performed to many stations to confirm the EC8 soil class derived from the geology, and if possible, to determine the V_{s30}. For soft-sediment stations, the dominant resonance frequency f_0 was calculated from one day of ambient noise data. Bedrock depth was then determined by converting the f_0 value to depth using the Van Noten *et al.* (2021) powerlaw conversion law for the Brussels and Mons areas and the Van Noten *et al.* (2015) powerlaw for the Brabant Walloon area. For stations in Flanders, bedrock depth values to the top of the Heers Formation in the *Databank Ondergrond Vlaanderen* (DOV; 2023) were used. Detailed results for each station are shown in Annex 1, with notation of the location of the station, number of recorded earthquakes, geological information, f_0 value for soft sediment stations, the bedrock depth, and the results and method used for the EC8 soil classification.

With this information, **the EPOS-BE objective for the site characterization of the current Belgian seismic network is reached** and even exceeds our objectives as also the temporary and dismantled networks were characterized. Most of the Belgian stations are or were installed on the bedrock (soil class A; 73 stations). The other stations were installed on soil class B (21) and C (30) substratum. Without detailed Quaternary geophysical research it is difficult to judge if stations belong to soil class E, but we tentatively suspect not. Only temporary stations installed in local arrays on recent alluvial deposits (e.g., SESAME project, Meuse valley in Liège) should be classified as class E.

4.2.3 Seismology conclusions

The renewal of the Belgian seismic network is, thanks to the ROB's investment plan, a continuous task. With the EPOS-BE support, stations and acquisition systems could be bought more efficiently. Our site characterization procedures and knowledge have strongly increased during EPOS-BE, which will help characterize new sites for permanent and temporary sensors. Moreover, fully mapping the entire network showed a lack in station density in Flanders, which needs to be tackled in the coming years, including funding of regional and federal agencies.

The site characterization of the full Belgian network, as presented in Annex 1, transcends the initial EPOS-BE objectives. The EC8 soil classification is of importance for ground motion simulation, and to verify or correct earthquake recordings and magnitude computations in the Belgian earthquake database (see the BRAIN-be 2.0 project BELSHAKE).

5. DISSEMINATION AND VALORISATION

5.1 GNSS

As detailed above, throughout the project, EPOS-BE has been in close interaction with the TCS "GNSS data and products" to ensure that the upgrades to the ROB's EUREF services were in-line with EPOS expectations. To reach this goal, ROB participated to many conferences and meetings were the EPOS-BE progress was discussed with EPOS stakeholders. Annex 3 contains the list of all events to which EPOS-BE participated. Due to the COVID-19 pandemic, a large part was held virtually. As can be seen from the conference contributions (section 6.3) and publications (section 6.1), EPOS-BE also presented the progress of its upgraded GNSS data and services to potential users (including the EPOS-BE follow-up committee).

EPOS-BE also co-organized an EPOS-GNSS webinar (18-19 January 2021) and an on-line EPOS-GNSS Technical Workshop (5-6 May 2022).

As explained in sections 4.1.1 to 4.1.4, EPOS-BE participated with its four upgraded EPOS services to the EPOS pilot operational testing (POT). The POT consisted of independent testing of ROB's GNSS services and associated web portals. The technical tests considered access to the services, their availability and performance, online documentation and quality assurance. In addition, user surveys were conducted to verify the usefulness of the services. After some iteration, all four ROB's GNSS services passed the EPOS POT testing and were labelled as pre-operational EPOS services.

Finally, thanks to the ROB-EUREF data node, the GNSS data of ROB's upgraded GNSS stations are now also discoverable from the EPOS data portal.

5.2 Seismology

The most unexpected impact of the seismology part of EPOS-BE is our built knowledge in using SmartSolo seismic nodes in array seismology, site characterization and geophysical prospection. Thanks to EPOS-BE, the functioning of these nodal systems was completely undressed, and their performance better understood. Results of the node performance, the station renewal and site characteristics of the BE network all have been presented in scientific papers and during national and international conferences (chapter 6.3).

Because of this newly gained knowledge, the ROB is now leading and collaborating in many research projects in which the nodes form the core of the data acquisition, such as the GeoCamb (BRAIN-be.be 2.0) and FaultCollab (FED-tWIN) projects, research in cave geophysics (PhD. A. Martin, Bruniquel cave characterisation) and public outreach events (schools, Nerdland 2022 festival). Beyond these projects, the ROB nodes are involved in ULB MSc and PhD teaching and research projects, serve in expertise projects and provide data in international collaborations with the BGR, Bensberg seismic station of the University of Cologne, LMU Munich, RESIF-FACT (FR) and ISTremor (Iceland). They are moreover used for studying potential new station locations, to investigate site characteristics of industrial geothermal projects and will be installed as rapid response to earthquake crises.

Hence, **BELSPO's investment in the ROB's non-stationary seismic infrastructure during EPOS-BE has definitely surpassed our expectations**.

6. PUBLICATIONS

6.1 Peer-reviewed publications

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E. (2019) GNSS Metadata and Data Validation in the EUREF Permanent Network. *GPS Sol*., 23(4), https://doi.org/10.1007/s10291-019-0880-9

Fernandes, R., Bruyninx, C., Crocker, P., Menut, J.-L., Socquet, A., Vergnolle, M., Avallone, A., Bos, M., Bruni, S., Cardoso, R., D'Agostino, N., Fabian, A., Holger, S., Janex, G., Kenyeres, A., Legrand, J., Ngo, K.-M., Lidberg, M., Liwosz, T., Manteigueiro, J., Miglio, A., Soehne, W., Toth, S., Dousa, J., Ganas, A. (2022) A new European Service to share GNSS Data and Products, *Annals of Geophysics* 65(3), https://doi.org/10.4401/ag-8776

Steffen, R., Legrand, J., Agren J., Steffen, H., Lidberg, M., (2022) HV-LSC-ex2: Velocity field interpolation using extended least-squares collocation, *Journal of Geodesy* 96, 15, https://doi.org/10.1007/s00190-022-01601-4

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6.2 Non peer-reviewed publications

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6.3 Internship reports

Heylen, M. (2023) *Site characterisation of the Tangissart (TGA) permanent seismic station.* Internship report at Royal Observatory of Belgium. Université libre de Bruxelles. Supervision by Van Noten, K. and Zeckra, M., Brussels. 43 p.

6.4 Conference contributions

2019

Bruyninx C., Pottiaux E., Pacione R., Fabian A., Legrand J., *On the Future High-Precision European GNSS CORS Infrastructure* (invited presentation, EGU2019-9205). EGU General Assembly 2019, April 7-12, 2019, Vienna , Austria

Bruyninx C., Legrand J., Fabian A., Pottiaux E., *Towards Operational Data Quality Monitoring of EPN Stations* (presentation, EGU2019-7847). EGU General Assembly 2019, April 7-12, 2019, Vienna, Austria

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E., Roosbeek, F., *EPN data quality in a multi-GNSS environment* (presentation). EUREF symposium 2019, May 20-22, 2019, Tallinn, Estonia

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Bruyninx, C., Legrand, J., Fabian, A., Miglio, A., Avallone, A., Bos, M., Crocker, P., Dousa, J., Fernandes, R., Kenyeres, A., Lidberg, M., Liwosz, T., Menut, J.-L., Socquet, A., Söhne, W., Vergnolle, M. *Construction of the GNSS component of the European Plate Observing System (EPOS*) (invited presentation), EUREF AC Workshop, October 16-17, 2019, Warsaw, Poland

Fabian, A., Bruyninx, C., Legrand, J. *New Functionalities in M^3G (Metadata management and distribution system for Multiple GNSS Networks)* (poster). EUREF symposium 2019, May 20-22, 2019, Tallinn, Estonia

Kenyeres, A., Bruyninx, C., Sacher, M., Denker, H., Fernandes, R. *EUREF's pan-European Geodetic Infrastructures in Support of Geosciences* (poster). EUREF symposium 2019, May 20-22, 2019, Tallinn, Estonia

Kenyeres, A., Bruyninx, C., Sacher, M., Denker, H., Fernandes, R., *EUREF's pan-European Geodetic Infrastructures in Support of Geosciences* (poster, EGU2019-15310). EGU General Assembly 2019, April 7-12, 2019, Vienna, Austria

Legrand, J., Bruyninx, C. *EPN Multi-year Position/Velocity Product* (presentation*).* EUREF symposium 2019, May 20-22, 2019, Tallin, Estonia

Legrand, J., Bruyninx, C., *Stability of velocity estimations and quality assessment of the EPN stations* (poster, EGU2019-10317). EGU General Assembly 2019, April 7-12, 2019, Vienna, Austria

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Van Noten, K., *Insights in site characterisation from the SERA workshop applicable to EPOS-BE* (presentation), RMS Meeting, April 2 2019, Bensberg, Germany

2020

Bruyninx, C., Fabian, A., Legrand, J., Miglio, A., *GNSS Station Metadata Revisited in Response to Evolving Needs*, EGU General Assembly, 4–8 May 2020, Online

Fabian, A., Bruyninx, C., Legrand, J., Miglio, A., *GNSS data quality check in the EPN network*, EGU General Assembly, 4–8 May 2020, Online

Legrand, J., Bruyninx, C., *Quality assessment of GNSS reference stations*: *Criteria and Thresholds,* EGU General Assembly, 4–8 May 2020, Online

Zeckra, M., Van Camp, M., Van Noten, K., Lecocq, T., *Site Characterization of Belgian permanent stations*, RMS (Rhine-Meuse-Seismologists) meeting, November 19, 2020, Online-meeting.

Zeckra, M., *Waffles, Fries & Arrayseismology – site characterization in Belgium*, University of Potsdam (online seminar), December 8, 2020, Potsdam, Germany.

2021

Bruyninx, C., Legrand, J., Fabian, A., *Performance of the EUREF Permanent GNSS Network*, presentation at EUREF symposium, 26-28 May 2021, virtual

Bruyninx, C., *GNSS Services in EPOS' Pilot Operational Phase*, presentation at EUREF symposium, 26-28 May 2021, virtual

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Zeckra, M., Van Noten, K., Lecocq, T., *Site-characterization of permanent stations using industrial purpose, three-component, short-period sensors,* 37th General Assembly of the European Seismological Commission, 23 September 2021, Online (ePoster)

Zeckra, M., Van Noten, K., Lecocq, T., *Towards a site-characteristic database for the Belgian permanent seismic network*, 7th International Geologica Belgica Meeting, 17 September 2021, Tervuren, Belgium.

2022

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Legrand, J., Bruyninx, C.: *Reference frame Coordination Status Report*, EUREF symposium 2022, Zagreb, Croatia, 1-3 June 2022

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2023

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ANNEX 1 – SITE CHARACTERIZATION TABLE OF THE BELGIAN SEISMIC NETWORK

Site characterization characteristics of Temporary (T), Dismantled (D), Current (C) and Accelerometric (A) stations installed in the Belgian seismic network. *T*: Type. *N rec*: nr of earthquake recordings by this station. *Station*: network.station. *Altitude*: Altitude of station installation. *Depth*: Depth of station. *Soil class*: EC8 soil class. *Method*: method by which the soil class was derived, i.e., from geological maps (geology), by raydec method, relative by f_0, relative to site characteristics of another station, array techniques or well logging. *Stratigraphic Formation*: official stratigraphic name of surface and bedrock. *f_0*: resonance frequency at the site. *Bedrock depth*: depth to seismogenic bedrock.

T	N rec	Station	Place-Locality	Lat	Lon	Altitude	Depth	Soil class	Method	Soft or bedrock	Stratigraphic Formation	f_0	Bedrock depth
T	7	BE.MN1	Mons - Lotto Mons Expo	50.458	3.939	50	0	C	geology	soft	Alluvial above Maastricht	0.87	~111±10
T	7	BE.MN2	Mons - Cité administrative	50.455	3.939	16	0	C	geology	soft	Alluvial/Ieper above Obourg	1.28	~59± 5.9
T		BE.MN3	MONS - Grands Prés	50.455	3.934	50	0	C	geology	soft	Alluvial/Kortrijk above Obourg	0.96	~94± 9.4
T	4	BE.MN4	Mons - IDEA station de pompage	50.461	3.947	50	0	C	geology	soft	Alluvial/Kortrijk above Obourg	1.01	~86± 8.6
T	5	BE.MN5	Mons - RW (DPA)	50.449	3.945	29	0	C	geology	soft	Alluvial/Kortrijk above Obourg	0.91	~101±10
T	6	BE.MN6	Mons - Muséum rég. des Sc. Nat.	50.457	3.948	35	0	C	raydec	soft	Kortrijk above Obourg	1.29	~58±6
T	7	BE.MN7	Mons - Maison de l'entreprise	50.460	3.928	50	0	C	geology	soft	Alluvial/Ieper above Obourg	1.29	~58±6
T	9	BE.MN8	Mons - Université de Mons	50.463	3.956	35	0	C	geology	soft	Kortrijk above Obourg	3.31	~13±2
T	7	BE.MN9	Mons - SWDE	50.443	3.944	25	0	C	geology	soft	Alluvial/Kortrijk above Trivières	1.08	~78±8
T	5	BE.MNA	Mons - CSC	50.455	3.946	50	0	C	geology	soft	Kortrijk above Obourg	1.54	~44±4
T	2	BE.MNB	Mons - Adeps	50.468	3.941	33	0	C	geology	soft	Alluvial/Ieper above Obourg	2.17	~25± 2.5
T	2	BE.MNC	Mons - Arcéa	50.453	3.972	33	0	C	geology	soft	Kortrijk above Obourg	1.14	~72± 7.2
T	1	BE.MND	Mons - Rés. Oultremont	50.467	3.904	45	0	C	geology	soft	Hannut	1.56	~43± 4.3
T	27	BE.GRZ	Grand Leez	50.579	4.767	155	0	A	relative (f0)	soft	Brussel above Abbaye de Villers	4.07	11.4
T	20	BE.OT1	OT1-Mellery	50.597	4.573	142.5	0	B	relative (f0)	soft	Brussel above Chevlipont	2.72	22.8
T	28	BE.OT2	OT2-Rixensart	50.704	4.525	105	0	B	relative (f0)	soft	Brussel above Tubize	1.60	57.0
T	25	BE.OT3	OT3-Dion-le-Mont	50.693	4.644	104	0	B	relative (f0)	soft	Brussel above Blanmont	2.03	38.1
T	7	BE.OT4	OT4-Limal	50.695	4.564	81.5	0	B	relative (f0)	soft	Brussel above Tubize	2.18	33.4
T	28	BE.OT5	OT5-Genappe	50.628	4.441	130	0	B	relative (f0)	soft	Brussel above Tubize	4.49	9.6
T	0	BE.OT6B	OT6B-Chastres	50.591	4.642	142	0	B	relative (f0)	soft	Brussel above Mousty	3.95	11.9
T	2	BE.OT7B	Faux	50.621	4.536	150	0	B	relative (f0)	soft	Brussel above Mousty	3.29	16.5
T	31	BE.OTT	Ottignies	50.659	4.560	67.5	0	A	relative (f0)	bedrock	Mousty	-	0
T	0	BE.PHR	Petit-Hornu	50.398	3.813	112	0	A	geology	bedrock	Coal Measures group	-	0
T	3	BE.BLA	Blaugies	50.373	3.814	130	0	A	geology	bedrock	Wépion	-	0
T	3	BE.MSR	Montignies-sur-roc	50.372	3.733	78	0	A	geology	bedrock	Burnot	-	0
T	0	BE.STA	Stambruges	50.512	3.715	58	0	A	geology	soft	Hannut above Lives	unk	7
T	24	BE.TMM1	Membach T	50.609	6.010	250	0	A	relative (MEMH)	bedrock	Acoz	-	0

T	24	BE.TMM2	Membach T	50.609	6.010	250	0	A	relative (MEMH)	bedrock	Acoz	-	0
T	24	BE.TMM3	Membach T	50.609	6.010	250	0	A	relative (MEMH)	bedrock	Acoz	-	0
T	24	BE.TMM4	Membach T	50.609	6.010	250	0	A	relative (MEMH)	bedrock	Acoz	-	0
T	1	BE.TBL1	Bilzen	50.873	5.533	61	0	C	geology	soft	Boom	0.91	67.73
T	1	BE.TBL2	Tongeren	50.787	5.456	100	0	C	geology	soft	Sint-Huibrechts-Hern	2-3	37.26
T	1	BE.TBL3	Zutendaal	50.970	5.557	90	0	C	geology	soft	Bolderberg	0.3	214.87
T	1	BE.TBL4	Kermt	50.948	5.268	30	0	C	geology	soft	Eigenbilzen	0.56	164.19
D	1	BE.AFT	Afst	50.337	6.377	563	0	A	geology	bedrock	Chooz	-	0
D	101	BE.AUL	Aulne	50.367	4.333	115	5	A	geology	soft	Alluvial above Burnot	11.04	<10
D	3	BE.BON	Bonnine	50.482	4.917	160	0	A	geology	bedrock	Terwagne	-	0
D		BE.BOU	Bougnies	50.419	5.302	235	8.0	A	geology	bedrock	Acoz	-	0
D	30	BE.BRE	Bree	51.185	5.676	32.5	1.5	A	geology	soft	Kiezeloöliet	unk	1249.83
D	2	BE.BUZ	Buzenol	49.619	5.584	280	0	A	geology	bedrock	Arlon	-	0
D	3	BE.COI	Cointe_1	50.618	5.564	0	0	A	geology	bedrock	Coal Measures group	-	0
D	41	BE.CSE	Court-Saint-Etienne	50.606	4.577	167	0	B	relative (f0)	soft	Brussel above Chevlipont	2.58	25.1
D	115	BE.CTH	Couthuin	50.530	5.118	122	37	A	geology	bedrock	Terwagne	-	0
D	44	BE.HEY	Heyd	50.357	5.568	195	0	A	geology	bedrock	Fromelennes	-	0
D	8	BE.HOF	Xhoffraix	50.459	6.073	521	0	A	geology	bedrock	Jalhay	-	0
D	8	BE.HOK	Hockay	50.485	5.988	543	0	A	geology	bedrock	La Venne	-	0
D	2	BE.HST	Hauset	50.701	6.064	250	0	A	relative (CLA)	bedrock	Neffe	-	0
D	10	BE.HU1	Humain	50.187	5.243	292	0	A	geology	bedrock	Fromelennes	-	0
D	120	BE.HUM	Humain	50.192	5.255	292	0	A	geology	bedrock	Fromelennes	-	0
D	3	BE.KAN	Kan	50.808	5.691	0	0	B	relative (BEBN)	??	Gulpen	-	0
D	8	BE.KIN	Kinrooi	51.145	5.774	33	0	C	geology	soft	Kiezeloöliet	unk	1069.15
D	62	BE.MEU	Meuville	50.396	5.769	335	0	A	geology	bedrock	Ottré	-	0
D	22	BE.PLT	La Plate Taille	50.192	4.385	215	0	A	geology	bedrock	Senzeille	-	0
D	4	BE.RIG	Rigi	50.512	6.078	671	0	A	relative (MRG)	bedrock	Maastricht	-	0
D	116	BE.ROB	Robertville	50.453	6.109	447	0	A	geology	bedrock	Marteau	-	0
D	6	BE.SOL	Solwaster	50.522	5.958	361	0	A	geology	bedrock	La Gleize	-	0
D	5	BE.SOY	Soye	50.450	4.730	97.5	0	A	geology	bedrock	Coal Measures group	-	0
D	1	BE.SPN	Spienness	50.428	3.997	48	0	A	relative (BEBN)	bedrock	Maastricht	-	0
D	1	BE.VEN	Vencimont	50.034	4.930	270	0	A	geology	bedrock	Mirwart	-	0
D	2	BE.VEV	Veve	50.217	4.990	190	0	A	geology	bedrock	Hastière	-	0
D	92	BE.WIB	Wibrin	50.163	5.724	425	0	A	geology	bedrock	La Roche	-	0
D	35	BE.WOR	Wortegem	50.855	3.506	-105	169	A	geology	bedrock	Oisquercq	-	0
D	10	BE.ZEV	Zevekote	51.137	2.900	2.5	0	C	raydec	soft	Alluvial	0.43	235.32
C	2	BE.BDHN	Bois d'Haine	50.512	4.216	122	-4	B	raydec	soft	Brussels above Lives	2.65	35
C	237	BE.BEBN	Eben-Emael	50.797	5.678	66.18	46.65	A	array, active	soft	Maastricht	-	0
C	14	BE.BOST	Oostende Borehole	51.238	2.939	-301	307.7	A	geology	bedrock	Oisquercq	-	0

C	tbd	BE.BLRG	Blaregnies	50.356	3.898	130	2	A	raydec	bedrock	Burnot	-	0
C	70	BE.BRQ	Bracquegnies	50.483	4.141	60	30.0	A	geology	bedrock	Thulin Marls Formation	-	0
C	184	BE.CLA	Clavier	50.419	5.302	235	0.0	A	array	bedrock	Neffe	-	0
C	282	BE.DOU	Dourbes	50.095	4.595	224	6.0	A	raydec	bedrock	Névremont	-	0
C	31	BE.DSLB	Dessel Borehole	51.232	5.065	-578	601.5	A	well logging	bedrock	Heers	-	0
C	11	BE.DSLS	Dessel Surface	51.232	5.065	22	1.5	C	well logging	soft	Melle Mol?		580.84
C	156	BE.GES	Gesves	50.385	5.087	295	0.1	A	array	bedrock	Ciney	-	0
C	52	BE.HOU	Houvegnez	50.354	6.005	490	4.0	A	raydec	bedrock	La Venne	-	0
C	87	BE.HRK	Herkenbosch	51.188	6.168	72	0	C	geology	soft	unknown	?	unknown
C	190	BE.KLB	Kalborn	50.100	6.109	474	0.0	A	raydec	bedrock	Ourthe	-	0
C	145	BE.LCH	La Chartreuse	50.639	5.599	65	0.0	A	raydec	bedrock	Coal Measures Group	-	0
C	96	BE.LES	Lessines	50.711	3.843	4	0.0	A	raydec	bedrock	Sill de Lessines	-	0
C	2	BE.MEMA	Membach	50.610	6.009	242.6	54.0	A	array	bedrock	Acoz	-	0
C	60	BE.MEMB	Membach	50.609	6.010	244.3	54.0	A	array	bedrock	Acoz	-	0
C	46	BE.MEMH	Membach	50.609	6.010	244	54.0	A	array	bedrock	Acoz	-	0
C	1	BE.MEMP	Membach				54.0	A	array	bedrock	Acoz	-	0
C	228	BE.MEMS	Membach	50.61	6.01	244	54.0	A	array	bedrock	Acoz	-	0
C	18	BE.MOL1	Mol	51.21	5.09	-96	120.9	B	geology	soft	Boom	Vb19	440.55
C	18	BE.MOL2	Mol	51.21	5.09	-198.75	223.65	B	geology	soft	Boom	Vb19	337.8
C	18	BE.MOL3	Mol	51.21	5.09	-196.5	221.4	B	geology	soft	Boom	Vb19	341.43
C	18	BE.MOL4	Mol	51.21	5.09	-198.5	223.4	B	geology	soft	Boom	Vb19	339.43
C	18	BE.MOL5	Mol	51.21	5.09	-198.25	223.15	B	geology	soft	Boom	Vb19	339.68
C	3	BE.MOLA	Mol	51.21	5.09	25	0	C	relative (DSLS)	soft	Melle or Mol?	Vb19	565.27
C	3	BE.MOLB	Mol	51.21	5.09	-198	222.9	B	geology	soft	Boom	Vb19	342.27
C	9	BE.MOLK	Mol	51.22	5.10	25	0	C	relative (DSLS)	soft	Melle or Mol?	Vb19	571.42
C	11	BE.MOLS	Mol	51.21	5.08	25	0.0	C	raydec	soft	Melle Mol?	0.26	560.95
C	49	BE.MOLT	Mol	51.21	5.09	-198	223.4	B	raydec	soft	Boom	Vb19	339.93
C	104	BE.MRD	Maredsous	50.30	4.77	215	1.1	A	raydec	bedrock	Neffe	-	0
C	36	BE.MRG	Mont Rigi	50.51	6.07	674	1.2	A	raydec	bedrock	Maastricht	-	0
C	31	BE.OPT	Opitter	51.11	5.64	51	2.4	C	array	soft	Bolderberg	0.28	355.81
C	18	BE.OPTB	Opitter Borehole	51.11	5.64	-328	381.4	A	array	bedrock	Heers	-	0
C	10	BE.OSP	Ospel	51.33	5.82	29	29	C	geology	soft	unknown	?	unknown
C	149	BE.RCHB	Rochefort Borehole	50.16	5.23	182	43.0	A	raydec	bedrock	Fromelennes	-	0
C	173	BE.RQR	Ronquières	50.61	4.22	35	25.0	A	array	bedrock	Brutia	-	0
C	161	BE.SKQ	Steenkerque	50.65	4.08	63	-0.5	A	array	bedrock	Steenkerque	-	0
C	228	BE.SNF	Seneffe	50.51	4.28	108	12.6	A	active	bedrock	Lives	-	0
C	222	BE.STI	Sart Tilmann	50.58	5.56	223	17.0	A	geology	bedrock	Burnot	-	0
C	8	BE.TGA	Tangissart	50.60	4.52	97	0.0	A	active	bedrock	Mousty	-	0
C	28	BE.TNL	Ternell	50.59	6.13	505	0.0	A	raydec	bedrock	Maastricht	24.63	<10

C	74	BE.UCCB	Uccle Borehole	50.80	4.36	#REF!	141.0	A	array	bedrock	Tubize	-	0
C	50	BE.UCCS	Uccle Surface	50.80	4.36	105	4	B	array	soft	Lede	0.9	114
C	153	BE.VIA	Vianden	49.94	6.20	252	12	A	raydec	bedrock	Our	-	0
C	238	BE.WLF	Walfordange	49.66	6.15	295	~80	A	raydec	bedrock	Gypsum	-	0
A	1	BE.ANSA	Ans	50.67	5.51	180	0	B	relative (BEBN)	soft	Maastricht	2.72	??
A	2	BE.BREA	Bree	51.14	5.60	34	0	C	geology	soft	Kiezeloöliet	0.29	666.29
A	1	BE.CLHA	Chapelle-Lez-Herlaimont	50.47	4.28	170	0	B	relative (f0)	soft	Brussel	1.84	unknown
A	1	BE.KINA	Kinrooi	51.14	5.77	33	0	C	geology	soft	Kiezeloöliet	0.23	1069.15
A	1	BE.LCHA	La Chartreuse	50.64	5.60	65	17	A	raydec	bedrock	Coal Measures group	-	0
A	1	BE.LLVA	La Louvière	50.48	4.18	130	0	A	relative (f0)	soft	Kortrijk	1.79	~34±3.4
A	3	BE.MASA	Maaseik	51.10	5.79	33	0	C	geology	soft	Alluvial above Burnot	0.22	1048.05
A	1	BE.MONA	Mons	50.45	3.95	30	0	C	geology	soft	Kortrijk above Obourg	1.56	~43±4.3
A	1	BE.MRCA	Marcinelle	50.39	4.45	125	0	A	geology	bedrock	Coal Measures group	-	0
A	1	BE.STIA	Sart Tilman	50.59	5.56	245	-5	A	relative (f0)	bedrock	Sables Argiles Oligocène above Burnot	31	~1
A	1	BE.STNA	Saint-Nicolas	50.63	5.54	130	20	A	geology	bedrock	Vaals	-	0
A	1	BE.STTA	Strepy-Thieu	50.48	4.11	112	0	A	relative (f0)	bedrock	Thulin Marls Formation	26.4	0
A	1	BE.STWA	Sainte-Walburge	50.66	5.57	200	0	A	geology	bedrock	Gulpen	2.58	unk
A	2	BE.THEA	Theux	50.49	5.79	290	0	A	geology	bedrock	Pépinster	-	0
A	8	BE.UCCA	Uccle	50.80	4.36	105	0	B	array	soft	Lede	0.9	119.7

ANNEX 2 – PARTICIPATION OF EPOS-BE TO EPOS-RELATED MEETINGS

Assemblies, symposia, conferences

- SERA site characterization workshop, 09-12/03/2019
- EGU, 08-12/04/2019, Vienna, Austria
- EUREF Symposium, 22-24/05/2019, Tallin, Estonia
- EPOS Services for Solid Earth Science, 26/09/2019, Madrid, Spain
- EPOS practical solutions to Data Interoperability & FAIRness, 27/09/2019, Madrid, Spain
- EUREF Analysis Centres Workshop, 17-18/10/2019, Warsaw, Poland
- EGU General Assembly 2020, 04-08/05/2020, virtual
- EPOS-GNSS webinar,18-19/01/2021, virtual
- EPOS SP workshop, 25/03/2021, virtual
- EGU General Assembly, 26-30/04/2021, virtual
- EUREF symposium, 26-28/05/2021, virtual
- 7th International Geologica Belgica Meeting, 17/09/2021, Tervuren, Belgium.
- 37th ESC conference, 23/09/2021, virtual
- EPOS policy workshop, 24/11/2021, virtual
- EPOS workshop on Ethics, 07/04/2022, virtual
- EPOS-GNSS technical workshop, 05-06/05/2022, virtual
- EGU General Assembly, 23-27/05/2022, virtual
- EUREF symposium, 01-03/06/2022, virtual
- EPOS SP workshop, 21-23/06/2022, virtual
- 3ECEES, 04-09/09/2022, Bucharest, Romania
- Geo-INQUIRE kick-off meeting: 04-05/10/2022, virtual
- REFAG "Reference Frames for Applications in Geosciences"symposium, 17-20/10/2022, Thessaloniki, Greece
- EPOS ERIC General Assembly, 13-14/12/2022, virtual

Commissions, working group meetings

- EPOS-IP Project Development Board task force, 14-15/03/2019, Kopenhagen, Denmark
- EPOS-IP Project Development Board, 11/04/2019, Vienna, Austria
- EPOS-GNSS Thematic Core Service, 24/09/2019, Madrid, Spain
- EPOS Project Development Board, 25/09/2019, Madrid, Spain
- EPOS-IP, Implementation Phase Council, 25/09/2019, Madrid, Spain
- ORFEUS Workshop, Grenoble, 7-11/10/2019
- EPOS-IP Final Review, 05-06/11/2019, Brussels, Belgium
- EPOS-GNSS Consortium Board, 30/01/2020, virtual
- EPOS-SP Kick-off, 10-12/02/2020, Brussels, Belgium
- EPOS Service Coordination Committee, 10 & 12/02/2020, Brussels, Belgium
- EPOS-GNSS Executive Board, 17/02/2020, 08/04/2020, 10/09/2020, 22/10/2020, 04/12/2020, virtual
- EPOS Service Coordination Committee, 10/03/2020, 20/04/2020, 30/04/2020, 25/05/2020, 28/05/2020, virtual
- CzechGeo/EPOS Scientific Advisory Board, 20/03/2020, virtual
- ORFEUS board of directors, 04/06/2020, virtual
- EPOS User Value Board, 08/06/2020, virtual
- EPOS-GNSS Consortium Board, 26/06/2020, 27/10/2020, virtual
- EPOS Service Coordination Committee, 17/09/2020, 06/11/2020, 02/12/2020, virtual
- ORFEUS board of directors, 09/11/2020, virtual

- EPOS User Value Board, 24/11/2020, virtual
- EPOS-GNSS Executive Board, 13/01/2021, 23/02/2021, 07/04/2021, 22/06/2021, 10/09/2021, 22/10/2021, 09/12/2021, virtual
- EPOS ICS-TCS Authorization meeting, 15/01/2021, virtual
- EPOS-GNSS webinar, 18-19/01/2021, virtual
- EPOS SP WP3 meeting, 15/02/2021, virtual
- ORFEUS vMEETING, 12/11/2021, virtual
- EPOS Service Coordination Committee, 24/02/2021, 26/05/2021, 11/06/2021, 22/10/2021, virtual
- ORFEUS board of directors, 21/02/2021
- EPOS-SP Project Council, 17/03/2021, virtual
- EPOS-GNSS Consortium Board, 26/04/2021, virtual
- EPOS-SP WP 3 meeting, 09/09/2021, virtual
- EPOS-SP WP 4 meeting, 14/09/2021, virtual
- EPOS TCS-ICS meeting, 15/09/2021, 19/11/2021, 06/12/2021, virtual
- EPOS-BE follow-up committee, 26/11/2021, virtual
- EPOS ERIC Implementation Rules working group, 03/12/2021, virtual
- EPOS-SP User value meeting, 03/12/2021, virtual
- EPOS-GNSS Executive Board, 14/01/2022, 09/03/2022, 19/04/2022, 02/09/2022, 25/10/2022, all virtual
- ORFEUS board of directors 21/02/2022
- EPOS-GNSS Consortium Board, 04/03/2022, virtual
- EPOS-GNSS Consortium Board, 29-30/09/202, Lisbon, Portugal
- EPOS Service Coordination Committee, 09/02/2022, 26/04/2022, 09/06/2022, all virtual
- ORFEUS meeting, Potsdam, Germany, 06-07/03/2022
- EPOS Service Coordination Committee, 21-22/10/2022, Rome, Italy
- EPOS ERIC Implementation Rules working group, 14/01/2022, 23/03/2022, 17/05/2022, 16/09/2022, 13/10/2022, 18/11/2022, all virtual
- EPOS ICS-TCS meeting, 06/01/2022, 14/01/2022, 16/01/2022, all virtual
- EPOS-SP Project Council, 21/06/2022, virtual
- ORFEUS board of directors 18/11/2022, virtual
- EPOS-BE Follow-up Committee, 06/12/2022, virtual
- ORFEUS board of directors, De Bilt, Utrecht, The Netherlands, 08-09/02/2023
- ORFEUS board of directors 14/07/2023