REPORT
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FINNSIP—The mobile Finnish Seismic Instrument Pool

Gregor Hillers * [1], **Emilia Koivisto** [2], **Päivi Haapanala** [1,10], **Ilmo Kukkonen** [2], **Roméo Courbis** [1], **Yinshuai Ding** [2], **Thomas Fordell** [3], **Suvi Heinonen** [4,11], **Niina Junno** [1], **Anssi Juntunen** [1], **Kari Komminaho** [1], **Elena Kozlovskaya** [5], **Jussi Leveinen** [6], **Kari Moisio** [5], **Jyri Näränen** [7], **Tahvo Oksanen** [1], **Piettari Skyttä** [8,12], **Eija Tanskanen** [9], **Timo Tiira** [1]

[1]Institute of Seismology, Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland, [2]Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland, [3]VTT Technical Research Center of Finland Ltd., National Metrology Institute VTT MIKES, Espoo, Finland, [4]Geologian tutkimuskeskus GTK–Geological Survey of Finland, Espoo, Finland, [5]Oulu Mining School, Faculty of Technology, University of Oulu, Oulu, Finland, [6]Department of Civil Engineering, Aalto University, Espoo, Finland, [7]Department of Geodesy and Geodynamics, Finnish Geospatial Research Institute FGI, National Land Survey of Finland, Espoo, Finland, [8]Department of Geography and Geology, University of Turku, Turku, Finland, [9]Sodankylä Geophysical Observatory, University of Oulu, Sodankylä, Finland, [10]now at Research Infrastructure Services, Natural Resources Institute Finland, Helsinki, Finland, [11]now at Institute of Seismology, Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland, [12]now at Structural Geology Company, Turku, Finland

Author contributions: *Conceptualization*: T. Fordell, S. Heinonen, G. Hillers, E. Koivisto, E. Kozlovskaya, I. Kukkonen, J. Leveinen, K. Moisio, J. Näränen, P. Skyttä, E. Tanskanen, T. Tiira. *Writing - original draft*: G. Hillers, P. Haapanala. *Writing - review & editing*: E. Koivisto, S. Heinonen, I. Kukkonen, E. Kozlovskaya, J. Leveinen, P. Skyttä. *Visualization*: R. Courbis, N. Junno, G. Hillers. *Project administration*: R. Courbis, Y. Ding, P. Haapanala, G. Hillers, N. Junno, A. Juntunen, E. Koivisto, K. Komminaho, I. Kukkonen, T. Oksanen. *Funding acquisition*: T. Fordell, S. Heinonen, N. Junno, E. Koivisto, E. Kozlovskaya, I. Kukkonen, J. Leveinen, J. Näränen, P. Skyttä, E. Tanskanen, T. Tiira.

Abstract We report on establishing the mobile Finnish Seismic Instrument Pool (FINNSIP) that is owned and operated by Finnish academic and research institutions. The pool supports domestic and international collaborative seismic research. At the conclusion of the 2020 to 2024 build-up stage, the instrumentation includes 46 broadband seismometers and digitizers, 5 accelerometers, and 1216 and 71 Geospace and Smart-Solo autonomous geophone units, respectively, making FINNSIP one of the largest and most coherent mobile seismic instrument pools in Europe in the public sector. We explain the utilization of the pool instruments and discuss the equipment, facilities, ownership and governance structure, fees, and the management and support system. Through Finland's membership in the Observatories and Research Facilities for European Seismology (ORFEUS) and the Finnish European Plate Observing System (EPOS) node, FINNSIP endorses and implements international data management standards and best practices as promoted in Europe. The importance of appropriate data and computing systems is highlighted by the $\sim$90 TB volume of formatted data that has been collected in 25 large-N projects between October 2021 and December 2024. We summarize a checklist for building, operating, and managing this extensive seismic pool that can inform the planning and establishment of other research infrastructure.

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1 Introduction

Research infrastructure is the foundation for doing science. It includes the large range of devices from the theoretician's proverbial pencil-and-paper to the iconic machines schemed by physicists and engineers to peek at the very smallest and largest structures of the universe. It also includes the research institutions and agencies, the administrative apparatuses, and the data management and dissemination systems that are essential to turn the collected data into knowledge. Research infrastructure can be critical in facilitating scientific innovation, collaboration, recruitment, and education, and it can play an influential role for the faring of economies.

Progress in our understanding of dynamic subsurface processes and our ability to resolve earth structure and its evolution is governed to a large degree by observations. The essential infrastructure for seismic research and exploration are permanent networks and portable deployments of standardized seismic equipment to sample the ground motion in space and time as well as waveform sharing protocols (Jiao and Alavi, 2020; Arrowsmith et al., 2022). Classically, this involves three-component (3C) seismometers and one- and three-component short-period geophones that record the translational wave motion. For decades, the single seismic sensor or a relatively sparse network defined the standard in seismological observatory practice, and seismologists have learned to tease out remarkably detailed information from single station data (Herrmann et al., 2019; Ceylan et al., 2023). Academic research institutions and governmental research agencies engaged with geoscience-related tasks operate pools of dozens or perhaps a few hundred short period instruments, but these pools are dwarfed in comparison to the resources applied by exploration seismology industry with its tens or hundreds of thousands of channels for on- and offshore seismic reflection surveys. However, the advent

*Corresponding author: gregor.hillers@helsinki.fi

of more powerful and efficient data storage, transmission, and computing systems, progress in the theoretical understanding of the seismic wavefield properties coupled with the development of new types of analysis techniques and algorithms, and the manufacturing of sensitive, affordable sensor systems has led to an evolution in the data acquisition styles of the public sector (Hand, 2014). Modern seismological and seismic land-based surveys now approach previously unattainable dense industry style-like deployments.

This trend can perhaps be traced back to the legacy of the 1995 Kobe, Japan, earthquake, that resulted in the dense permanent instrumentation of the Japan archipelago (Beroza, 2010), around the same time when the first rolling deployment on a continental scale was realized (van der Hilst et al., 1994). These examples have since been emulated, e.g., with the USArray (IRIS Transportable Array, 2003), AlpArray (AlpArray Seismic Network, 2015), IberArray (Institute Earth Sciences "Jaume Almera" CSIC (ICTJA Spain), 2007), AdriaArray (Friederich et al., 2022), ChinArray (Zeng et al., 2020), and their likes. At smaller scales, numerous public institutions-run or collaborative dense array projects have been completed since the first influential demonstrations supported by private sector agents (Lin et al., 2013; Ben-Zion et al., 2015; Karplus and Schmandt, 2018). Seismic arrays are no longer exclusively antennas carefully tuned for estimating the local wave propagation properties of coherent signals (Havskov and Ottemöller, 2010; Kennett et al., 2015). Today, large-N or nodal arrays can be spatially dense brute-force samplers of the seismic wavefield that can number into the thousands of quality instruments. Arrays can have a large range of layouts, from regularly organized 1D or 2D grids to those with variable size, shape, and station densities optimized for a specific data acquisition target (Mordret and Grushin, 2024), although a degree of uniformity typically produces well behaved data sets (Arrowsmith et al., 2022). Parallel developments for a more complete and denser seismic wavefield sampling include rotational sensors and six-degrees-of-freedom sensors (Sollberger et al., 2020; Bernauer et al., 2021), distributed acoustic sensing technologies (Jousset et al., 2018; Wang et al., 2020; Lindsey and Martin, 2021), the distribution of community sensors such as the RaspberryShake system (Anthony et al., 2018), or the collection of mobile phone acceleration data for strong-motion transients (Kong et al., 2016). Together with efficient harvesting and sharing protocols, innovative computing approaches, and machine learning algorithms, these new large volume data sets have led to the emergent Big Data Seismology paradigm (Arrowsmith et al., 2022). The associated increased gain in sensitivity and resolution continues to advance our basic understanding of wavefield properties, excitation mechanisms, and 4D earth structure.

Despite these promising developments, access to the quantity of seismic sensors needed for large-N deployments is not pervasive. Even in developed countries it is challenging for a single institution to acquire and maintain a sufficiently large pool of instruments that can be deployed temporarily, as opposed to the equipment dedicated to permanently installed national or international monitoring networks. A few European organizations maintain instrument pools for collaborative research purposes outside of the organization, similar to the PASSCAL shared instrument pool in the U.S. (Aster et al., 2005). Examples include the German Geophysical Instrument Pool Potsdam GIPP (Haberland and Ritter, 2016), established in 1993 and headquartered at the GFZ German Research Centre for Geosciences Potsdam, the British SEIS-UK (2001, University of Leicester), the French Ocean Bottom Seismometer Park (2001, National Institute of Sciences of the Universe–Institut de physique du globe de Paris) and EPOS France-Sismob (2002, University Grenoble-Alpes), and the Spanish LabSis (2015, GeoSciences Barcelona–Spanish National Research Council). Between these five, the number and types of instruments, the funding and governance, data management, and staff situation is rather diverse, and not systematically correlated. To develop and integrate pool operations, this group is collaborating towards the establishment of a new ORFEUS Service Management Committee for European mobile pools (Observatories and for European Seismology ORFEUS, 2025).

The Finnish seismic infrastructure consists of the permanent Finnish National Seismic Network (Institute of Seismology, 1980) for the general seismic monitoring in the country (Veikkolainen et al., 2021). The infrastructure further includes the primary seismic station or array FINES PS17 of the Comprehensive Nuclear-Test-Ban Treaty Organization–CTBTO International Monitoring System, and scattered local collections of tens of geophones, broadband instruments, and accelerometers, in addition to active seismic equipment for small surveys and educational deployments. For deployments that exceed the domestic capacities, Finland's geophysicists relied on seismic sensors from the Polish Academy of Science, the German Geophysical Instrument Pool, or other external suppliers or collaborators.

In response to the growing societal need for improved geoscience expertise, the Finnish community teamed up to boost the domestic geophysical infrastructure. Here we discuss the establishment of the mobile Finnish Seismic Instrument Pool FINNSIP, an extensive state-of-the-art pool of mobile seismic instruments run by Finnish universities and research organizations. The FINNSIP equipment is owned and collectively maintained by five FINNSIP consortium partners: Aalto University, the Geological Survey of Finland (Geologian tutkimuskeskus) GTK, and the Universities of Helsinki, Oulu, and Turku. FINNSIP was created to serve the diverse interests, mandates, applications, and goals of the involved institutions and their associated collaborators, stakeholders, and clients. Domestic and international collaboration is supported, however, it is mandatory that at least one FINNSIP consortium partner is involved in the project.

The pool was built between 2020 and 2024. The Research Council of Finland supported the project from 2020, and the first instruments and services for seismic experiments were provided by FINNSIP in the fall of 2021. At the end of the build-up period in 2024 the

Sensor	Quantity	Recorder and equipment	Data retrieval	Comments	Owner
Güralp 3ESPC broadbands	46	46 Minimus digitizer, 10 m GNSS cable	Continuous data transmission, copying data from Minimus 128 GB SD card	Digitizer can be used with range of sensors	U Helsinki
Güralp Fortis accelerometer	5				
Geospace large-N Land Cartesian 5 Hz geophones	1216	2 time stamp recorders, 12 line health recorders and 3 tablet PCs, 2 line viewers, 2 field notebooks for configuration and data retrieval, 30 BN25 & 120 BN32 batteries, 3 battery charging bays, 250 free battery connectors	Data download in Helsinki lab (6x48 slot racks), 24- and 48-slot field racks available	1166 GSBs with internal battery, 50 GSX3-LTE for wireless transfer, limited field data retrieval and battery charging	Aalto U, GTK, U Helsinki, U Turku, U Oulu
SmartSolo IGU-16HR 5 Hz geophones	71	16 dedicated All-In-One data exchange units, 2 field servers, 16-slot box for battery charging	User based download using dedicated All-In-One data exchange units	Limited user support	GTK

Table 1 FINNSIP equipment overview.

pool consists of 46 Güralp 3ESPC Compact broadband seismic instruments and digitizers, 5 Fortis accelerometers, and 1229 and 71 stand-alone three-component (3C) short-period Geospace and SmartSolo geophone systems, respectively, in addition to data management, computing, and other support systems. The equipment supports controlled source seismic surveys, earthquake seismology, and ambient seismic field studies. Battery life, digitizer versatility, and data storage capacity support diverse deployment styles and durations.

The goal of this paper, following the key recommendations of the ORFEUS Initiative of European Mobile Seismic Instrument Pools (Observatories and for European Seismology ORFEUS, 2025), is to highlight the FINNSIP research infrastructure and to give details about instrument capabilities and availability to researchers. We discuss the equipment in Section 2 and the management and governance structure in Section 3, where we also provide a more detailed overview of the five FINNSIP consortium partner organizations and their expertise. Section 4 discusses elements of our method of operation that are relevant for users and collaborators. In Section 5, we compile essential lessons learned during the build-up period that started in 2020. We conclude in Section 6 with nine suggestions for building, maintaining, and running a mobile seismic instrument pool that can be informative for other communities that consider engaging in similar infrastructure projects.

2 The FINNSIP infrastructure

The FINNSIP webpage - https://finnsip.fi - is the reference point for the interaction with the infrastructure. It provides information about the application process and the instrumentation, collects essential documents including the principles of operation, reservation calendars, and manuals and tutorials, and supplies contact information to the pool management team and to the involved institutions and representatives.

2.1 Seismic instrumentation

The choice of instrumentation (Table 1, Figure 1) was determined to offer the best performance for the diverse acquisition styles ranging from active source near-surface applications and cryosphere research over passive imaging and monitoring to structural analysis.

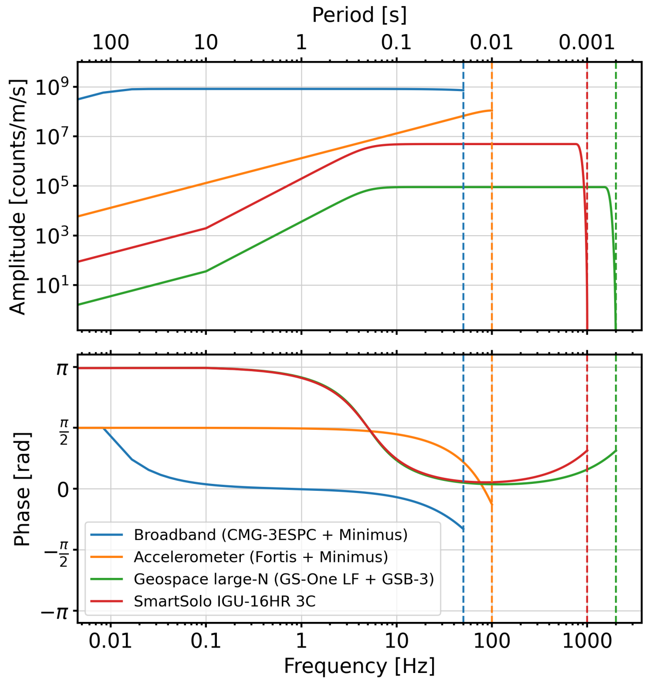

Figure 1 Instrument responses. Dashed lines indicate the Nyquist frequency. The responses for the SmartSolo IGU-16HR 3C and the Geospace GSB-3 recorder plus the GS-One LF sensor are very similar. To enhance the clarity of the figure we show the instrument responses for different parameters. For the SmartSolo IGU-16HR 3C we set a preamplifier gain of $36\,\mathrm{dB}$, a sampling rate of $2\,\mathrm{kHz}$, a linear phase filter, and the DC filter is turned off. For the Geospace GSB-3 and GS-One LF instruments, we use a preamplifier gain of $0\,\mathrm{dB}$, a sampling rate of $4\,\mathrm{kHz}$, a linear phase filter, and the DC filter is turned off.

2.1.1 Güralp broadband sensors

The tendering process resulted in Güralp 3ESPC Compact broadband three-axis, analogue, force-feedback seismometers with a $120\,\mathrm{s}$ natural period (Figures 1, 2a). The $8.4\,\mathrm{kg}$ seismometer is connected with a $5\,\mathrm{m}$ long rigid cable to a 24-bit 4 channel Güralp Minimus digitizer (Figure 2c) that supports a maximum $5\,\mathrm{kHz}$ sample rate. The compact digitizer is equipped with a $128\,\mathrm{GB}$ microSD card, and a second microSD card facilitates hot data storage swaps. A Global Navigation Satellite System (GNSS) antenna is connected to a $10\,\mathrm{m}$ cable (Figure 2e). An instrument is contained and can be shipped in manufacturer provided upright $40\,\mathrm{cm} \times 38\,\mathrm{cm} \times 60\,\mathrm{cm}$ boxes (Figure 2j). The power supply of the broadband instruments is organized by each project individually. The Güralp instrumentation includes a power cable for a connection to the grid (Figure 2h). The available cabling (Figure 2g) can be used for connections to solar panels, but FINNSIP does not supply solar panels. FINNSIP hosts 46 $22\,\mathrm{kg}$, $12\,\mathrm{V}$, $70\,\mathrm{A\,h}$ rechargeable gel batteries (Figure 2i) that can power a broadband system for approximately one month at moderate temperatures. The purchase of the 46 broadband systems was completed in 2022.

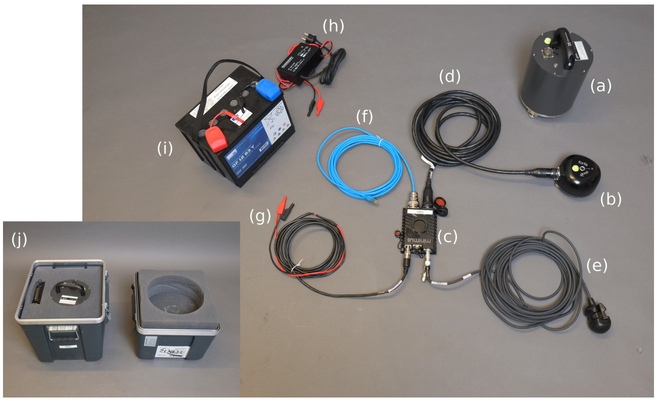

Figure 2 Broadband and accelerometer equipment. (a) Güralp 3ESPC Compact broadband seismometer. (b) Güralp Fortis accelerometer. (c) Güralp Minimus digitizer. (d) $5\,\mathrm{m}$ long instrument-digitizer connector cable. (e) $10\,\mathrm{m}$ long GNSS antenna cable. (f) Digitizer ethernet connection. (g) Power supply connector. (h) Power plug. (i) External battery with connectors. (j) Storage and transportation box for the broadband sensor, digitizer, and cable.

2.1.2 Fortis accelerometers

The FINNSIP pool includes five $1.1\,\mathrm{kg}$ triaxial orthogonal Güralp Fortis accelerometers (Figures 1, 2b). Like the broadband sensor, the accelerometer operates in connection with the Güralp Minimus digitizer. The gain can be set to 0.5, 1, 2, or $4.0\,\mathrm{g}$. The standard acceleration output band is DC-to-$100\,\mathrm{Hz}$ and can be extended to $200\,\mathrm{Hz}$.

2.1.3 Geospace geophones

For the short-period large-N instruments, the consortium chose a Geospace solution consisting of $5\,\mathrm{Hz}$ 3C Land Cartesian GS-One LF geophones coupled to GSB-3 seismic recorders with 24-bit resolution, an internal battery, and a $64\,\mathrm{GB}$ solid-state flash memory (Figures 1, 3a, 3b). The GSB recorders are switched on and off by executing a specific turning pattern. Sample-interval options are 0.25, 0.5, 1, 2, $4\,\mathrm{ms}$ equal to 4, 2, 1, 0.5, $0.25\,\mathrm{kHz}$ rates, respectively. The pre-amplifier gain can be set in the range between $0\,\mathrm{dB}$ and $36\,\mathrm{dB}$. The geophone unit and the recorder weigh $1.3\,\mathrm{kg}$ and $1.0\,\mathrm{kg}$, respectively. From 2021 to 2024, the cumulative number of FINNSIP GSB-3 systems increased from 657 to 1166. The support products include two Geospace SDRX time stamp or source decoder recorders (Figure 3c), and 250 battery cables with a Mueller clip for universal external battery fit (Figure 3b). The equipment includes 12 GSB line health recorders (LHR) for GSB status verification and collecting QC data on system functions (Figure 3c), but there is no real-time data viewing ability. The geophones can record continuously or for a user-specified set time interval during the day. Shot and receiver gather data for controlled seismic surveys are extracted from the continuous records based on the time stamps of the sources.

The LHRs come in tandem with one GSB line viewer which allows the user to view the line health data in the field with a laptop PC (Figure 3f). The LHR data can also be accessed in real time in the field using an Android app on a mobile phone or tablet PC. FINNSIP provides three tablet PCs, but the user can also arrange for their own devices. The downloading and charging racks (Figure 3e) described below are part of the workshop or lab facilities at the University of Helsinki and should be deployed to field campaigns only in exceptional cases. The GSB seismic recorders need to be connected to the racks and the server to be programmed and configured prior to sending them to the field. Typically, the data is downloaded and further data products, e.g., shot gathers for active seismic surveys, are extracted after the recorders

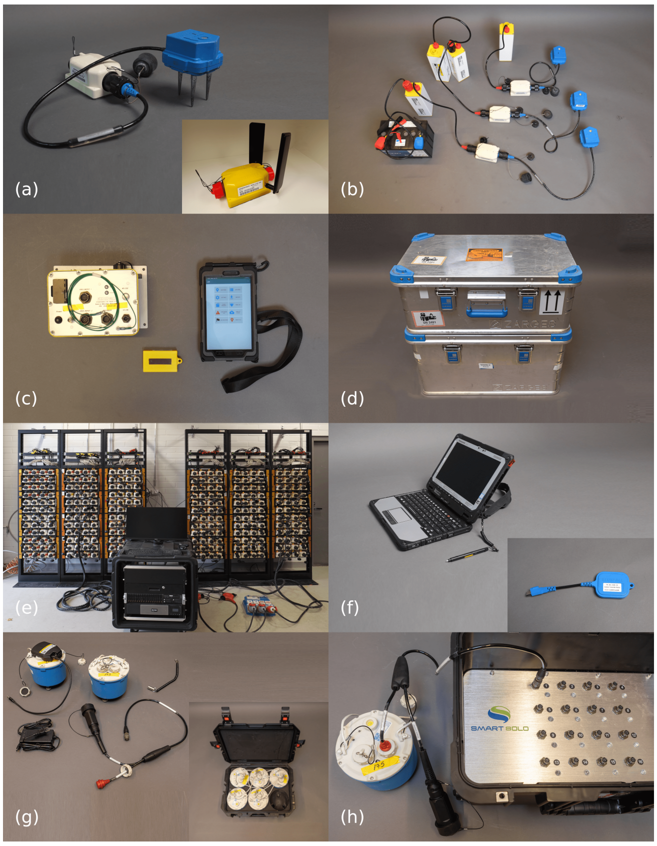

Figure 3 Large-N instrumentation, data exchange and processing equipment, and SmartSolo equipment. (a) Geospace $5\,\mathrm{Hz}$ 3C Land Cartesian GS-One LF geophone and GSB-3 seismic recorder. The inset shows the GSX3-LTE (renamed to GSX3-C) recorder with cellular network access. (b) Three acquisition configurations with one (top) or two (center, bottom) external battery solutions. (c) From left to right, source decoder, line health recorder, and tablet PC with line health viewer app. (d) Storage and transportation boxes for 16 GSB recorders (top) and 16 geophones (bottom). (e) Downloading, charging, and configuration racks for $6{\times}4{\times}12{=}288$ GSB recorders. The unit in the front contains the Geospace GeoRes-XTC system manager server. (f) Laptop field server with line health data receiver in the inset. (g) Clockwise from the upper left: SmartSolo three-component $5\,\mathrm{Hz}$ geophone with black Single Port Dedicated All-In-One (AIO) data exchange unit, $5\,\mathrm{Hz}$ geophone without the AIO unit, magnet to switch the units on and off, connector, power plug, storage and transportation box in the inset. (h) Geophone connected to one of 16 slots in the battery charging box.

return to the FINNSIP lab facility. We discuss the mobile solutions for limited on-site configuration, charging, and data retrieval using field racks and field servers in Section 4.3.2.

The internal batteries of the GSB units support 40 days continuous recording at an optimal $23\,°C$, but the capacity decreases significantly below $0\,°C$. We have 30 external Geospace BN25 lithium batteries (Figure 3b) and 120 BN32 batteries that can extend the acquisition of one unit for additional 180 days and 200 days, respectively. One battery weighs $4\,kg$. The batteries can be deployed in series for extended power supply. We have three 12-unit portable battery chargers. Our $60\,cm \times 38\,cm \times 34\,cm$ storage and transportation aluminum boxes contain 16 $5\,Hz$ geophones, and the $60\,cm \times 38\,cm \times 24\,cm$ boxes contain 16 GSB recorders (Figure 3d). We CAD (Computer Aided Design) modeled and cut the foam molds for the GSB boxes. With the $5\,kg$ weight of an aluminum box, a packed sensor and recorder box weighs approximately $23\,kg$ and $21\,kg$, respectively.

In 2024, the pool integrated 50 University of Oulu-owned Geospace systems with the recorder model GSX3-LTE (renamed to GSX3-C), resulting in a pool-total of 1216 Geospace geophone units. In comparison to the standard large-N GSB recorder, the GSX3-LTE design includes a modem for cellular network access instead of an internal battery (Figure 3a). This allows wireless data transfer using a Subscriber Identity Module or SIM card that is purchased from a Finnish mobile phone company. The units are exclusively powered by the external batteries. The University of Oulu explores and develops methods for wireless seismic data transmission over the cellular network to support real-time monitoring.

2.1.4 SmartSolo geophones

In 2023 GTK purchased 71 SmartSolo three-component IGU-16HR AIO (All-In-One) 5 Hz geophones (Figures 1, 3). The internal recorder operates with 32-bit ADC resolution. A Bluetooth communication function allows users to collect battery and GNSS status and acquisition parameters in real time using an app on a mobile phone or tablet PC, and to display seismic waveform data. An instrument weighs $2.8\,kg$, has $64\,GB$ data storage, and can operate 40 days continuously or 80 days in an intermittent 12-hour mode. The internal power supply can be extended by external power sources using the provided charging connectors. Supported sample intervals are 0.25, 0.5, 1, 2, 4, 8, 10, and $20\,ms$ equal to 4, 2, 1, 0.5, 0.25, 0.125, 0.1, and $0.05\,kHz$ rates, respectively. The pre-amplifier gain can be set in the range between $0\,dB$ and $36\,dB$. A small magnetic key is used to switch the instruments on and off (Figure 3g). A 16-slot box is used to charge the internal battery (Figure 3h). A so-called Single Port Dedicated AIO (All-In-One) device (Figure 3g) is connected through a multiple-slot USB (universal serial bus) hub to a laptop for configuration and data reaping. FINNSIP has two laptops and 16 AIOs to facilitate data download. We have 12 boxes for transportation and storage (Figure 3g). One box can hold six instruments. Loaded, the $63\,cm \times 50\,cm \times 37\,cm$ boxes weigh $21\,kg$. GTK does not supply fully configured instruments to clients, therefore, no mobilization fees are collected, but users are provided instructions for proper system operation.

2.2 Data management

FINNSIP does not support project data management for data collected with the broadband and accelerometer instruments, nor with the SmartSolo devices. Two laptops with $1\,TB$ large solid state drives together with the AIO units allow the user to manage the SmartSolo data independently.

For the large-N pool, the FINNSIP lab is equipped with six wall racks that hold 48 GSB bays each to download data, recharge or drain batteries, and configure acquisition parameters (Figure 3e). These mounted installations are complemented by two mobile GSB portable data transfer and charger modules with 48 and 24 bays, respectively. Mobile options are discussed in Section 4.3.2. The data from the modules are transferred to a Geospace GeoRes-XTC system manager server with 40 $3.1\,GHz$ cores, $128\,GB$ random-access memory, two $512\,GB$ large solid state drives, and $60\,TB$ storage capacity. The large-N operations depend critically on this system. As backup and support we have a tower computer with $60\,TB$ storage capacity. The rack and GeoRes-XTC system can process up to 288 GSBs simultaneously. The integrated GSB data management software can be used to collect, quality control, and store the GSB memory data, and to extract survey data products and export data in SEG-D, SEG-Y, SEED, and miniSEED format. This solution is sufficient to manage the quality control and first processing tasks. The download speed depends on the local network speed between racks and server and the hard drive writing speed. For our configuration we achieve an average download speed of $150\,MB/s$. A $500\,Hz$ sampled 24-hour long data segment of a 3C unit can be downloaded and written in miniSEED format in about $4\,s$.

To improve the intermittent data storage and backup solution based on external hard drives we purchased resources from the University of Helsinki IT4Science DataCloud service that are connected via a fiber optic line to the FINNSIP lab facility. This outsources the data storage maintenance to the local IT4Science service. The access to the $50\,TB$ storage portal will be available for five years, it can be extended, but it is not a permanently funded solution. Clients can access their data sets through the DataCloud portal.

The challenge to establish an efficient data transmission and processing workflow for large-N array data is characteristic for the Big Data Seismology framework (Arrowsmith et al., 2022). The integration into established High Performance Computing centers such as the Finnish IT Center for Science Ltd CSC may not be optimal considering the specific architectural needs of high-throughput algorithms including machine learning approaches for detection, feature extraction, seismicity analysis, and correlation techniques and other high-resolution imaging approaches (Arrowsmith et al., 2022). An exclusive reliance on cloud computing solutions (Krauss et al., 2023) raises concerns about its sustainability, and about controlling the data and the compliance with FAIR principles (Wilkinson et al., 2016). FINNSIP has not converged to a community solution that integrates computational infrastructure, data processing, distribution, and archiving. Best practices, including software tools, for efficient data management for mobile pools are envisioned to be developed in collaboration with other European seismic pool infrastructures.

All data are collected within the framework of the national FIN-EPOS and international EPOS infrastructures (Haslinger et al., 2022). The FINNSIP community adopts the EPOS data policy and FAIR principles (Wilkinson et al., 2016). Each client is responsible for the FAIR project data management including formatting, dissemination, and archiving, unless otherwise agreed, and unless a robust community solution is established that can potentially include a Finnish EIDA node (Datacenters of the European Integrated Data Archive. Strollo et al., 2021). All projects produce open metadata and data under an open data license such as CC:BY. Metadata should be published in a repository relevant to the field of study. The quality-checked experimental time series data are expected to be accessible after an optional embargo period of three years that starts at the end of an acquisition, when the dataset is available to the project. After this the data should be open, yet data with commercial interest may require an access fee. Fees have to be negotiated individually for commercial projects and differ between the involved FINNSIP partners.

2.3 The FINNSIP facilities

The consortium partners agreed that the University of Helsinki is the primary hosting organization of the FINNSIP instruments. The 46 broadband instruments and 5 accelerometers are kept in the laboratory space of the Institute of Seismology in the Exactum building of the University of Helsinki Kumpula science campus. The large-N short period instruments, including the 50 GSX3-LTEs after 2025, are stored in a specifically renovated lab space with convenient street-level access in the adjacent Physicum building on the same campus. The renovation included an upgrade of the fire safety situation considering the high density of potentially hazardous lithium batteries in the facility. The floor space is approximately $36\,\mathrm{m}^2$. One wall has been furnished with industrial shelves to hold an additional layer of pallets with the aluminum instrument boxes. The room accommodates the wall racks and the server. A boom and a warehouse lifter support the maneuvering, however, the restricted area of the premises limits the amount of physical support available for moderate to large projects. The University of Helsinki charges the partners annual rental fees in proportion to instrument ownership. The 71 SmartSolo instruments are owned by the Geological Survey of Finland GTK and maintained at its premises in the Helsinki area.

3 Ownership and governance

During the build-up period, the FINNSIP ownership and governance is controlled by the financing structure. It involves several layers of national and international temporary projects and long-term commitments. The seismic instrument pool has been established as part of the national FLEX-EPOS project ("Flexible instrument network for enhanced geophysical observations and multi-disciplinary research") funded by the Research Council of Finland for the period between 2020 and 2024. The project objective is to create a national research infrastructure of geophysical instruments and multi-disciplinary geophysical superstations to be utilized in separately funded research projects that target scientific questions in seismology, geomagnetism, and geodesy. In addition to the FINNSIP seismic pool, the FLEX-EPOS project consists of a geomagnetic instrument pool and a geodetic instrument pool not discussed here.

3.1 The FINNSIP partner institutions

The seismic equipment is owned and collectively governed by the five FINNSIP partners: Aalto University (ca. 6%), the Geological Survey of Finland GTK (28%), and the Universities of Helsinki (48%), Oulu (8%), and Turku (11%), where the percentages indicate the ownership share (Figure 4). This uneven distribution is only relevant for administration. During the build-up period, the pool governance structure includes two additional FLEX-EPOS project consortium members: the VTT Technical Research Centre of Finland and the Finnish Geospatial Research Institute/National Land Survey of Finland. We introduce the five FINNSIP partners to help identify contact points for external collaborators.

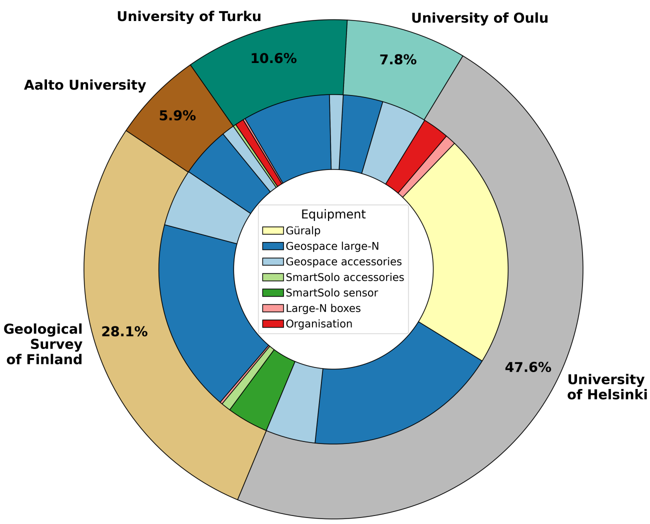

Figure 4 Ownership data. Outer ring: Total ownership percentage by institution. Inner ring: Ownership by equipment type. The legend corresponds to the inner ring.

3.1.1 Aalto University

The instrument pool related activities at Aalto University are led by the Department of Civil Engineering. The research involves geotechnical engineering and structural engineering, with a specific focus on dynamic geomechanical properties, vibrations-based structural health monitoring, and the seismic response of the built environment and critical infrastructure such as bridges. Aalto University researchers collaborate with national and international partners and lead projects associated with the green transition and digital transition initiatives. The group provides education to both bachelor and master students, covering a diverse array of topics in structural dynamics and several branches of geotechnics. The seismic pool instruments are utilized in relevant courses to enhance the learning experience.

3.1.2 The Geological Survey of Finland

The Geological Survey of Finland GTK is governed by the Ministry of Economic Affairs and Employment. Its operations are based on high-quality research and strong national and international partnerships with a focus on mineral resources, the circular economy, and solutions related to energy, water, and environmental problems. GTK's duties include providing expertise for the mineral resources policies of Finland and the European Union, mapping geological resources, and maintaining a national geoscience database. GTK is producing geological information to support decision-making and to help facilitate growth and innovation of the Finnish economy. Its applied research strategy aims to create solutions that accelerate the transition to a sustainable, carbon neutral world. The Geophysical Solutions (GFR) unit employs about 25 researchers and geophysicists and 12 field personnel to perform various geophysical measurements. GFR researchers are typically the principal investigators of the projects that utilize the mobile seismic pool instruments, and the field crew supports cost-effective large deployments. GTK uses the mobile pool instruments mainly for active seismic surveys at various scales. Surveys support the investigation of groundwater resources (Ahokangas et al., 2020; Afonin et al., 2021; Malinowski et al., 2023; Khalili et al., 2023; Brodic et al., 2023), the mapping of mineral deposits (Malehmir et al., 2017; Heinonen et al., 2019; Singh et al., 2019; Chamarczuk et al., 2019; Tirronniemi et al., 2024), and they help study bedrock fracturing for geoenergy developments and to constrain post-glacial fault properties (Abdi et al., 2015). Various geoscientific reports and data acquired in Finland can be accessed through the Hakku–Gateway to Finland's geological information data service that is provided by the Geological Survey.

3.1.3 The University of Helsinki

At the University of Helsinki, the Institute of Seismology and the Geophysics research group at the Department of Geosciences and Geography are involved in the mobile pool operations and applications. The Institute of Seismology has a permanent staff of 15. The observatory's mandatory tasks include the operation of the Finnish National Seismic Network including the primary station PS17 of the CTBTO International Monitoring System, seismicity and macroseismicity analysis, serving in the LUOVA Natural Disaster Warning System, consulting for public service institutions, and seismic hazard assessment associated with energy production. Together with the six-person strong Solid Earth Geophysics unit, the research focuses on lithosphere imaging (Tiira et al., 2020; Ding et al., 2021; Ding and Malehmir, 2021), seismicity analysis (Uski and Tuppurainen, 1996; Hillers et al., 2020; Rintamäki et al., 2021; Taylor et al., 2021; Eulenfeld et al., 2023), macroseismicity (Mäntyniemi, 2004, 2017), and seismic network performance (Kortström et al., 2016; Veikkolainen et al., 2021). The connection of the lithospheric structure to past plate tectonic processes is studied using a variety of approaches, including geodynamic modeling (Schütt and Whipp, 2020), magnetic methods (Salminen et al., 2023), field observations, low-temperature thermochronology (Green et al., 2022; Whipp et al., 2022), and heat flow studies (Veikkolainen and Kukkonen, 2019). This supports the exploration and development of natural resource deposits including groundwater (Eeva et al., 2023), mineral resources (Koivisto et al., 2012, 2015; Riedel et al., 2018), and geothermal energy (Kwiatek et al., 2019; Kukkonen et al., 2023). Seismologists develop and apply large array based passive seismic imaging and monitoring techniques to tectonic (Hillers et al., 2016, 2019; Chmiel et al., 2019), cryosphere (Moreau et al., 2020; Albaric et al., 2021), and environmental targets (Hillers et al., 2014; Lecocq et al., 2020). The group educates and trains students in a wide range of geophysical and seismological concepts and techniques, and the seismic pool instruments are utilized in field courses. The University of Helsinki represents Finland in the ORFEUS Board of Directors.

3.1.4 The University of Oulu

The activities at the University of Oulu are headed by the four staff of the Oulu Mining School of the Faculty of Technology that seek solutions to the pending ecological, social, economic, and cultural sustainability challenges. Integrating observations from the Sodankylä Geophysical Observatory, topics in sustainable development include the responsible use of natural resources, the impact of environmental factors on health, climate change impacts in the North, and research on the changing environment in the Arctic and Boreal zones (Afonin et al., 2021; Aleshin et al., 2023). Teaching and post-graduate education focuses on geosciences, applied geophysics methods, and mining engineering. The Oulu Mining School integrates scientific disciplines along the mining value chain, and the pool supports research targeting the sustainable management of a modern mine throughout all stages from prospecting to reclamation and mineral processing in the harsh Arctic climate and its fragile socio-ecological systems (Zhang et al., 2023). For this, the Oulu Mining School collaborates with mining companies in several commercial and non-commercial projects to promote cost-effective prospecting technologies for the exploration of green transition-critical raw materials in the European Union. Together with the Kerttu Saalasti Institute, the unit develops projects for the industrialization and informatization of the mining sector including mining waste management (Mollehuara Canales et al., 2020; Mollehuara Canales et al., 2021; Mollehuara-Canales et al., 2021; Afonin et al., 2022), and the seismic instrumentation is used for microseismic and acoustic emission monitoring to complement optical, electric, and electromagnetic methods. Environmental studies include dynamic processes in the critical zone caused by extreme weather and their effect on urban infrastructures (Afonin et al., 2023; Okkonen et al., 2020).

3.1.5 The University of Turku

The University of Turku is involved in the seismic pool through the Department of Geography and Geology with its 40 permanent staff. The main subsurface research interests associated with the pool infrastructure relate to modeling the 3D structure of the bedrock with applications to geo-resources and engineering geology (Dehghannejad et al., 2010; Lindqvist et al., 2017; Skyttä et al., 2019; Colombero et al., 2022), the depth to the bedrock and overburden thickness in urban areas, and the internal structure of the glacifluvial deposits, which act as primary aquifers in Finland (Ahokangas et al., 2020). The pool research projects and datasets are used for undergraduate courses in geospatial modeling.

3.2 Governance

The University of Helsinki hosts most of the pool instruments. University of Helsinki staff manages the pool operations and organizes the allocation of all instruments in coordination with the other instrument owners and hosting organizations. University of Helsinki staff implements resolutions of the governing FLEX-EPOS Steering Group that is the highest decision-making body of the FINNSIP (Figure 5a). Each of the seven FLEX-EPOS consortium members has an equal representation in the Steering Group. The chair is recruited from the University of Helsinki. The Steering Group sets the FINNSIP operational rules, decides and monitors the instrument usage, and is involved in planning the data management. The University of Helsinki FINNSIP coordinator is the contact person concerning technical and administrative issues related to the overall pool operations.

The FLEX-EPOS project received Finnish Research Infrastructure (FIRI) funding from the Research Council of Finland (the Academy of Finland prior to June 2023) between 2020 and 2024 to build up the infrastructure. The funding agency provided 70% of the costs and 30% were provided by the participating organizations. During the build-up period, the FLEX-EPOS FIRI funding was used to purchase the instruments and auxiliary equipment, to support travel and exchange, and to create education material and instructions. The funds do not cover operational costs. The project partners are required to organize the funding to establish the IT infrastructure and data management and dissemination systems, and to maintain the functionality of the pool from 2025 onward, through instrument renewal, repairs, and upgrades.

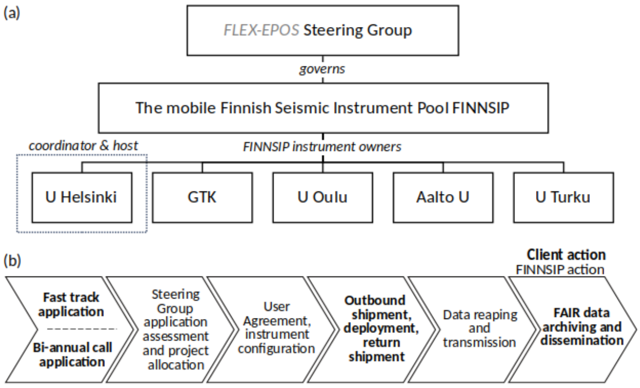

Figure 5 FINNSIP organization and project management. (a) Summary chart of the pool infrastructure and governance. During the build-up period the pool is governed by the FLEX-EPOS project related Steering Group. This includes representatives of the five indicated instrument owning and the two project consortium partner institutions VTT and FGI. This Steering Group composition changes after 2024. (b) Summary of key project management elements.

The FIRI funding is granted under the umbrella of the permanent national FIN-EPOS research infrastructure that connects the domestic solid earth science community to EPOS at the European level. Through this connection, the FINNSIP operations are incentivized to be compatible with EPOS rules governing FAIR data management principles. The FINNSIP build-up stage governance is tied to the FLEX-EPOS funding period that ends December 2024. The future governance and financial structure of the pool requires an updated legislation through the consent of the FLEX-EPOS Steering Group and the FIN-EPOS council. An update can also include the change from the current observer status to an active member of the ORFEUS Initiative of European Mobile Seismic Instrument Pools.

The FINNSIP coordinator reports to the FLEX-EPOS Steering Group about the pool operations during the FLEX-EPOS project supported build-up period, as do the coordinators of the parallel evolving geomagnetic and geodetic pools. The FLEX-EPOS project reports to the funding agency about the build-up activities after the project completion. The updated legislation can lead to a policy change concerning the relation between FINNSIP and the supported acquisition projects. Until now, the FINNSIP clients are not required to report to the pool management, but it is mandatory for future project reports and pool supported publications to refer to this paper.

4 Method of operation and project workflow

4.1 Personnel

During the 2020 to 2024 FINNSIP build-up period, the University of Helsinki employed one seismologist and two technicians for the pool operations. This core team is supported by a lecturer in Geophysics, the FLEX-EPOS project leader, the FIN-EPOS coordinator, and the FINNSIP coordinator. All contributed to the regular project related work during the build-up period during which best practices for efficient processing and management had to be developed. The tasks were accomplished in addition to the existing observatory, research, teaching, and administrative duties. The 2023 early recruitment of the successor of the staff seismologist helped stabilize the pool operations. The team can tap into a pool of students from the University of Helsinki Master's Program in Geology and Geophysics or doctoral candidates to mitigate peak workloads associated with instrument testing or the preparation of large deployments. Significant time was spent during the tendering and procurement processes, to develop the administrative and legal framework, for the preparation of the lab space, the boxes, and other facilities, and for instrument on-boarding, testing, and troubleshooting. Before the build-up stage, staff from all consortium members contributed to establishing the consortium that underpins the FLEX-EPOS project.

4.2 Application procedure and project allocation

The Steering Group allocates instruments for seismic deployments through an application process (Figure 5). Domestic and international collaboration projects are considered, but the main applicant or the project principal investigator (PI) must be affiliated to one of the seven FLEX-EPOS consortium members. Applications with industry engagement and a commercial component, i.e., economic and business projects, can be supported but they are ranked with lower priority in the decision-making process compared to non-economic research and education projects. The funding organization has limited the commercial deployment of the instruments to a maximum 20% of the pool's annual allocations.

We organize bi-annual calls for applications in the November–January and the June–August time windows. Calls for the applications are opened two months prior to the Steering Group meetings where the decisions are made. The deadline for receiving applications is one week prior to the meetings. In addition, a permanent fast-track application procedure exists for small projects (Figure 5b). A small project is defined either to use less than 50% of the monthly capacity of the available instruments or less than 75% of all instruments for a period not exceeding one month. The Steering Group aims to accommodate user needs, but a regular or extensive exploitation of the fast-track application is not supported.

All applications must be submitted through a web form. Key application elements include the dates, the number and type of instruments, the project funding situation, and a one page summary description. FINNSIP reservations are approved at most two years in advance. Determinants are the dates of the Steering Group meeting and the project starting date. A positively evaluated project reservation may be extended up to four years due to a justified reason, such as project extension or pending funding decision. Applications can be made with a confirmed or pending support funding, which influences the ranking. A party making a preliminary reservation must inform the Steering Group immediately if the project is delayed or canceled.

The goal of the FINNSIP approval process is to maximize instruments field deployment time and, when needed, negotiate solutions to support all project applications. In case of conflicting applications, the ranking considers to balance the average FINNSIP usage of the applying institutions and their ownership share. The Steering Group may use outside experts to assist with the project allocation in the case of contested decision making.

4.3 Project management

4.3.1 Administration

The applicant is informed about a successful application after the Steering Group has approved the project request (Figure 5b). The project principal investigator must specify a list of required instruments and auxiliary devices at least one month before the scheduled deployment. This list will be used to determine the mobilization fee that covers the working hours of the pool staff required to prepare the instruments and to reap, format, and disseminate the data to the project PI after the deployment. The mobilization fee for projects with a commercial component is determined according to market prices and an instrument rental fee applies. The fee is set by the owner of the allocated instruments on a case-by-case basis. In all cases, a user agreement is signed by the PI, the instrument owners, and the pool coordinator. The PI is responsible for equipment insurance.

4.3.2 Project data

Data collected from successful deployments is handled differently depending on the types of instruments used. The Minimus loggers allow the users to manage the data independently during or after deployment. The transportable SmartSolo All-In-One solutions grant the projects full autonomy concerning battery and data handling. The pool instrument owners offer the support necessary to operate these systems.

There are two options for a large-N deployment. In the first option, the PI communicates the deployment-specific parameter choices such as sample rate and data format for instrument preparation to the responsible University of Helsinki specialist. All configuring and charging is completed in Helsinki, the instruments are deployed, potentially with external batteries, and upon return the data are reaped and made available through the DataCloud system. Line health viewers allow on-site system checks but do not verify data quality.

The second option includes shipping the mobile rack and, optionally, the external battery charger, along with a choice of one of two Toughbook laptops referred to as field server. Both laptops feature Geospace processing software usable for a range of deployments. This option allows for management and data processing from the field. However, with limited support equipment available in the pool, choosing this option can constrain the time availability for the project. This is the only option available for overseas projects, since the internal GSB and external BN lithium batteries must be discharged for airfreight. Other options for powering the equipment using external sources are possible using connectors to the instruments. The mobile racks, for example, can be programmed to charge the batteries of the GSBs automatically without being connected to a server. One extended domestic monitoring project swapped the nodes in the field; another project in the Americas organized a portable Geospace rack and battery support to be sent independently from the U.S. for cost-savings. The wireless communication available on the 50 GSX3-LTEs can further facilitate deployment management. Projects can combine options, however, PIs should consult the FINNSIP coordinator before filing an application for a customized solution. We iterate that each project is individually responsible for FAIR data management including archiving and dissemination. A domestic repository that is also minting digital object identifiers is the CSC Fairdata Service IDA.

5 Discussion

Steep learning curves had to be navigated concerning the FINNSIP development and integration of procedures. As noted, managing the tendering process, building online resources, and preparing documents to organize instrument usage are time-consuming tasks. Software tools for device management had to be created, independent of the persistent data management challenges.

Overall the seismic instrumentation purchased has met expectations. Large temperature drops of 20 °C and more highlight the need for proper broadband sensor site design for arctic and subarctic conditions. The large-N devices do support passive seismology experiments. We found, however, that the expectation of conducting active seismic surveys is built into the workflow and into the proprietary processing software, requiring repeated exchanges with the supplier. We mention the bias of academic system administrators towards Unix based systems, in particular in the environment where the Linux kernel was invented (Torvalds, 1997), and we suggest an advantageous system feature of generating the large-N instrument response function in a standard seismology format.

From the 2021 to 2024 application calls, FINNSIP supported 39 academic projects and one commercial research project (Figure 6) with variable instrument usage (Figure 7). In five cases, the instruments were deployed outside Finland (Supplementary Material). For these 40 projects, the numbers of short-period and broadband instruments ranged between 24 and 900 and between 1 and 20, respectively. The project duration varied between seven days and two years. Mobilization fees varied between 40 and 3960 Euros. For the large-N experiments completed by 2025, the raw data volumes ranged between 24 GB and 9 TB. At the end of 2024, the cumulative data volume in the proprietary Geospace format and the user-requested seismic data format from the large-N devices was about 55 TB and 95 TB, respectively (Figure 8).

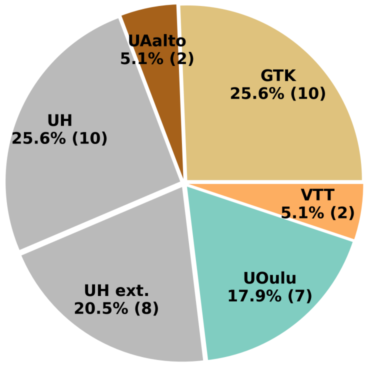

Figure 6 Number of projects from each applicant institution from all application calls in the build-up period. External collaborations are indicated as 'ext.'.

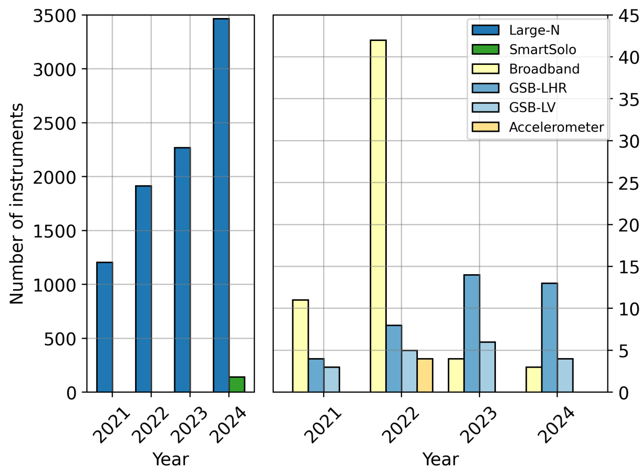

Figure 7 Cumulative sum of deployed instruments per type in the build-up period. In 2024, 142 SmartSolo instruments were deployed. Instruments for multi-year projects are registered in the first year.

The irregular temporal pattern of the FINNSIP utilization displayed in Figure 9 highlights the uneven workload distribution associated with the instrument management at the beginning and end of a project. The preparation and data services of the large-N experiments require most of the pool management resources. Figure 10 shows that the majority of large-N projects use up to 200 sensors, i.e., only a fraction of the full pool instrumentation. With one exception, all projects involving more than 400 sensors are active seismic studies. These active surveys contribute to the cluster of comparatively short project durations illustrated in Figure 11. The second cluster of around half a year duration is governed by passive geophone surveys, the few long duration experiments mostly involve the broad-

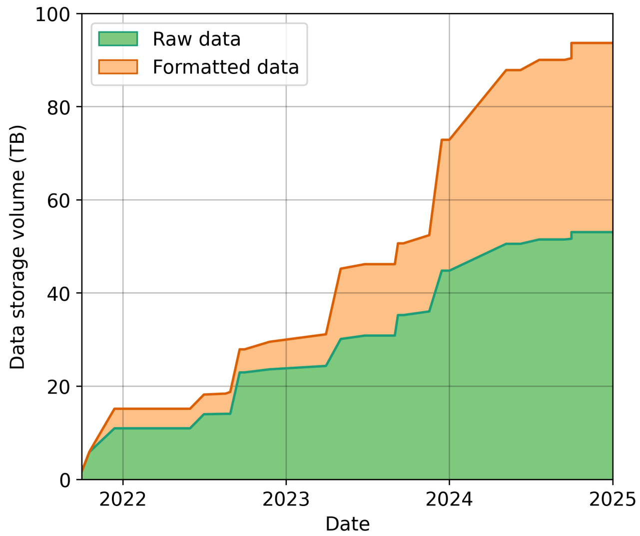

Figure 8 Cumulative data volume collected by large-N deployments during the build-up period. We distinguish between the original Geospace data format and a converted data format that differs for active and passive acquisitions.

band sensors.

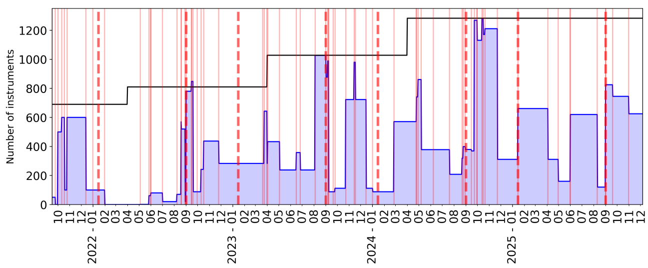

Figure 9 Usage of broadband seismometers and of Geospace and SmartSolo geophones since the first project in October 2021. Black line: Total number of available broadband and short-period systems. Blue: Project reservations. Dashed red line: Application call deadline. Solid red line: Start and end of project reservations.

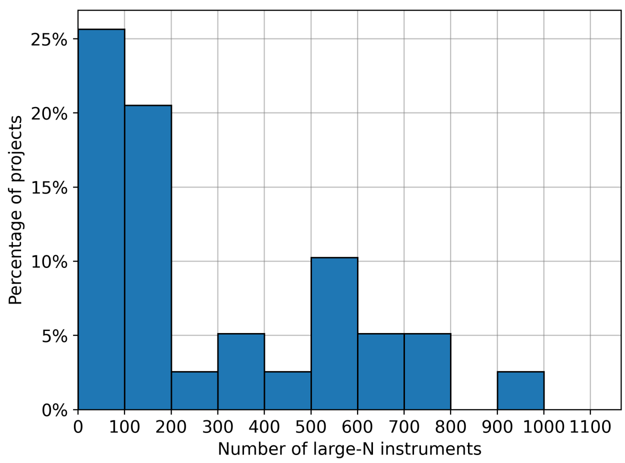

Figure 10 Distribution of the project dependent number of Geospace large-N instruments for the build-up period.

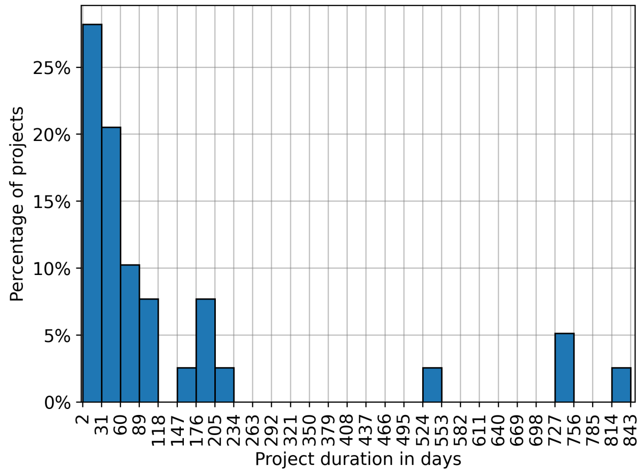

Figure 11 Duration data of all projects in the build-up period including broadband sensors, accelerometers, and Geospace and SmartSolo geophones.

The number of FINNSIP instruments is relatively large in comparison to the mobile seismic instrument pools in, say, Germany, the U.K., and France. This large size was established within a short time compared to the more evolutionary expansion over many years with the other pools. On the other hand, the number of staff responsible for the pool operations and the instrument handling is comparatively small. Together with the restricted lab space, these circumstances pose considerable challenges to a smooth operation, however, the homogeneous pool instrumentation supports the scaling efficiency.

The granular ownership situation resulting from legal boundary conditions of the involved institutions (Figure 4) has a negative impact on the overall efficiency of the pool. During the project preparation phase, it can complicate the agreement paperwork and add difficulty in ensuring proper insurance. For example, FINNSIP brokers the agreement between the user and the affected instrument owning institutions, which can be up to five for large-N experiments. It can also cause delays and force errors in the instrument preparation and post-deployment phases. This situation can be simplified after the build-up period with an updated consortium agreement.

Our academic units and institutions are easily saturated with the management of one dense or large-N deployment that utilizes a considerable fraction of the available pool instruments. Modern Big Data processing with strong method development elements for scientific renewal requires adequate external funding support. This imposes a limit on the utilization per institution. An increased usage rate can be achieved by international collaborations. The pool instruments make the involved consortium members interesting partners for joint projects, and the FINNSIP community shares the goals of the ORFEUS Initiative of European Mobile Seismic Instrument Pools to “enhance availability of instruments for users, improve information about and access to instruments, increase utilization of the instruments, support large international experiments, and improve expertise on and availability of new instrument types" (Observatories and for European Seismology ORFEUS, 2025).

The mobile Finnish Seismic Instrument Pool is a modern scientific infrastructure with the capacity to generate huge data volumes. FINNSIP stands in the seismological tradition of a collaborative, open data science and commits to FAIR principles. We thus face the challenge to make the data sets available to the scientific community. This challenge highlights the need for initiatives that strive "to enhance, give access to, and make interoperable datasets" (Cotton et al., 2023), and FINNSIP can therefore be a driver for the development of protocols and standards to disseminate large-N data and metadata. Elements of an intermittent solution can include FINNSIP FDSN web services (Suarez et al., 2008) that facilitate the ObsPy-based (Beyreuther et al., 2010; Megies et al., 2011) access to project data products by clients and external users. This can be used in tandem with or instead of the current web browser-based DataCloud solution, and can eventually be developed into an EIDA node (Strollo et al., 2021). An integration of FNSN network and FINNSIP pool services can diversify the possibilities of acquiring stable support for an adequately resourced data center.

6 Conclusions

The mobile Finnish Seismic Instrument Pool provides the Finnish and international geoscience communities with a state-of-the-art research infrastructure. The large number of seismic instruments together with the overall homogeneity of the equipment support diverse modern acquisition styles that target fundamental research questions and help find solutions for practical problems. FINNSIP data integration with records from other sensor types including fiber-optic cables, atmospheric pressure gauges, microphones, micro-electromechanical systems, or cellphones support novel approaches to study atmospheric, environmental, urban, and biological phenomena, wavefields, and soundscapes.

Based on our experience between 2018 and 2024 from the preparation of the funding application to the first approximately 3.5 years of operation, we can summarize a checklist of nine suggestions for building, operating, and managing a mobile seismic instrument pool. Some of the generalized principles help also inform the planning and organization of research infrastructure projects in general. Our work can further contribute to the development of community standards and best practices for streamlining projects and for providing access to data, products, and services. The nine suggestions are:

1. Confirm that the staff and room situation, task description, and working time allocation support all preparation, build-up, and operational stages.

2. Brief the hierarchy and administrative including legal support staff about the detailed implications and seek support at all levels, in particular at the infrastructure host institution.

3. Reach out to existing similar infrastructures for best practices, templates, and advice.

4. Simplify and tailor the government, legal, and ownership structure to facilitate project support and operations.

5. Rigorously implement acceptance procedures in accordance with regulatory and manufacturer specifications.

6. Be prepared for continued updating of firmware and software to keep the systems functioning, and be aware of differences in terminology between active-source and passive-source instrumentation.

7. Computing, data management, archiving, and distribution must be considered essential elements of a functional and effective seismic pool infrastructure. The lack of adequate computing and data infrastructure can be a peril to full functionality.

8. Databases and tools for internal book-keeping and scheduling can be the source for public calendars and inventories. These tools can supply the local instrument availability to international, higher-level platforms.

9. Ensure adequate cross-training amongst staff and devote resources towards documentation to improve staffing resilience and reduce single point-of-failures.

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Data and code availability

No data or software was used in this article. Online information about FINNSIP and the application process can be accessed at https://finnsip.fi. The GTK Hakku data portal can be accessed at https://hakku.gtk.fi/en. Details about the FINNSIP instrumentation can be obtained from the pool webpage or from the manufacturer online material for the Güralp 3ESPC sensor www.guralp.com/products/3espc-series, the Minimus digitizer www.guralp.com/products/minimus-digitisers, the Fortis accelerometer www.guralp.com/products/fortis-and-fortimus, the Geospace GS-One LF sensor www.geospace.com/products/sensors/gs-one-lf, the GSB-3 recorder www.geospace.com/products/land-exploration/gsb-3, the recorder with cellular network access www.geospace.com/products/land-exploration/gsx-c, the BN batteries www.geospace.com/products/land-exploration/bn-batteries, the portable battery management system www.geospace.com/products/land-exploration/portable-bms, and the SmartSolo 5 Hz geophone www.smartsolosci.com.

Competing interests

The authors have no competing interests.

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