SFI CENTRE FOR GEOPHYSICAL FORECASTING

Turning geophysical data into knowledge and understanding

ANNUAL REPORT 2021

sfi Centre for Research-based Innovation

The Research Council of Norway

CGF SFI Centre for Geophysical Forecasting

NTNU

BANE NOR

NVE

ALCATEL SUBMARINE NETWORKS

AkerBP

tampnet

SHEARWATER

equinor

tietoevry

magseis fairfield

Statens vegvesen

UNINETT

Digital Geologi AS

JAMSTEC

NORSAR

NTNU | Department of Computer Science

NTNU | Department of Geoscience and Petroleum

NTNU | Department of Mathematical Sciences

NTNU | Department of Electronic Systems

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FOREWORD

CGF, Martin Landrø Director

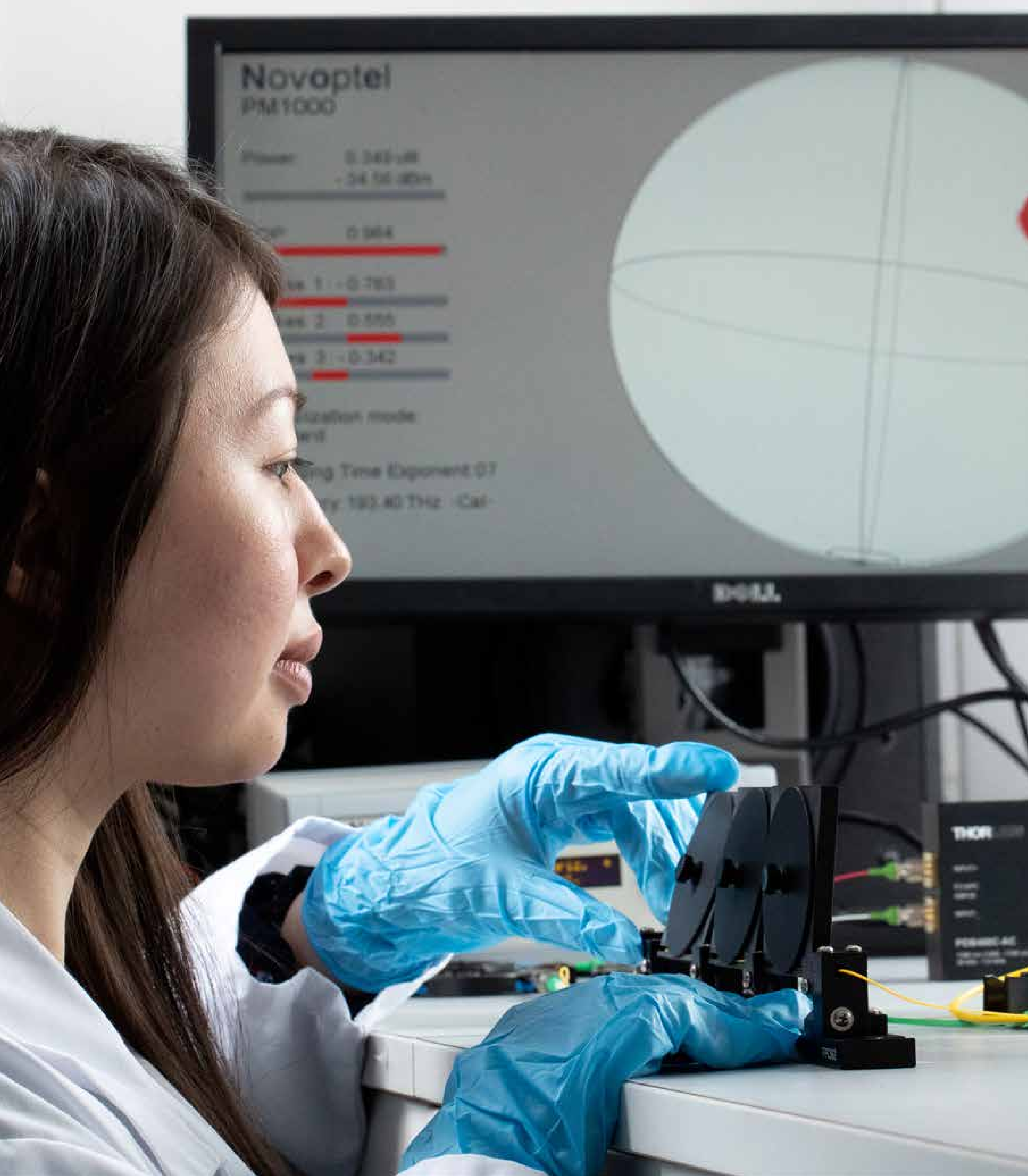
Late in the afternoon on 11th June 2020 I received an email from the Norwegian Research Council that the Centre for Geophysical Forecasting (CGF) had been selected as one of the new Centres for research-based innovation in Norway.

Our (now) 12 industrial partners, together with our research partners NORSAR and JAMSTEC and four NTNU departments, were asked to create a new organisation, with research and innovation as the focus. Our partners and NTNU team-members span a wide range of disciplines, so it is both challenging and exciting to build a new team that includes a wide range of activities with a common overall objective: Find new and innovative methods to monitor and improve our knowledge of the earth, both offshore and onshore. This challenge has not been made easier by the Covid-19 pandemic that has engulfed us. While this has impacted everyone, and has rarely made life easier, it is particularly difficult to build new trust and working relationships between team members in the absence of physical contact. While video conferencing provides a much-needed meeting platform that is perhaps sufficient to enable established working patterns, the experiential bandwidth is a poor substitute for in-person contact, so important for building new relationships.

Since CGF is a new entity, and a physical hub to build it around was a requirement, it was decided early on to establish the physical centre at NTNU even if we cannot, for the moment, welcome everyone into it. We are now located in the historical "Gamle Elektro" at NTNU's main campus at Gløshaugen in Trondheim. The faculty of Information Technology and Electrical Engineering and the host department of Electrical Systems have worked with and supported us in creating a fantastic centre where researchers, students and visitors from partner organisations can physically work together. The support of the Norwegian Research Council has been invaluable in this start-up phase.

Our ambitions are high: to instrument and exploit existing infrastructure (e.g. fibre-optic telecommunication cables) to monitor and increase our knowledge of the earth. By bringing experienced industry partners, professors and young students together we have mapped out a strategy to create an innovative environment.

Our logo was created by Ane Nordvik Hasselberg and beautifully captures our focal points: the instrumentation, mountains and oceans and the globe which we all care about.



SUMMARY

The SFI Centre for Geophysical Forecasting (CGF) was established in December 2020. The CGF has three research partners (NORSAR, JAMSTEC and NTNU) and was originally set up with 10 industry partners (AkerBP, ASN, Bane NOR, Digital Geology, Equinor, NVE, Statens Vegvesen, Tampnet, TietoEvry and Uninett). During 2021 we have had the pleasure to welcome two additional industrial partners. MagSeis Fairfield and Shearwater, bringing our consortium partner numbers up to 12. We are delighted that several exciting new projects and potential innovation activities have been launched during 2021, with engagement from several partners.

Covid-19 has, of course, impacted us all. There is no doubt that it has made 2021 a challenging first year for CGF. Digital meetings, long periods of home office and almost no travel to seminars and conferences have impacted our work significantly. While online meetings may suffice for colleagues with whom one already has an established working relationship, the lack of direct and spontaneous contact with both students and colleagues has been particularly damaging to the teambuilding and identity formation in the nascent stages of this new Centre.

Despite these circumstances, we have strived to provide attractive office and common space facilities and develop a welcoming and open culture. We have been able to establish and renovate CGF office space in the historic 'Gamle Elektro' building on NTNU's Gløshaugen campus, including the provision of a valuable common meeting room with presentation, kitchen and social facilities that serve as a hub for discussions, planning, lunch, regular meetings and social contact. We have also inaugurated three different seminar series, serving partners, research groups and students, and a regular 'Pizza Party' social event each month. The three types of CGF seminars are:

- SASHIMI; where our partners present challenges and results from their side.
- SUSHI; presentations by research partners and researchers in CGF, and
- LAKS; seminars intended for informal presentations and not-fully-developed ideas to be presented, tailored to support Masters and PhD students.

On the research and innovation front, a key objective for 2021 has been to focus on the acquisition of geophysical data, and especially acoustic data measured on a Fibre-Optic (FO) telecommunication cable, known as Distributed Acoustic Sensing (DAS).

In 2020 two DAS datasets were acquired that have been used for intensive analysis by CGF researchers during 2021. The first acquired data from the FO cable that crosses the Trondheimsfjord, connecting Trondheim and Rissa. This was a one-day test where we used a small electric seismic source from a boat that sailed directly above the seabed-trenched cable. The second experiment was at Svalbard in cooperation between ASN, Uninett and NTNU.

The key instrument for acquiring DAS data from a FO cable is a DAS interrogator. CGF bought one such interrogator in 2021, and in 2022 we plan to buy at least one more. Although expensive, these advanced DAS data acquisition systems are essential. They open up unique possibilities to monitor acoustic signals in time and space. For the Svalbard test case we streamed (continuously and in real-time) a total of 250 TB of data, sampling every 10 m along 120 km of cable. With some 7 TB of data arriving every day, a data management plan is also essential. A terrestrial DAS test was also conducted with ASN, NTNU and BaneNOR on 50km of FO cable running beside a railway track from Marienborg to Støren. The data show a startling array of detections, not only of trains, but also road traffic and even quite small test signals. We are therefore spending a significant portion of our budget on computers and data storage.

VISION/OBJECTIVES

Our vision is to create the world-leading research and innovation Centre for Geophysical Forecasting and sustainable resource exploitation.

Norway is already at the forefront of global exploration geophysics; we intend to leverage that expertise to catalyse a new wave of geophysical capabilities, applying disruptive new technologies to novel enterprises that will be game changers in the transition from hydrocarbon geophysics to the new blue economy, in addition to important terrestrial geohazard risk monitoring and early warning applications, founded on sustainable geophysical applications.

PRIMARY QUANTITATIVE OBJECTIVES OF CGF:

- Bring valuable, cost-effective and robust geophysical monitoring and forecasting services to CCS, hydrocarbon and geohazard/geoengineering markets.
- Establish 4-6 successful spin off companies, creating new market segments for partners.

SECONDARY OBJECTIVES:

- Improve our understanding of property variations in the earth's upper subsurface.
- Advance DAS to provide continuous monitoring products and services.
- Develop cost-effective and accurate methods for monitoring reservoirs and CO_2-storage sites.
- Develop methods exploiting passive data (acoustic noise, gravity, magneto-tellurics etc.) for monitoring.
- Develop methods for geophysical monitoring of road infrastructures, coastal zones and harbours.
- Design early warning systems based on new methods for statistical design of geophysical experiments.
- Develop HPC tools and frameworks as an enabler.
- Publish 100 peer-reviewed articles in internationally conferences and journals within the first 6 years.

To achieve these objectives, a fundamental reorientation is needed in the way we view geophysical sampling and exploitation, shifting from traditional campaign-based approaches to continuous monitoring and forecasting in 4 dimensions (space and time). This requires both novel interdisciplinary synergy across the mathematical sciences, geosciences, geomechanics, computer science and physics coupled with the application of emerging technologies.

The CGF is breaking new ground in applying leading-edge wave propagation methods, advances in Distributed Acoustic Sensing (DAS) and cutting-edge Artificial Intelligence (AI) and statistical methods such as Data Mining and Deep Learning on Big Data.

Key innovation areas include new ways to monitor the geological storage of CO_2, reconfiguring petroleum production, and developing geohazard early warning systems for land-based infrastructures such as roads, dams, windfarms, viaducts, ports and other structures. The objective is to better understand and sustainably exploit the tremendous value of the earth's uppermost crust.

RESEARCH PLAN/STRATEGY

CGF RESEARCH IS ORGANISED INTO 6 COUPLED WORK PACKAGES (WP):

WP1: DISTRIBUTED ACOUSTIC SENSING (DAS)

In this WP we develop the competency required to address many nascent DAS applications, addressing key limitations currently holding us back, including the lack of geophysical models and signal processing tools optimized for DAS data.

WP2: CO_2 AND GAS/ENERGY STORAGE

WP2 will develop cutting edge geophysical monitoring methods for storage of CO_2, methane, hydrogen and energy as part of the low-carbon energy transition.

WP3: EFFECTIVE MONITORING AND FORECASTING SYSTEMS, OFFSHORE, COASTAL AND ONSHORE

WP3 is developing and testing approaches to map and monitor pressure and salt variations in areas of particular interest. Seismic monitoring of the ground conditions close to roads, harbours and other infrastructures is a key application area.

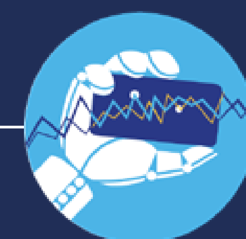
WP4: GEOHAZARD PREDICTION AND DEEP MAPPING OF EARTH'S CRUST

There is an increased societal concern and focus on geohazard prediction and measures taken to reduce risk and implement effective mitigation. Both onshore and offshore geohazards are in focus. Deep earth mapping flow is crucial for improved understanding of the shallow crust, such as earthquakes, volcanoes and shallow fluid flow.

WP5: HPC TOOLS AND TECHNIQUES FOR MODEL FITTING THE SUBSURFACE

Many geophysical simulations are computationally demanding. This WP will develop methods and tools to harness the computational power of HPC systems, including GPUs. The codes targeted will include Full Waveform Inversion (FWI) codes for seismic processing.

WP6: DATA ASSIMILATION AND UNCERTAINTY QUANTIFICATION



With myriads of geophysical data at different spatial and temporal scales, statistics is one of the enabling technologies for coherent assimilation and uncertainty quantification to generate decision support in geophysical forecasting.

WORK PACKAGE 7: MANAGEMENT, INNOVATION AND COMMUNICATION

Management

The CGF is managed by a compact leadership team with the support of Innovation and Research Advisory Boards, overseen by the governing CGF board, illustrated in Fig. 1.

The CGF is physically located in the historic Gamle Elektro building on Gløshaugen campus. The Centre offices provide space for key researchers, PhD students and PostDocs, in addition to coordinator and administrative offices. There is also space for partner team members, and a common room where discussions, meetings and informal breaks can be taken, facilitating internal communication.

The CGF is hosted by the Department of Electronic Systems and Directed by Professor Martin Landrø. Four departments from two faculties are involved: Electronic Systems, Mathematical Sciences, Computer and Information Science, and Geoscience and Petroleum. NTNU provides laboratory space, computer facilities, office space, 1 MNOK/year, 3 PhDs and 3 postdocs.

The Governing, Research and Innovation boards are composed as follows:

CGF BOARD

- Hilde Nakstad, ASN (leader)
- Lasse Amundsen, Equinor
- Steinar Bjørnstad, Tampnet
- Arve Mjelva, NORSAR
- Thomas Tybell, NTNU
- Kari-Lise Rørvik, Gassnova
- Tom Røtting, Uninett
- Ingrid Schjølberg, NTNU
- Secretary: Martin Landrø, NTNU

CGF RESEARCH ADVISORY BOARD

- Karin Andreassen, Univ of Tromsø, Norway
- Steven Constable, Scripps Inst, US
- Dario Grana, Univ of Wyoming, US
- Shuichi Kodaira, JAMSTEC, Japan
- Vera Schlindwein, Alfred Wegener Inst, Germany
- Serge Shapiro, Freie Univ Berlin, Germany
- Secretary: Jo Eidsvik, NTNU

CGF INNOVATION ADVISORY BOARD

- Kent Andorsen, Aker BP
- Solveig Christensen, Exero Tech
- Duncan Irving, TietoEVRY
- Camilla Larsen, TTO, NTNU
- Olaf Schjelderup, UNINETT
- Mark Thompson, Equinor
- Secretary: Ståle Johansen, NTNU

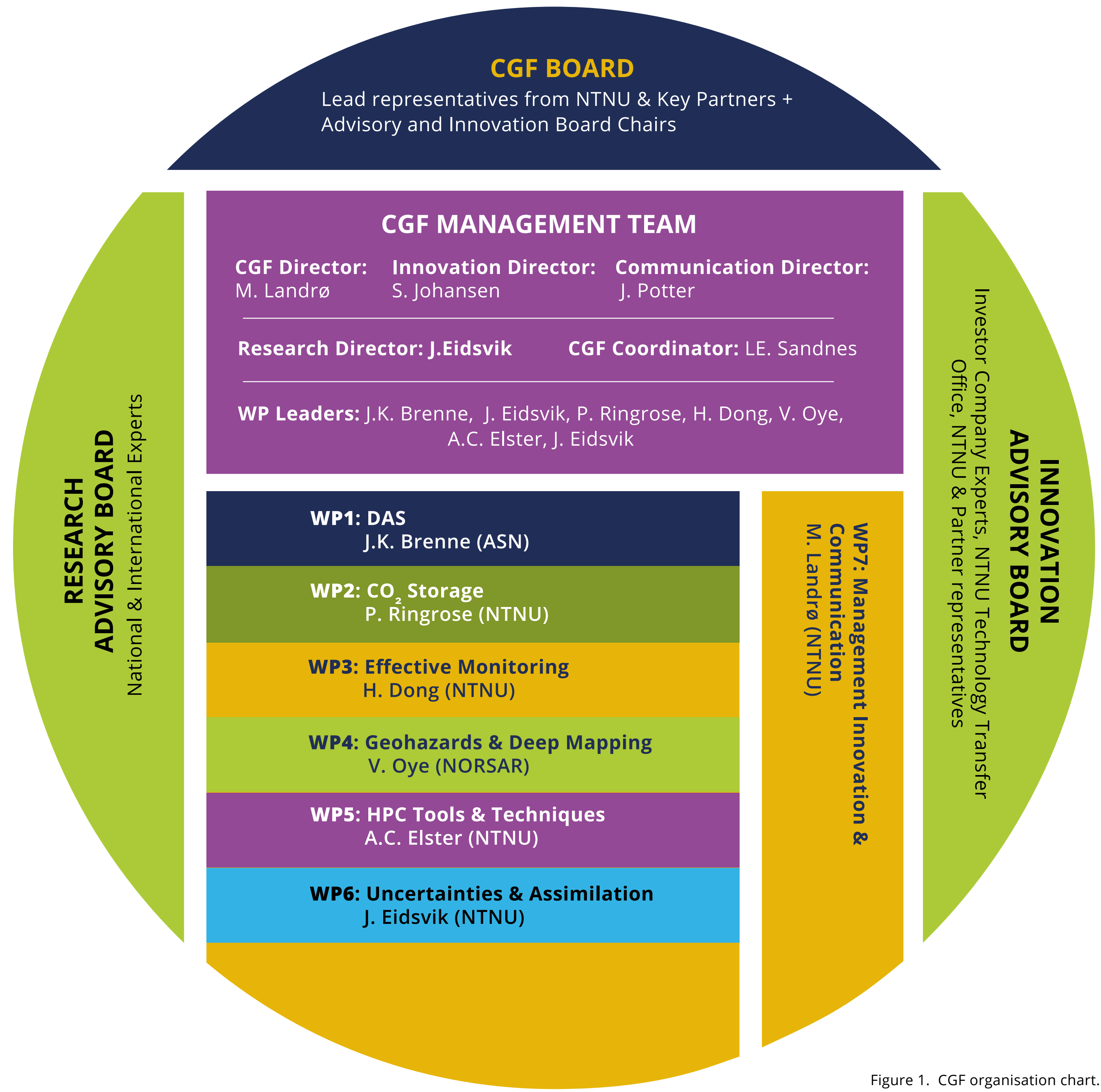


Figure 1. CGF organisation chart.

Innovation plan/strategy

The primary innovation objectives for the Centre are to bring valuable, cost-effective and robust geophysical monitoring and forecasting services to CCS, hydrocarbon and geohazard/geoengineering markets and to establish 4-6 successful spin off companies, creating new market segments for partners.

Our strategy is to create value within the core business areas of the partners by bringing research results and cross-disciplinary innovations to existing products and services. Where we generate results that are outside existing core business areas, these could form the core of spin-off companies.

Communication Plan/Strategy

In a multi-disciplinary centre, spanning a wide range of competencies, experience and approaches, not to mention cultural diversity, communication is key to forming an effective team. This is even more critical for an innovation-based research centre, where the research results from the academic work must be effectively transitioned across the 'valley of death' to generate valuable new products and services in the hands of our industrial partners and/or new spin-off companies.

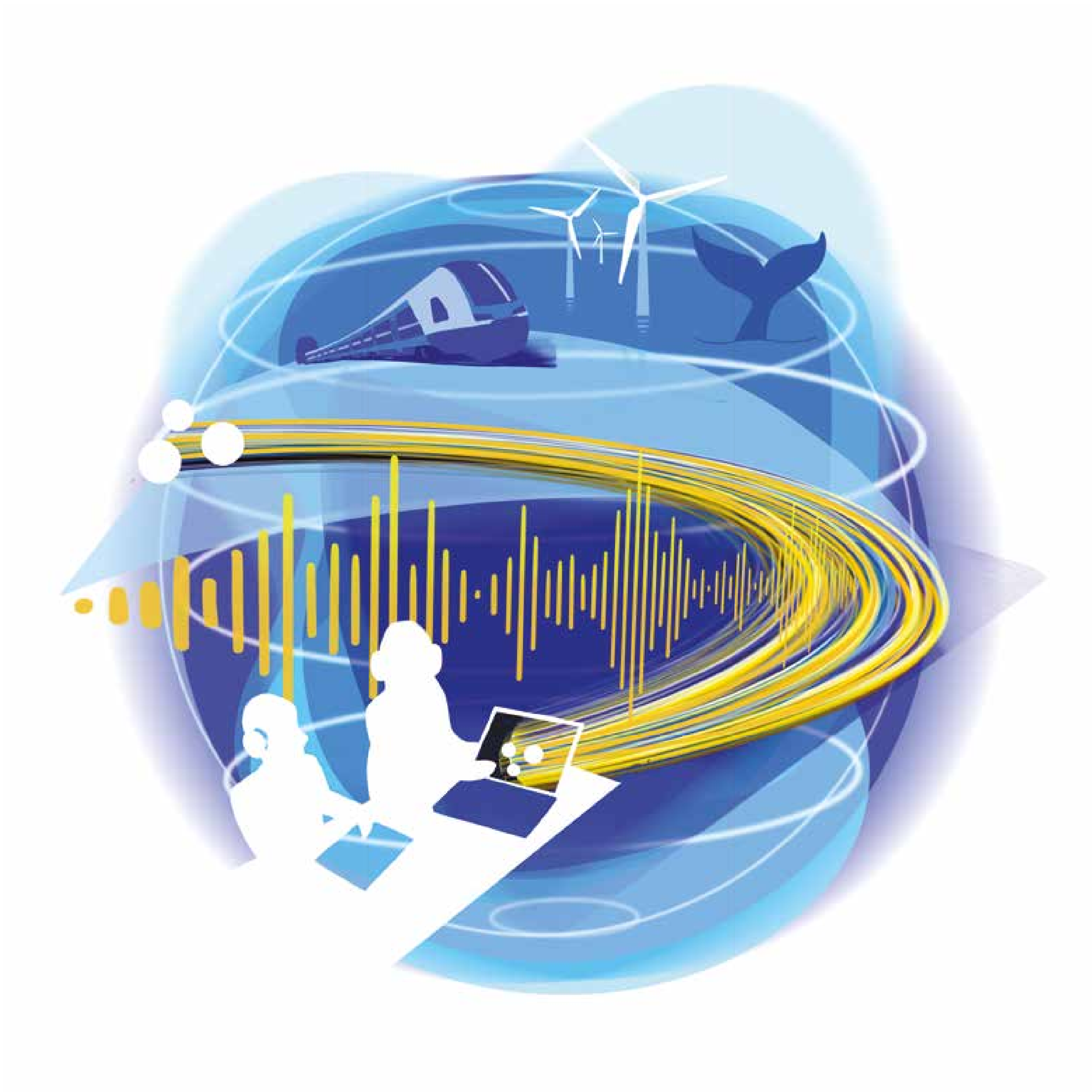
Industrial Partners

The CGF industrial partners are a critical group of collaborating industry and research organisations, providing not only real-life problems and applications, but also research guidance, data, infrastructure facilities, and of course the landing pads for the final products – innovations in their products and services. The CGF partners come from a wide range of fields, spanning the CGF vision landscape and complementing each other with little overlap or competition.

Originally, there were founding 10 partners, but in 2021 the CGF has been delighted to welcome two additional partners; Shearwater and Magseis Fairfield, bringing our current total to 12:

- AkerBP
- Alcatel Submarine Networks (ASN)
- Bane Nor
- Digital Geologi
- Equinor
- Magseis Fairfield
- Statens Vegvesen (NPRA)
- Norwegian Water Resources and Energy Directorate (NVE)
- Shearwater
- Tampnet
- TietoEVRY
- Uninett

By exposing PhD students and PostDocs to a mixture of academic and industrial working environments with open and regular communication among all players, we stimulate innovations that are closely coupled to industrial needs. We plan shorter and longer stays for the students both in industry and with our international partners.



SCIENTIFIC ACTIVITIES AND RESULTS IN 2021

WORK PACKAGE 1: DISTRIBUTED ACOUSTIC SENSING (DAS)

ACTING WP LEADER SUSANN WIENECKE
AND WP LEADER JAN KRISTOFFER BRENNE, ASN NORWAY

This work package aims to achieve technology acceptance for DAS by demonstrating its capabilities within several applications such as geohazards and soil monitoring (geotechnical applications), whale and vessel monitoring (oceanographic applications), car and train traffic monitoring (terrestrial applications).

We are also working on state-of-polarisation (SOP) sensing, which is a lowcost promising technique for sensing over long distances (>200km) allowing use of the worldwide telecom network. This year, we hired Ph. D. student Kristina Shizuka Yamase Skarvang for this project, and she has already started initial laboratory measurements and feasibility studies.

During 2021 WP1 engaged with other WPs and several partners (e.g. AkerBP, ASN, BaneNOR, Digital Geology, TietoEvry, Equinor, NORSAR, Uninett, Shearwater and Tampnet) to explore future collaborations. DAS datasets were delivered according to the work plan and ASN supported DAS data processing and interpretation.
The datasets have been shared with WP5 and WP6 to prepare for work on methods and algorithms for DAS data compression, processing, feature extraction and edge computing.

The following two field trials, conducted in 2021, illustrate core achievements and key deliveries concerning DAS data acquisition and preliminary analysis:

- Rissa - geotechnical applications (quick clay)
- Marienborg - train traffic monitoring.

Rissa/Fosen field trial

This project involves cooperation from several partners (NTNU, NORSAR and Magseis Fairfield). ASN participated as partner of CGF but also as work package leader for WP1.

CGF selected a test site near Botn in Rissa at Fosen, in an area of quick clay, where construction work related to a new road (Fylkesveg 717) is being carried out. It was crucial to acquire DAS-data before this work began, to establish a baseline for geophysical monitoring of the soil and detecting changes in the geomechanical properties.

The motivation from ASN as partner of CGF is to understand customer needs and fine-tune parameters enabling geophysical applications concerning signals of smaller wavelengths, such as tube waves and Rayleigh waves, that can be used to infer changes in the shear modulus; an important parameter determining the formation strength.

The main goal for this field trial was to evaluate the suitability of DAS for soil monitoring and to compare the results from the OptoDAS interrogation to the measurements using conventional equipment in active seismic, such as nodes and hydrophones. Post processing, imaging and interpretation of DAS-data and comparison to conventional data will be done by PhD students from NTNU and NORSAR as part of their PhD work.

ASN planned and executed the installation of the FO equipment (Fig. 2). A control room was established in a barn close to the construction work site. This room was used to protect the interrogator and serve as a start- and -end point for the cables that are interrogated. The FO cable was trenched to a depth of approximately 40 cm in and outside the area of quick clay deposits.

The FO cable was interrogated with a gauge length of 3.1m, spatial decimation 2m, and sampling frequency 10 kHz. The data were temporally decimated by a factor of 10 to reduce the data volume to be stored.

One aim is to investigate the effect of ground coupling to the FO cable and the effect of temperature changes. Therefore, two FO cables with different properties, so-called loose- and tight tube FO cables, were spliced together. It will be also investigated whether looping of FO cables for signal stacking could be beneficial regarding detection of smaller wavelengths.

We expect innovation potential to be generated with higher spatial sampling and covering large areas, potentially of great benefit in quick clay mapping and monitoring, compared to conventional methods (such as ground penetrating radar and electromagnetic surveys).

In the future, using more advanced techniques for signal processing, we hope that feature classification and machine learning methods will enable the development of warning and forecasting systems for quick clay monitoring and other geotechnical applications.

Figure 2. Preparation of DAS data acquisition with interrogator in the barn, installation and trenching of fiberoptic cables.

DISTRIBUTED ACOUSTIC SENSING (DAS)

Fig. 3 provides an overview of the cable layout, divided in sections A, B and C. Section A is close to the control room (barn), section B comprises the area of wells, with a loop from well 1 to well 2 and back and section C covers the area outside quick clay, close to a street.

DAS is proving surprisingly sensitive to people walking in the field and animals (deer). The measurements are displayed as RMS value of integrated phase ranging from -45 (magenta) to -85db (marine blue).

This field trial increased our understanding of the OptoDAS capabilities and revealed possibilities beyond initial motivations and goals. Signals from moving objects close to the cable where easily detected (cars, trucks, humans, animals) and differentiated (e.g. Fig. 4).

Regarding the effects of coupling of the Fibre-Optic (FO) cable to the ground and the sensitivity to temperature changes in the surrounding sediments on different types of FO cable, we have noticed that the signal is slightly stronger for the tight tube (Hexatronic) cable in Section A. In Section B, on each side of the wells, the tight tube cable is much more sensitive to temperature changes.

In Section C, outside the quick clay, there are small differences between the two types of FO cable.

Marienborg/Trondheim field trial

This field trial was carried out with ASN, NTNU and Bane NOR. Bane NOR provided access to 50km of FO cable running from Marienborg to Støren, expressing their business interest in DAS monitoring methods for safety applications (detection and monitoring of people, cattle, cars, trucks etc.) close to railway tracks and crossings. Bane NOR also provided office space at Marienborg, used to house the OptoDAS interrogator.

Besides tracking trains, there is an interest in monitoring the integrity and anomalies in the train and railway tracks, in addition to the underlaying foundation, because of possible damage caused by quick clay and flooding.

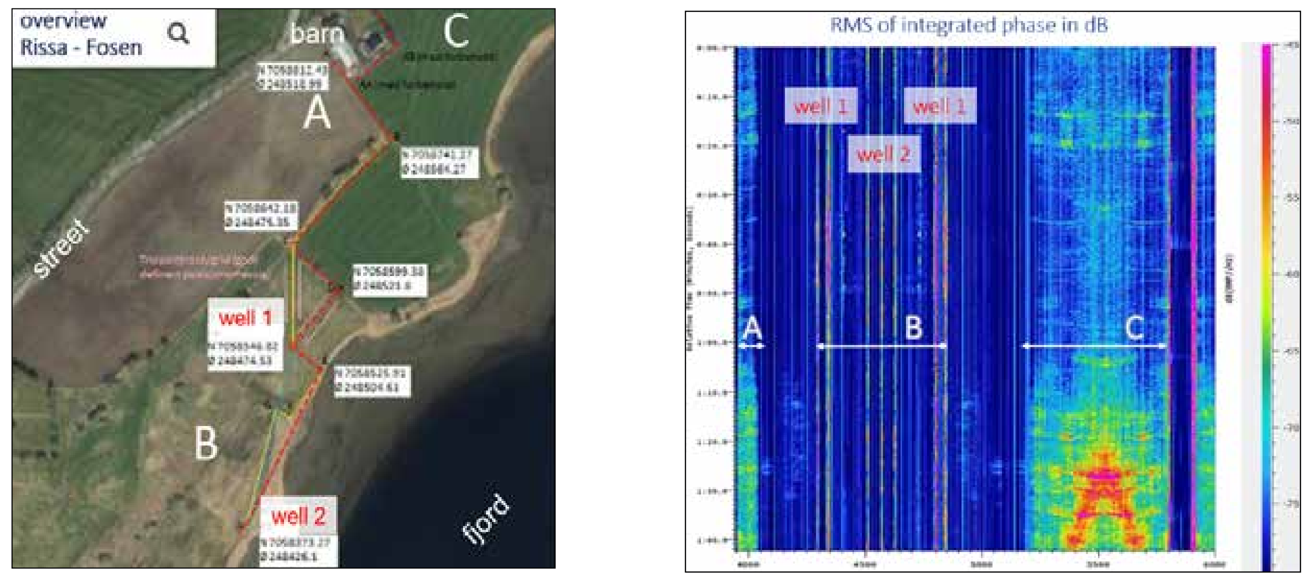


Figure 3. Plan view of the FO cable sections (left panel) and RMS value of integrated phase (right panel).

The sensitivity to detect smaller signals was remarkable. In a field test with real time data measurements and visu-alconfirmation a 30mm diameter stone was thrown close to the railway tracks, and the signal was detectable (upper white circle in Fig. 5), even although the event occurred only 2 minutes after a train had passed. The train signal is obviously much stronger than that from the small rock. With conventional DAS technology, it is challenging to measure small signals shortly after a very large signal.

The train signal shows modulation by the varying geo-mechanical properties of the land, pointing towards the possibility of using trains as opportunistic sources for geotechnical and monitoring applications.

This pilot study illustrates that the high sensitivity and dynamic range of the interrogator provides significant innovation potential for new business applications related to tunnel and ground stability, geohazards and the moni-toring of people, animals and cars close to railway tracks and crossings.

Fig. 6 shows DAS measurements over the entire 50km cable length (x-axis) from Trondheim to Støren for ca. 30 min (y-axis). Road vehicles of various sizes are easily seen and their speed estimated, with the "lines" they generate varying in strength depending on the distance of the road to the railway.

A regional train can be seen to travel from Støren to Trondheim and the change in speed easily monitored. There is also a local train, with a distinct signal that is easily distinguished from the larger, faster regional train.

This field trial is considered a great success by all parties involved, and an innovation prospect has already been established and is being pursued.

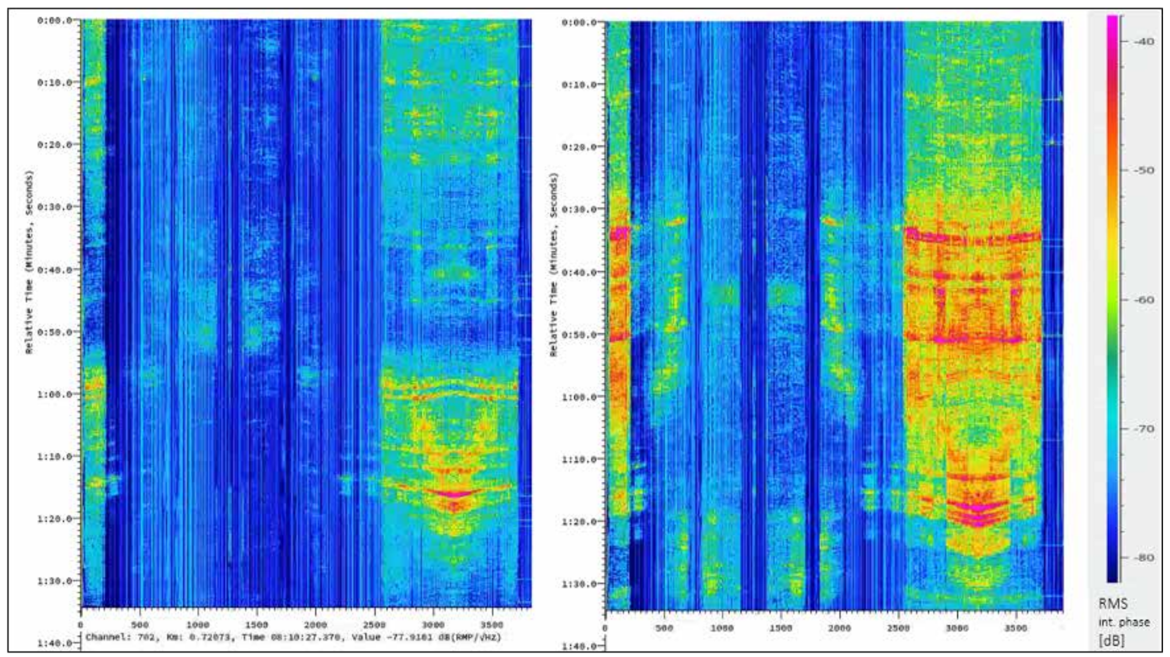


Figure 4. Signal of a car (left) vs. truck (right).

DISTRIBUTED ACOUSTIC SENSING (DAS)

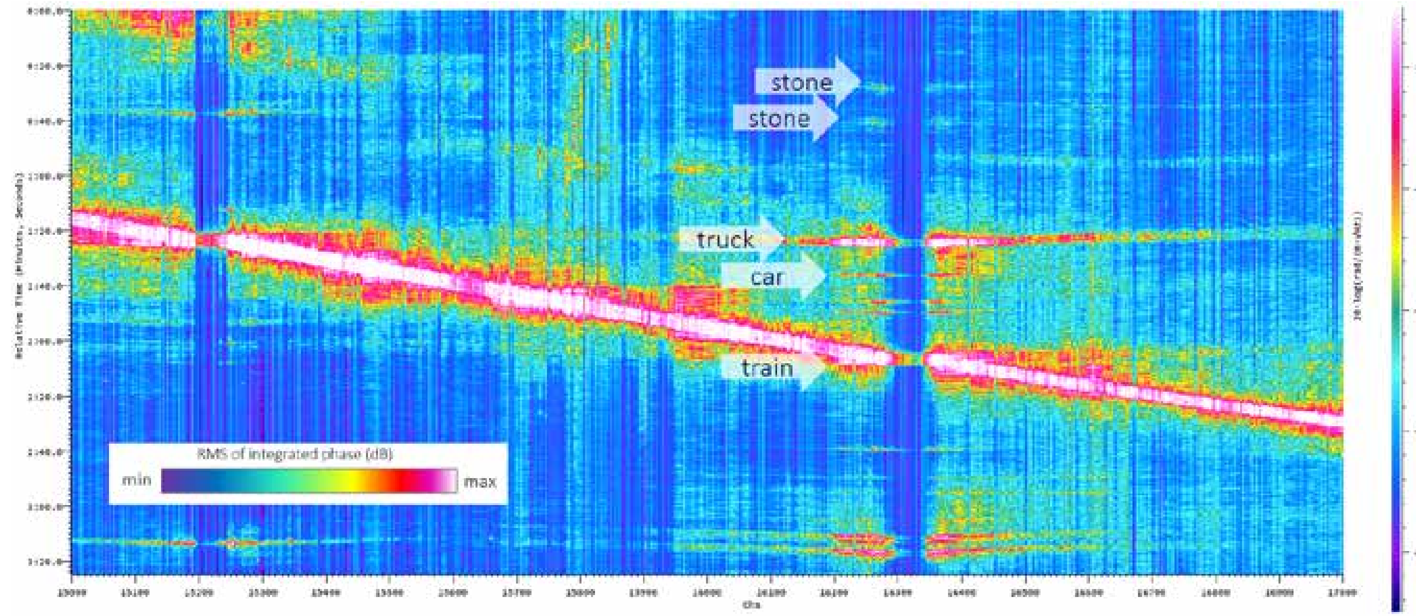


Figure 5. Field experiment for DAS sensitivity. The signal of a 30 mm diameter stone impacting the ground close to the railway was detected, 2 minutes after a train passed. Data measurements are displayed as RMS value of the integrated phase in dB (maximum values in magenta, minimum values in blue).phase varying from -38 (pink color) to -82 dB (blue color).

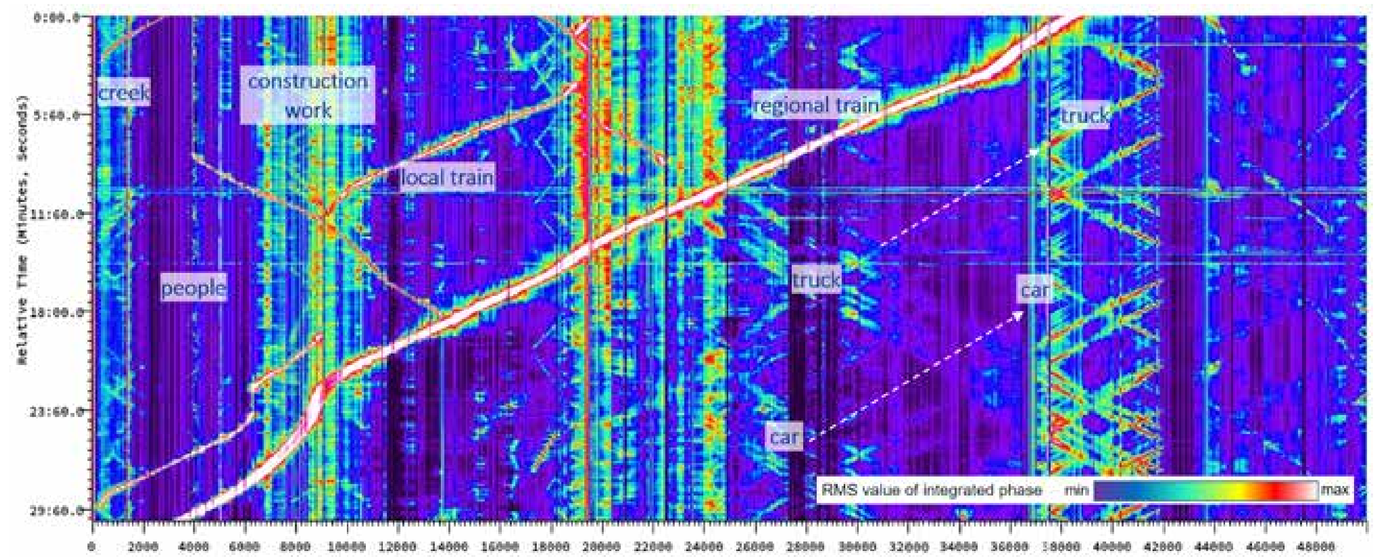


Figure 6. DAS measurements over the entire 50km cable length (x-axis) from Trondheim to Støren for ca. 30 min (y-axis). Data displayed in RMS value of integrated phase in dB.

WORK PACKAGE 2: CO_2 AND GAS/ENERGY STORAGE

WP LEADER PHIL RINGROSE, NTNU & EQUINOR

This WP advances methods for geophysical monitoring and forecasting of CO_2 storage projects, using existing projects (like Sleipner) and emerging sites (like the Northern Lights). Using scaled laboratory experiments, high-resolution earth models and seismic imaging datasets we work on:

- How accurately can we detect a 'cloud' of CO_2 in the subsurface?
- Better ways to predict fluid flow and ground deformation around injection sites
- The behaviour of hydrogen and methane in seasonal energy storage systems

During 2021 the main focus has been on starting up two PhD projects:

- WP2-PhD-1: Improved detection of 'leading edge' up-dip and down-dip lateral migration of CO_2 plumes using coupled plume-dynamics models and 4D seismic processing
- WP2-PhD-2: Improved geophysical detection and forecasting of vertical migration and leakage of CO_2 (dense phase and gas phase) into realistic high-resolution models of overburden sequences.

In September 2021, two PhD candidates were appointed, Ricardo Martinez and Andrea Santi. Both these PhD positions are administered under the Institute for Geoscience and Petroleum. For WP2-PhD-1 the lead supervisor is Kenneth Duffaut with co-supervisors Philip Ringrose and Martin Landrø. For WP2-PhD-2 the lead supervisor is Philip Ringrose with co-supervisors Martin Landrø and Kenneth Duffaut.

As part of setting the framework for this research activity, a review article was compiled and published in the 'Annual Reviews' publication series (Ringrose, Furre, Gilfillan et al. 2021). This paper summarises the state of the art in the field of CO_2 storage in saline aquifers including the following main themes:

- Fluid dynamics CO_2 in a brine-saturated porous medium
- Dissolution and mineralization of CO_2
- Injectivity and well constraints
- Trap capacity and pressure limits
- Monitoring to optimise and confirm storage

The last of these topics is the main research focus of WP2, with the challenges for monitoring CO_2 plumes in terms of edge detection of an expanding CO_2 plume illustrated in Fig. 7. The two PhD research projects mentioned above will focus on different aspects of this problem.

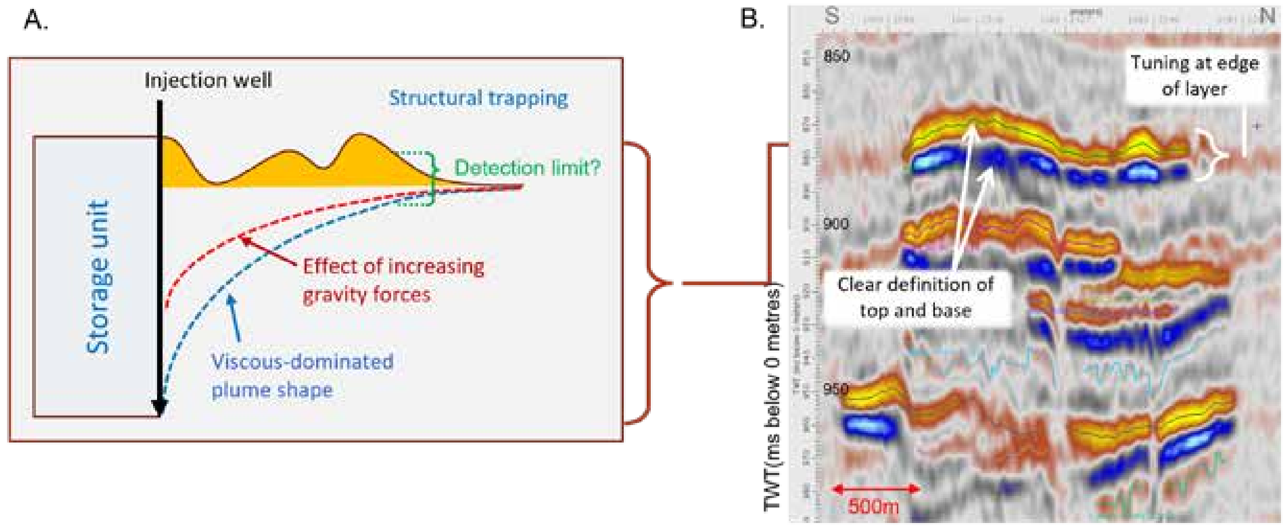


Figure 7. Illustration of the challenges in edge detection of an expanding CO_2 plume: (A) Sketch of the fluid dynamical factors affecting the shape of an expanding CO_2 plume; (B) Cross-section through the 2010 seismic amplitude data at the Sleipner CO_2 storage site showing amplitude variation for the CO_2 plume in Layer 9 (modified from Ringrose et. al. 2021)

Towards the end of 2021 the PhD research had matured enough to prepare two conference abstracts, submitted in January 2022.

Other publications this year were related to PhD research projects funded from other sources but co-supervised by Prof. Ringrose. The paper by Weber et al (2021) is focused on the use of Noble gas tracers as a CCS monitoring method, which can be an important complement to geophysical methods. The paper by Nhabanga et al. (2021) concerns rock-physics analysis of mudrocks and shales – an important part of assessing caprock effectiveness for hydrocarbon and CO_2 containment systems.

Phil Ringrose and Martin Landrø participated in a new extensive EAGE short course on geological CO_2 storage to be launched in January 2022. The course has been initiated by EAGE and is a collaboration of Carbon Capture and Storage (CCS) experts including researchers from Heriot-Watt and NTNU.

In November 2021, the CGF hosted a visit of Dr. Markus Pieper, Member of the European Parliament for Germany, as a part of a fact-finding visit (hosted by Equinor) to gain an overview of R&D on CCS, renewables and low-carbon hydrogen. Prof. Philip Ringrose and Prof. Martin Landrø presented an overview of CO_2 storage research with a focus on emerging geophysical methods, including the latest DAS findings, that can support future expansion of CCS in a low-emissions society.

As part of public outreach, Landrø and Ringrose published a chronicle feature in the newspaper Adressavisen, which sparked a spirited debate on the cost and urgency of CCS. Ringrose also published a feature article in the UK-based Geoscientist magazine presenting a discussion on 'reimagining' applied geoscience for the energy transition as part of a series published for the COP26 Climate summit in Glasgow, 31 October – 13 November 2021. A commentary on Next generation geophysical sensing was also published in the journal First Break with inputs form all of the CGF work packages (Ringrose, Landrø, Potter et al. (2021).

CO_2 Lab and digital datasets

CGF is host to a scaled CO_2-lab facility, funded as part of the ECCSEL initiative (the European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage), Fig. 8.

During 2021 this facility was developed and tested demonstrating the function of the acoustic transducers in active and passive detection mode.

Smart offshore acquisition concepts and proposals

The WP2 team has worked closely with industry partners to develop and 'brainstorm' ideas and concepts for novel geophysical monitoring concepts focused on CO_2 storage monitoring challenges. Together with Magseis Fairfield we explored concepts for a potential offshore test of a low-density/low-cost subsea node deployment for geophysical investigation of the Øygarden Fault. The Øygarden

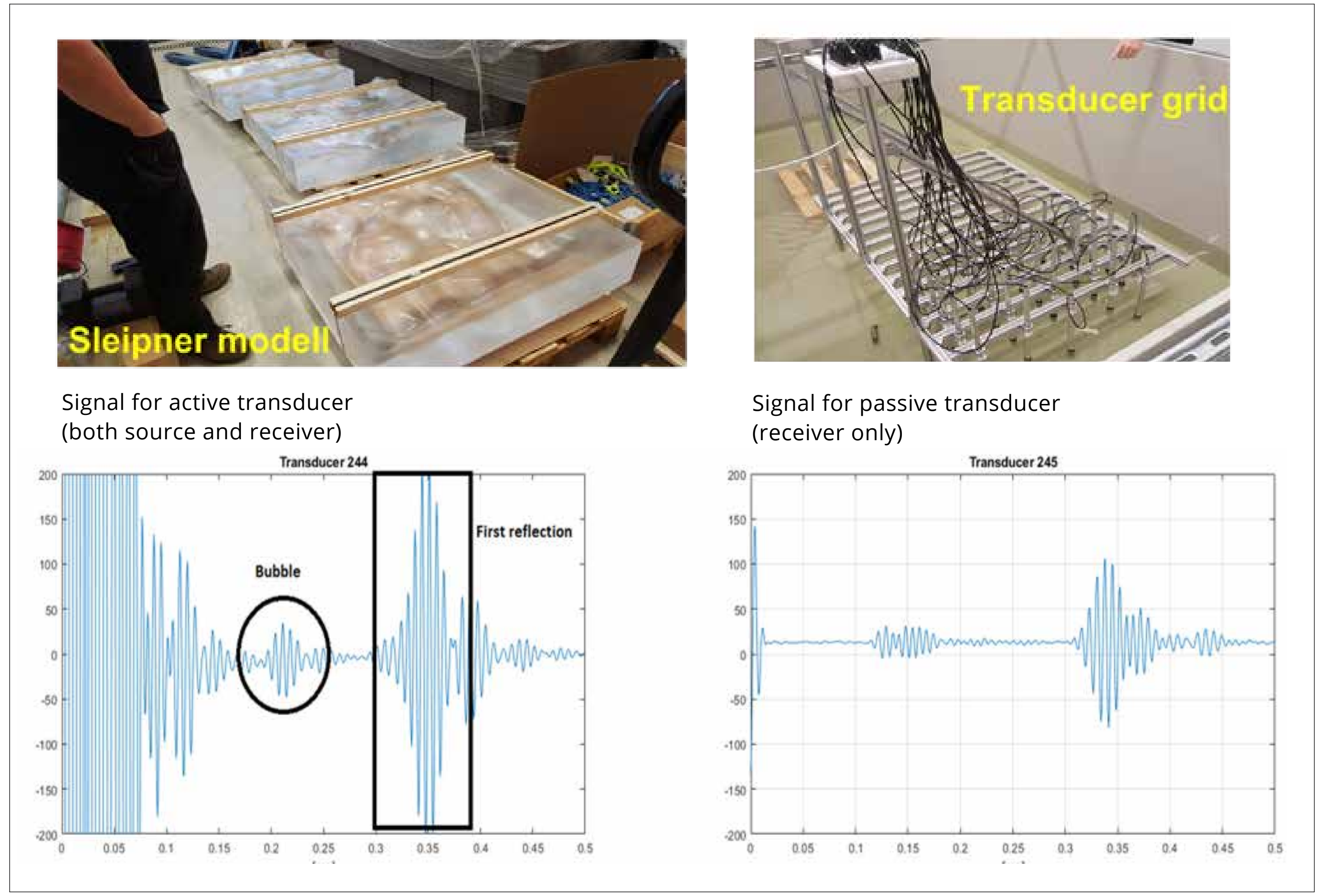


Figure 8. Images form the scaled CO_2-lab facility in the development and testing phase (top) and results from testing of transducers (below).

CO_2 AND GAS/ENERGY STORAGE

Fault represents a key uncertainty for future CO_2 storage scale-up in the Horda platform region, and Magseis Fairfield has offered 50 OBN nodes.

The proposed test has several scientific objectives that will help constrain and quantify risks associated with future CO_2 storage developments offshore Norway:

- Acquire high-resolution geological imaging of a section of the Øygarden fault
- Demonstrate novel use of refracted and reflected wave imaging and FWI methods using a sparse OBN system
- Assess the velocity field variation in a region with large subsurface uncertainties
- Demonstrate passive seismic monitoring using a targeted OBN system, especially to understand shallow versus deep seismicity
- Mature 'response technology' for assessment of shallow overburden anomalies as part of the technology development for CO_2 storage.

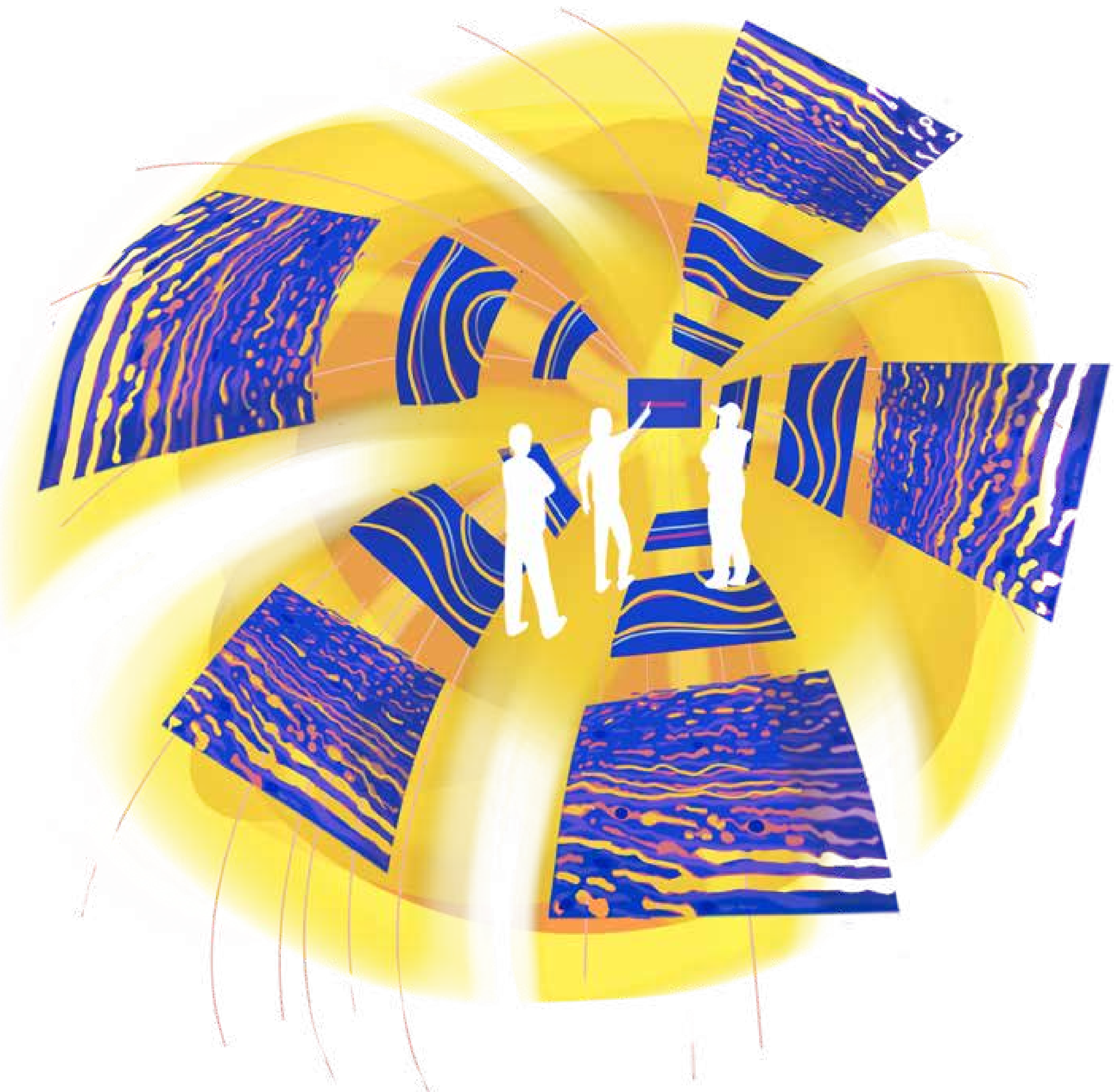
A key research goal is to find optimal ways of using diving waves to improve the velocity model while also having sufficiently dense spacing for improved imaging. The WP2 team is developing options for hybrid dense and sparse OBN acquisitions to address these challenges. This should open up options for smart 'de-risking' seismic surveys over areas of interest such as the geologically complex Øygarden fault, which is an identified as a specific risk factor for CO_2 storage in the Northern Lights region offshore Norway (Wu et al. 2021).

Together with CGF partner Shearwater WP2 has also discussed ways of developing novel/optimal towed marine streamer seismic acquisition surveys, focused on using both high frequency (HF) and low frequency source (LF) in a setup that could provide both high-resolution near-offset data suitable for imaging, as well as long-offset low-frequency data suitable for FWI model building. These novel acquisition concept will be developed further in 2022 for possible execution in the 2022-2023 timeframe.

Master's student project and other collaborations

During 2021 we engaged three Master's students in a project on analysis of pressure decay for multiple CO_2 storage projects at the basin scale using the Smeaheia storage prospects model as a case study. The project applies analytical approaches to modelling pressure increase and decrease in sealed and/or leaky fault blocks. Initial conditions can be estimated from regional basin datasets, but the rate and flux terms have large uncertainties. The objective of the project is to apply machine learning methods for optimisation of this problem. The work is in collaboration with WP5 on the application of HPC tools and methods to CO_2 storage challenges. CO_2 fluid flow modelling and methods to handle CO_2 migration in the overburden are also being studied.

Ringrose and Nhabanga are developing a global comparison shale sealing behaviour for CH_4 and CO_2 containment systems. This work is funded by the CGF in partnership with Eduardo Mondlane University in Mozambique. The work has been submitted for publication, with preliminary findings presented at the virtual PESGB/HGS Africa E&P Conference (14-15 September 2021). Other collaborations included work with the Universities of Oslo and Edinburgh on the use of noble gas geochemistry as a complement to geophysical monitoring methods for assessing CO_2 storage system



WORK PACKAGE 3: EFFECTIVE MONITORING AND FORECASTING SYSTEMS OFFSHORE, COASTAL AND ONSHORE

WP LEADER HEFENG DONG, NTNU

WP3 develops new 4D seismic analysis methods exploiting full-waveform inversion and refracted waves. These methods depend on close collaboration with WP5, applying cutting-edge HPC technologies. By combining regular 4D PRM-seismic data with sparse surveys and passive data, the goal is to generate valuable innovative monitoring capabilities. Combining 4D seismic with gravity, EM-data, DAS and other data sources will improve the accuracy of estimated saturation and pressure changes in a reservoir or CO_2 storage site.

WP3 has followed the work plan for recruiting and collaboration with other WPs, planning data acquisition, acquiring data, and analysis of both active and passive data.

Three projects have been established, with three new Ph.D. students starting in September 2021.

Distributed Acoustic Sensing for shallow subsurface monitoring as a tool for landslide forecasting.

Ph. D. student Kevin Growe has been recruited for this project, which uses DAS to monitor shallow subsurface properties as a potential tool for landslide forecasting. DAS capabilities will be tested in two field experiments, analysing surface and compressional waves. Due to the higher frequency content, compressional waves are strongly attenuated in clay and will need stacking to be visible. Geophones are also deployed to collect 3-component data for comparison. Further, to obtain references values for the subsurface parameters, a sample of quick clay has been taken and measured in the lab.

Multiphysics modeling for in-well monitoring of production/injection wells using FO data.

Ph. D. student Nicholas Bradley has been recruited for this project, which is in collaboration with our partner Equinor, focusing on multi-physics modelling for in-well monitoring of production and injection wells using FO data. Preliminary research will focus on low-frequency data processing and analysis of production and well-integrity monitoring datasets allowing for interpretation of tube waves and other dispersive modes. Variability of in-well pressure and temperature changes will be examined alongside production profiles.

Diving waves in anisotropic media

Ph. D. student Kristoffer Tesdal Galtung has been recruited for this project, applying ray theory to model diving waves in anisotropic media with orthorhombic anisotropy to obtain information about elastic properties. A possible approach is to do tray tracing analytically using factorised anisotropy models. An inversion code will be developed for estimating the elastic properties of anisotropic media using a forward ray tracing model applied to field data from AkerBP. Current work includes a literature study on the -state-of-art and search for existing ray tracing codes to find out the codes' availability and capabilities. Currently, one of these is being compared to doing ray tracing analytically using factorised anisotropic models (elliptical and orthorhombic), which necessitates coding in Mathematica. The code will serve as a benchmark for a new code to be developed. DAS and geophone data have been acquired from two sites: RISSA and NOR-FROST.

Rissa test site

The RISSA site is located near Trondheim Fjord in a quick clay area and is the site of a major historical landslide in 1978. A new road (Fylkesveg 717) is being constructed in the area, which will increase the load on the subsurface. In collaboration with WP1 and CGF partner Magseis Fairfield, a project was established for observing and monitoring any changes in the subsoil and quick clay conditions when building the road. Multiple kilometers of FO cable have been trenched to a maximum depth of 40 cm, approximately parallel to the new road (Fig. 2, 3), to monitor large-scale subsurface changes related to construction at the site, including water content and freeze/thawing.

Figure 9. Data acquisition at RISSA site. CGF personnel preparing for deployment of geophones (left) and acquiring DAS and geophone data in July 2021 (middle), and taking core sample in October 2021.

Two wells were drilled along the side of the planned road, separated by 169 m. Three-component land nodes from Magseis Fairfield were deployed and a hydrophone array was installed in one of the wells for measuring tube waves. A core sample of the quick clay was taken close to one of the wells and will be measured in the lab to obtain in-situ properties (Fig. 9). Since July 2021 five active acquisitions have been carried out and passive DAS data have been collected. Both active and passive DAS data were acquired for the entire period, while the geophone data (for comparison purposes) were acquired during the first 40 days, together with hydrophone data recorded during a subset of the active shots. Some DAS and geophone data have already been analysed with REVEAL software in collaboration with CGF partner Shearwater. Time-frequency analysis of a single active shot clearly shows the dispersive Rayleigh wave with four modes, Fig. 10. These can be used to estimate the near-surface properties of the quick clay. Preliminary analysis results show good agreement with those from NGI's 2015 report on the same site, indicating that the near-surface has not been affected by the road construction work so far.

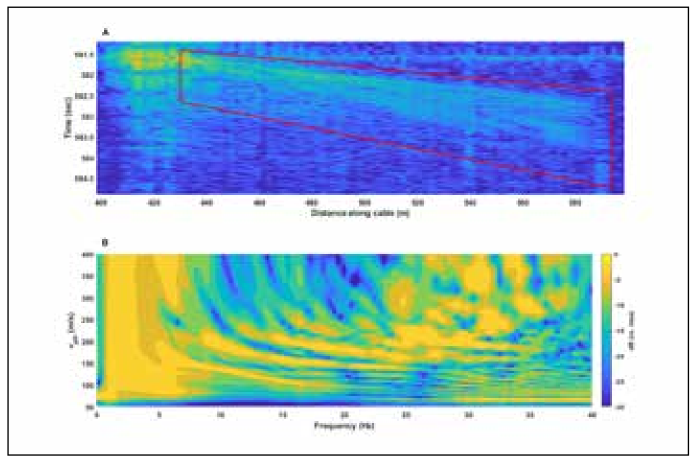


Figure 10. DAS data from one active shot at Rissa (upper panel) and phase-velocity dispersion spectrum (lower panel) showing clear dispersion modes.

NOR-FROST test site

Within the CODAS activity of the ECSSEL research infrastructure project, the NOR-FROST site was established at NORSAR. Different FO cables were buried at three different depths in three trenches filled with three different materials (sand, gravel, concrete, Fig. 11, 12). The temperature and humidity of the materials are also collected by hygrometers buried at different locations in one of the trenches for monitoring the seasonal variation, which affects the seismic properties of the material. The purpose of the test site is to investigate the potential of DAS for the characterisation of the near-surface properties and their cyclic changes. Complementary to the active acquisition, ambient noise tomography techniques will be applied to aid the analysis. Additionally, for validation, the DAS data will be compared to geophone data that are collected along the surface. The aim is to resolve cyclic changes in the subsurface related to heavy rainfalls, freezing and thawing. Additionally, we will conduct a controlled experiment adding a load on the surface and monitor the dynamic stress change. So far, some initial active test data have been acquired, processed, and evaluated. Based on the evaluation the acquisition configuration will be modified to improve the data quality and extract the maximum of information. New test data will be acquired in early Spring 2022. If the data quality is approved, the long-term monitoring of the site will begin in April/May 2022.

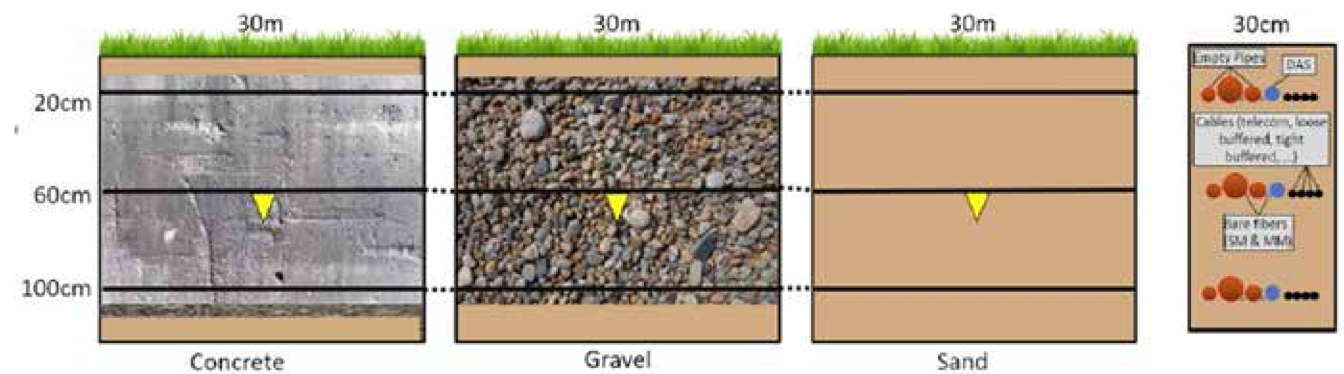


Figure 11. NOR-FROST test site, where FO cables are buried at three different depths in concrete, gravel and sand trenches. Right panel indicates the recording system.

Figure 12. Acquisition of DAS and geophone data at the NOR-FROST test site behind the NORSAR office building in Kjeller.

WORK PACKAGE 4: GEOHAZARD PREDICTION AND DEEP MAPPING OF THE EARTH'S CRUST

WP LEADER VOLKER OYE, NORSAR, NORWAY

Avalanches and rock slides are major geohazards for Norway and other mountainous regions. WP4 projects include avalanche monitoring in collaboration with Statens Vegvesen (SVV) at the Grasdalen test-site (Strynfjellet), and rock slide monitoring at Åknes in Møre Romsdalen in collaboration with NVE.

In addition, we investigate the potential for monitoring of geophysical property changes in quick-clay regions and evaluate how the detection and location of earthquakes, and especially their depth, can be improved by using offshore FO infrastructure.

WP4 also investigates deep mapping of earth's crust by combining data from active seismic, electromagnetic and earthquake seismology to better understand the structure and composition of plate boundaries such as the mid-Atlantic ridge and subduction zones offshore Japan.

Avalanches are problematic wherever their paths potentially cross road or train traffic. Ideally, there will be mitigation actions such that avalanches are deviated with barriers or obstacles, or roads are placed in tunnels or galleries. However, this is not always practically or economically feasible, and in such cases avalanches do run over roads or train tracks. Real-time alerting of incoming avalanches is certainly of interest as one mitigation process, but also simply alarming of an avalanche that did cross a road, and potentially buried traffic is of high interest. This will allow to plough the roads as soon as possible, allow traffic to pass quicker and in some cases may even save lives.

Grasdalen test site

At Grasdalen in Stryn, Vestland fylke, SVV has the possibility to trigger controlled avalanches by detonation. WP4 is testing DAS to sense and send alerts in real-time in case an avalanche impacts the road (Fig. 13, 14). NORSAR has deployed a DAS interrogator unit in a safe cabin within the tunnel at the site (Fig. 15), connected to a FO cable deployed at the side of the road. We will sample this ~1.1 km long FO cable at 1 kHz with a 1m resolution. The large amount of real-time DAS data can then be processed to alert both about potential avalanches covering the road and also inform about crossing or stopped traffic. These data are now being collected and characteristic signatures will need to be investigated and understood, so that automatic real-time processes can be implemented.

Figure 13. Road stretch at Grasdalen, equipped with FO cable for ~1.1 km length from Grasdalstunnelen (west) to Oppljostunnelen (east). The interrogator unit is deployed in Grasdalstunnelen at K6. The common avalanche break-off zone is on top of the mountain and typical high risk avalanche slopes are indicated with white arrows. Before the avalanches cross the road, most of the energy is supposed to be stopped by the avalanche break mounds. WP4 will analyse detonation released avalanches, potentially self-triggered avalanches and road traffic.

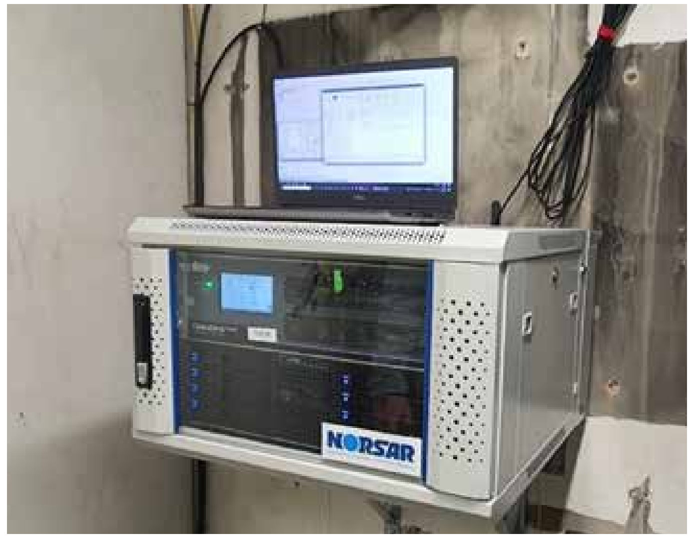


Figure 15. DAS interrogator unit installed in the tunnel at site K6.

Figure 14. Experts at the tunnel entrance, inspecting the slopes with potential avalanche paths.

GEOHAZARD PREDICTION
AND DEEP MAPPING OF THE EARTH'S CRUST

Figure 16. The borehole within the Åknes rock slope. The existing surface geophone network at the top scarp did establish that different types of seismic events are evident, and can be differentiated with machine learning methods like the Convolutional Neural Networks, and in WP6 are working on new types of machine learning, including ensemble processing.

Åknes site

The other main type of geohazard in Norway is related to rock slides. One particularly prominent rock slide is at Åknes in Møre og Romsdal, where a huge mass of rock is slowly but steadily moving towards the fjord and scenarios have been calculated that a tsunami of up to 80 m height may reach villages within the fjord in the event that it breaks free and plunges into the water. This is also the site of the Norwegian catastrophe movie "Bølgen".

NORSAR and NVE are collaborating to collect and process data from this site. In 2021, an 8-level geophone string was re-deployed in a 55 m deep borehole in the moving part of the slope (Fig. 16,17,18) with the purpose of better identifying and characterising microseismic events along the rock slope and trying to assign these events to either movement along the sliding plane or cracking and fracturing within the slide itself.

Figure 17 (L). A helicopter is needed to access the borehole to transport any equipment. Logistics are challenging and field-work is only possible during summer months.

Figure 18 (R). 3-component borehole geophones re-equipped with centralizers to stabilise them within the borehole to improve signal to noise levels.

WORK PACKAGE 5: HPC TOOLS AND TECHNIQUES FOR MODEL FITTING THE SUBSURFACE

WP LEADER ANNE ELSTER, NTNU

2021 featured work by two existing PhD students (funded by other sources) in addition to 10+ Master students who were part of HPC-Lab. HPC-Lab is part of CGF and hosted by the Department of Computer Science at NTNU.

Bart van Blokland defended his Ph.D. in December 2021 and could become a PostDoc at CGF while 3 of the current Masters' students may continue as PhD students when they finish their theses in the summer of 2022. Additionally, we have plans to recruit additional personnel in 2022, increasing our capacity to engage with other work packages.

Our work in 2021 focused on the following projects.

Autotuning GPU Codes

Autotuning enables low-level optimisation without having to hand-code applications for a specific hardware. Traditionally, autotuning has been achieved by time-consuming trial and error search methods. We have investigated whether Machine Learning (ML) could be applied to make these time-consuming searches more efficient.

One of the biggest challenges in succeeding with ML techniques is having access to good enough datasets. In 2020 we built a Large-Scale CUDA AutoTuning (LS-CAT) dataset, a parameterised dataset with close to 20 000 kernels that was constructed from all open CUDA source codes available on github that we were able to clean up. This dataset has been made publicly available and has gained interest from potential future European partners. In 2021 we used this set as training data for ML-based autotuning where we investigated whether ML can be used to select efficient thread-block sizes to increase kernel performance.

We implemented several custom Natural Language Processing (NLP)-ML pipelines to evaluate ML-based thread-coarsening using our LS-CAT dataset, and a custom scoring function to find the performance impact for any choice. Several model configurations were able to beat both random choice, (0.9400) and only selecting the largest thread-block (0.9437). The best model achieved a score of 0.9483, giving an average performance increase of 0.49% over selecting the largest thread-block.

There is also a challenge comparing autotuning frameworks that have pursued different methods. Elster & Tørring´s Master's students Ingunn Sund and Knut Kirkhorn created BAT: A Benchmark suite for AutoTuners, described in their theses, and in 2021 this was presented as a paper co-written with Tørring and Elster at the Norwegian ICT Conference for Research and Education (NIKT). Several other international groups are now keen to collaborate and build on our work.

BAT was benchmarked on both in our IBM Power systems with V100 GPUs and our NVIDIA DGX2 system (Fig. 19), with 16 tightly coupled NVSWITCHed GPUs. The latter is also being used in Tørring´s research on autotuning.

GPU optimisation techniques – Full Wave Inversion and Spectral Element Method

In seismic inverse problems the internal mechanical properties of the earth are estimated from surface measurements. Modern approaches rely on the ability to numerically simulate seismic wave propagation accurately and efficiently. Full Waveform Inversion (FWI) is a procedure to determine the elastic parameters of the Earth by reducing the misfit between observed elastodynamic wavefields and their full wavefield propagation model counterparts. The Spectral Element Method (SEM) is central to seismic simulations, including FWI (Fig. 20).

Figure 19. Anne proudly pointing out the recently-acquired NVIDIA DGX2-PXL, the world's first 2 petaFLOPS system for Deep learning and AI.

We are thus investigating how to optimise such methods for GPUs. Master's student Maren Wessel-Berg worked with Børge Arntsen and Anne Elster on a well-known package (SPECFEM) with the objective of increasing computational speed by effective use of GPUs.

Wessel-Berg and several other of our Master's students have been taking advantage of the new NVIDIA GTX 3090 cards we were able to purchase in late 2020 (Fig. 21). We expect to acquire more GPUs in 2022 and have applied for additional grants to cover research equipment.

Elastodynamic FWI on GPUs with time-space tiling and wavefield reconstruction

FWI numerical solutions are computationally expensive and the performance is typically bandwidth bound. Further complexity arises due to computing the zero-lag cross-correlation of two wavefields propagating in opposite temporal directions.

PhD student Ole Edvard Aaker and Børge Arntsen developed codes that use GPUs for their high memory bandwidth. They combined two principal optimisations in

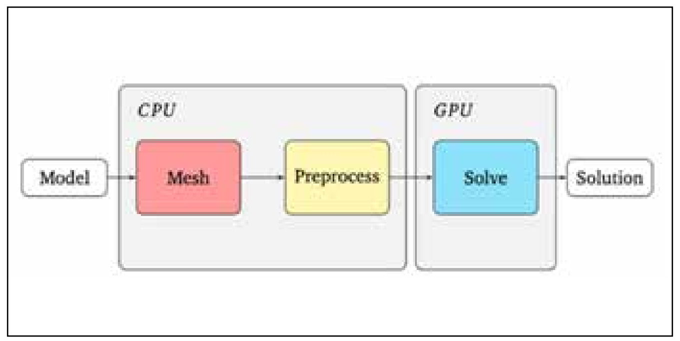


Figure 20. The Spectral Element Method – Main 3 steps.The codes were analysed using NVIDIA Nsight Systems and Nsight Compute. These are the tools that also were used by Ingvild Høgstøyl, one of Elster´s Master's student who has analysed code for CERN. Ingvild´s co-advisor was Dr. Maria Girone, CTO CERN OpenLab who is also the co-superviser of HPC-Lab Master's student Lars Sørlie who joined in the autumn of 2021. Their projects provide insights both for CGF and CERN with regard to analysing physics-based codes.

HPC TOOLS AND TECHNIQUES
FOR MODEL FITTING THE SUBSURFACE

Figure 21. NVIDIA RTX 3090 GPU at the HPC-Lab

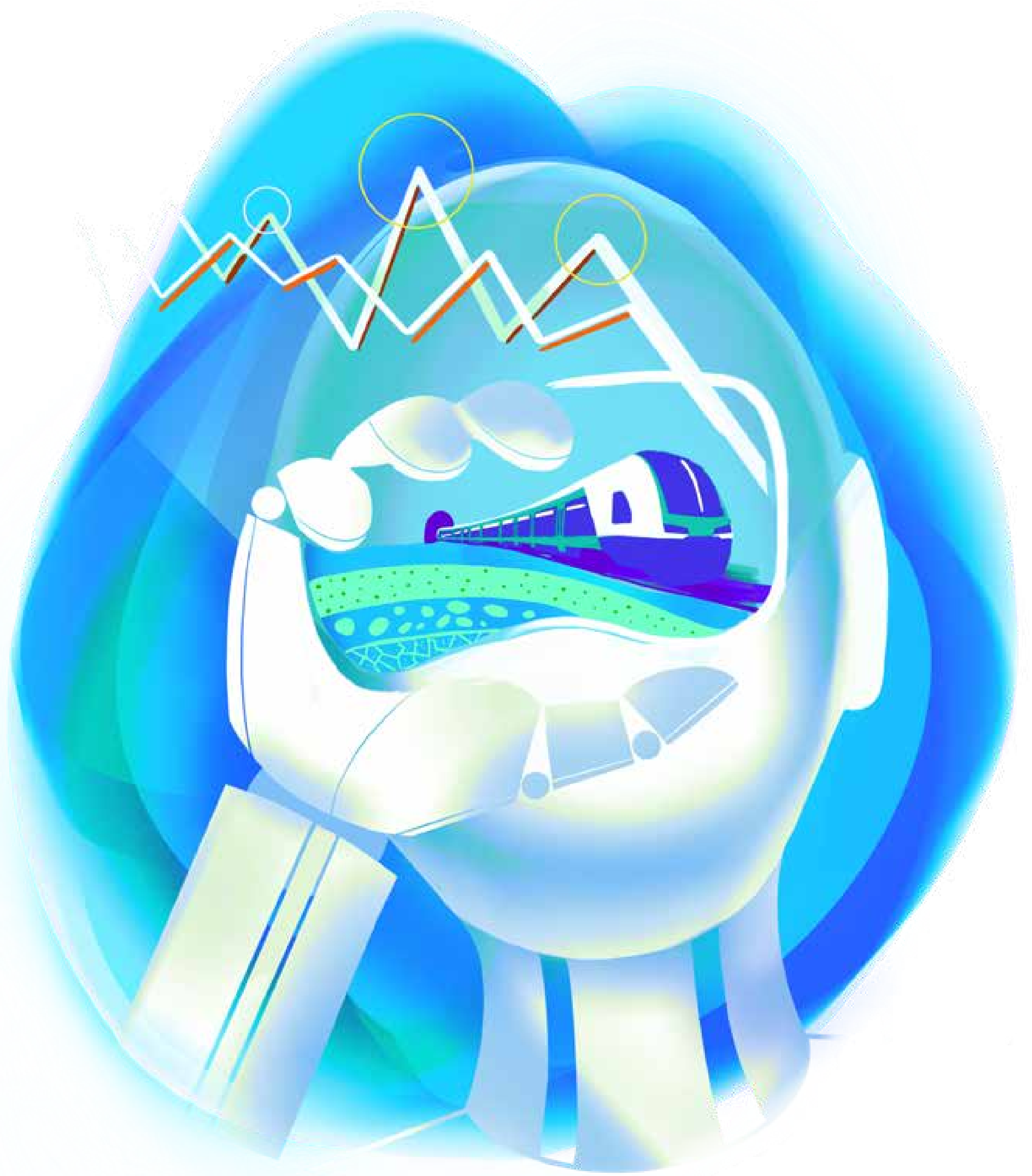
order to compute FWI gradients on large models and for long simulation times. Wavefield reconstruction methods allowed efficient gradient computations with minimal memory requirements and interconnection transfers.

Time-space tiling techniques permitted us to transcend the limited amount of GPU memory while avoiding dramatic slowdowns due to the low interconnection bandwidth. The implementation considered a task-oriented, hybrid usage of explicitly-managed and Unified Memory in order to satisfy the requirements. Benchmarks demonstrate that the proposed approach was able to preserve 78 – 90% of the original performance, when oversubscribing the amount of physical memory available on GPUs. Comparison with existing methods highlights the benefits of the method.

Collaboration with WP2 on CO_2 storage and other HPC-Lab projects related to CGF.

We also had HPC-Lab Master's student Tobias Dyngeland join us in the autumn of 2021. He has been working with two of Phil Ringrose´s Master's students on a project related to CO_2 storage. Dygeland and HPC-Lab Master's student Haugdahl have both expressed strong interest in continuing as CGF PhD students.

Several of the other current Master's projects, including ones connected to the HPC-Lab snow simulation, ray tracing, and Vulkan API projects, are also expected to benefit CGF.



WORK PACKAGE 6:
DATA ASSIMILATION AND UNCERTAINTY QUANTIFICATION

WP LEADER JO EIDSVIK, NTNU

WP6 develops methods and algorithms within the domains of mathematical statistics, machine learning and artificial intelligence. Within a probabilistic Bayesian approach for modeling and data assimilation, we will build models from geological and geophysical principles, and incorporate the sensor measurement tool reliability. Models will be updated with diverse in-situ data in space and time for reliable geophysical forecasting. This framework enables interpretable analysis of cause and effects, and further eases the deliverables of alarm detection systems and event-based monitoring systems. The work will have a strong motivation and integration with WP1-5, ensuring cross-disciplinary learning in the CGF and fostering research and innovation results relevant to partners.

WP6 recruited a PostDoc (The Tien Mai) in September 2021. He comes from a PhD in France and a PostDoc at the University of Oslo. In his CGF research he is mainly working on DAS processing and analysis. He is also working on Markov chain Monte Carlo methods for seismic inversion.

During Autumn 2021, WP6 delivered a 5-lecture course on Statistics and Uncertainty Quantification for CGF. The target group was PhD students, PostDocs, researchers and project partners in the CGF interested in knowing more about probabilistic modeling and using statistics and uncertainty quantification in their applications. There was a good number of participants, ranging from 10-40 during the five lectures. The content of the lectures included:

- Discrete and continuous probability models
- Conditional probability and Bayes' ruleGraphical models such as Markov chains and Bayesian networks
- Gaussian process model and Bayesian inversion
- Non- linear geophysical inversion methods such as Markov chain Monte Carlo sampling and the ensemble Kalman filter.

Throughout the short-course, there were illustrative examples from seismic inversion, CO_2 storage monitoring, prospect evaluation, and reservoir simulation, emphasizing practical applications rather than mathematical derivations.

In the Spring of 2021, WP6 organised presentations from all the other WPs in addition to some working seminars from partners Equinor and TietoEVRY, who gave presentations on research relevant to data assimilation and uncertainty quantification.

WP6 has received strong interest in working on DAS data. In WP6, we have mainly focused on the data gathered on the BaneNOR FO cable between Marienborg and Støren

(50 km). Based on the high-quality data from this test, we have worked on developing methods for data processing and conducting analysis for classification of targets (trains, cars, and other events) and tracking of target positions and velocities. The work has mainly been driven by NTNU, but partner TietoEVRY also took part in some discussions and data analysis.

To motivate the ideas behind some of this work, we indicate results in a simulation study (Fig. 22). Here, we mimic DAS data over 5000 channels (x-axis) and for 160 seconds (y-axis). Such simulation studies allow us to experiment with various noise levels and complexities of the setup. In the DAS energy plot (left panel) we can recognize two trains (larger amplitudes and going on for many seconds) and several cars (smaller amplitudes and lasting shorter). There are also several minor events that do not show much coherence. In the analysis, we first use an automatic picking routine to find channel-separated high-amplitude events (middle panel). In this step, we further associate signature characteristics to each of these events (amplitude, width, frequency content). These events are then used in a multi-target data association filter where we also embed a classification algorithm. This can be applicable in an online application where the goal is to classify and predict properties of the events in real time. The results of this kind of filtering exercise (right panel) show that we can classify trains quite well (black), most cars (blue) and most noisy events (red).

In collaboration with WP4 and NORSAR, we have also worked on classification methods for various types of rock fall at the Åknes rock slope. The data provided by NORSAR and NVE consist of several thousand events of rock fall that have been manually classified by NORSAR. For each event, there are 16 seconds of multi-component recordings from eight geophones.

To avoid tedious labeling of individual events, it is valuable to develop automatic classification algorithms and our goal has been to improve on the state of the art for such classification. To evaluate the quality of different approaches, one must first check the performance on the manually labeled data. By implementing new machine learning algorithms and tailoring them to this application with multi-component geophones, we have substantially improved the accuracy of automatic classifiers. The approach we are using (Fig. 23) is to rely on machine learning approaches to transform the multivariate time series into more independent components (Variance-Invariance-better-Covariance Regularization - Vibcreg), thus getting more information out of the features. We further apply an ensemble-learning approach over the multiple geophones.

WP6 has also been working with CO_2 monitoring approaches in collaboration with WP2, where the goal is to blend percolation theory with a statistical Markov chain modelling to predict the leakage probability of injected CO_2. Such models could help predict the leakage risk prior to injection and could also facilitate decision support tools associated with injection strategies and how monitoring programs are useful to map the injected CO_2.

DATA ASSIMILATION
AND UNCERTAINTY QUANTIFICATION

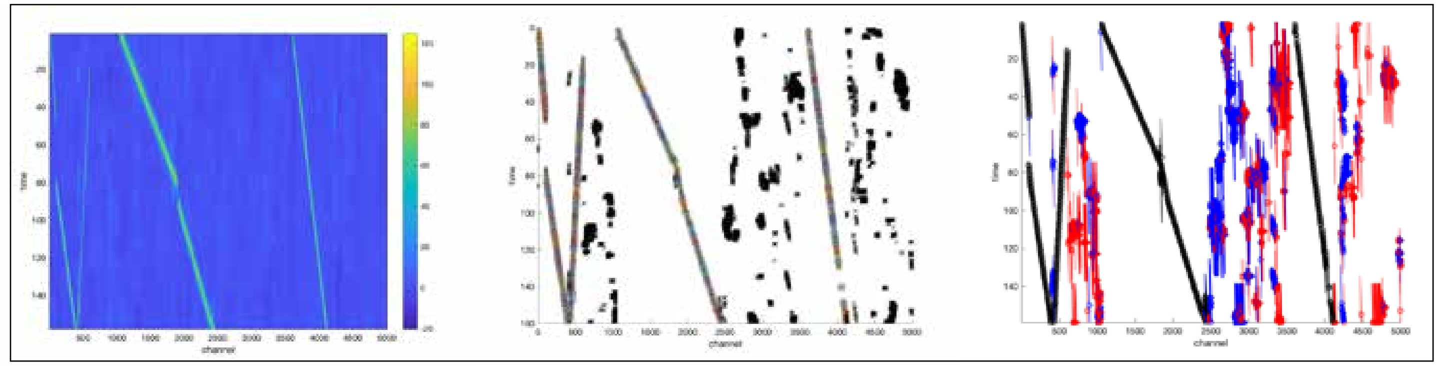


Figure 22. Example of DAS data analysis: Illustration of DAS energy (left), processed data picks (middle) and colour-coded tracking results (right).

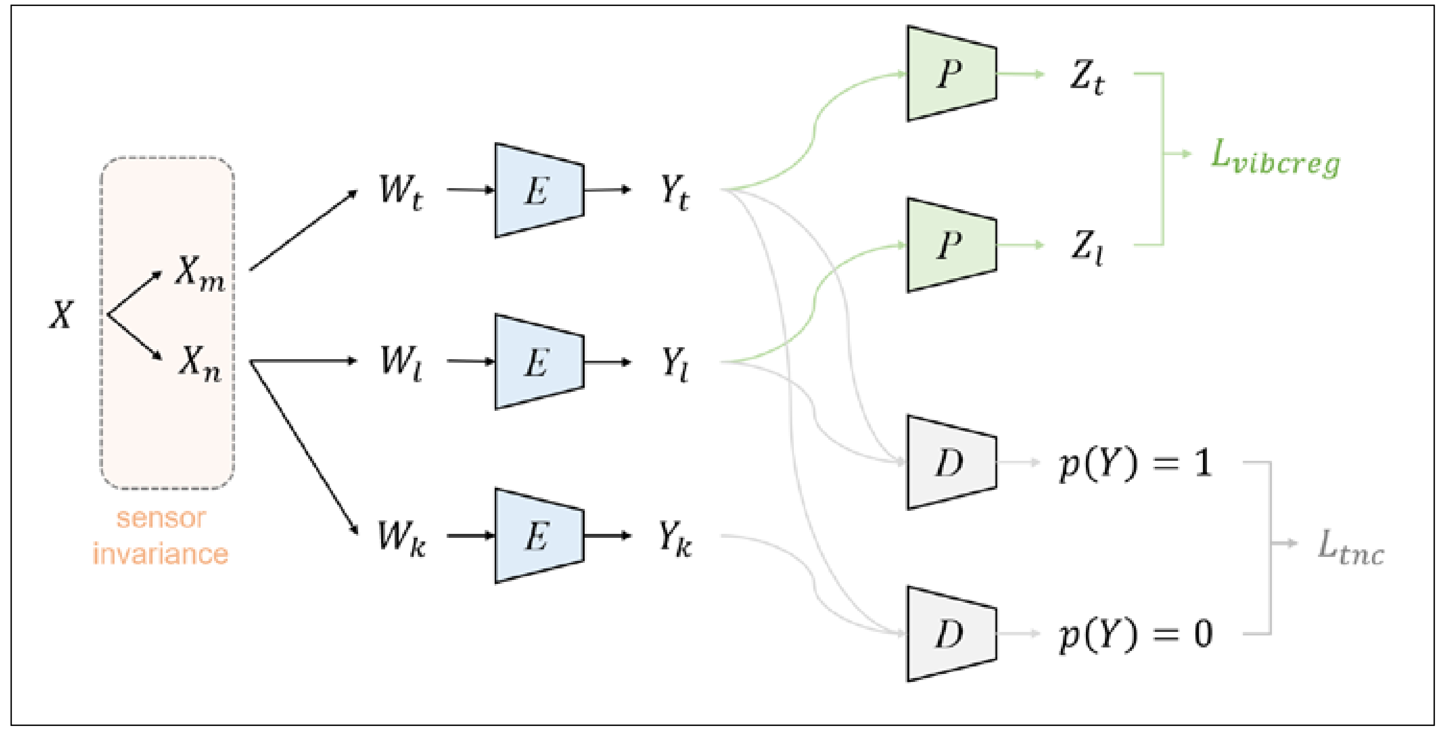


Figure 23. Example of Vibcreg learning: The data are transformed to achieve more independent subsets that improve the classification results.

WORK PACKAGE 7: MANAGEMENT, INNOVATION AND COMMUNICATION

WP LEADER MARTIN LANDRØ, NTNU.

The CGF has advertised some 12 PhD positions and several PostDocs in 2021, and has been successful in recruiting 8 new staff to date, as many of the WP reports indicate. Further recruitment campaigns are underway. The guiding principle on recruitment has been to only make offers to strong applicants that not only meet or exceed the baseline training and experience requirements, but who impress the selection board with their approach and who we believe will be a good fit to a vibrant innovation Centre. The CGF is founded on its personnel, and it is important that an innovative and collaborative culture is developed, even if it means growing a little more slowly that we would ideally prefer.

The recently recruited PhD Student and PostDoc staff:

Nicholas Bradley: I have BSc and MSc degrees in Geosciences from the University of Aberdeen alongside a second MSc degree in Applied Geophysics obtained as part of the IDEA League program between TU Delft, ETH Zürich and RWTH Aachen. My PhD research will be in collaboration with Equinor, focusing on understanding DAS/DTS data for an in-well setting wells using FO data. Preliminary research focus on low-frequency data processing and analysis of production and well-integrity monitoring datasets allowing for interpretation of tube waves and other dispersive modes. A tentative PhD thesis title is 'Multi-physics modelling for in-well monitoring'

Kristoffer T Galtung: I graduated with a MSc degree in Geophysics from the University of Bergen. This work was related to the use of acoustic waves to estimate temperatures in the ocean, where the focus was on forward modelling in the Fram Strait where the presence of non-geometrical arrivals is causing difficulties in analysing the acoustic data. My PhD research will be on diving waves in anisotropic media. Diving waves occur when the elastic properties of a geological medium are changing with depth, and they provide substantial information about the seismic velocities in the subsurface. A tentative PhD thesis title is 'Applying ray theory to model diving waves in mediums with orthorhombic anisotropy'

Kevin Growe: After my BSc in Geoscience, I worked for 1.5 years at GEOMAR Kiel and IPG Paris on seismic data from the Mid-Atlantic-Ridge, imaging crustal and upper mantle structures. Afterwards I pursued the IDEA LEAGUE MSc in Applied Geophysics at TU Delft, ETH Zürich and RWTH Aachen. My PhD research will focus on using DAS for monitoring shallow subsurface properties as a potential tool for landslide forecasting. The monitoring capabilities of DAS are tested within two field experiments, including the NORFROST site at NORSAR. A tentative PhD thesis title is 'DAS for monitoring shallow subsurface properties as a tool for landslide forecasting'

Franz Kleine: I am a geophysicist from Germany. During my studies, I mainly focused on active seismic data, writing my MSc thesis about a Vertical Seismic Profiling experiment that was conducted in New Zealand. In my PhD, I am working on Distributed Acoustic Sensing (DAS) for geohazard detection in cooperation with NORSAR. A tentative PhD thesis title is: 'Geohazards monitoring from various geophysical data'

Ricardo Martinez: I am a Geophysicist, with degrees from universities USB in Venezuela and NTNU in Norway. I have worked the last 3 years at CGG in the UK, doing both seismic data processing and velocity model building. My PhD research will have a strong focus on improved CO_2 detection and quantification using 4D seismic methods. A tentative PhD thesis title is: 'Leading-edge detection of lateral migration of CO_2 plumes using plume-dynamics models and 4D seismic processing'

Andrea Santi: I am a geologist from Brazil who has worked in the energy industry in the US, UK and Norway, getting extensive experience in fit-for-purpose reservoir modelling and integrated uncertainty analysis. In my MSc thesis I worked on factors impacting multi-layer plume distributions in CO_2 storage reservoirs followed by involvement in the Northern Lights project while working as a consultant for Equinor in Trondheim. My PhD research will focus on improving quantification of CO_2 migration into the overburden and detection of possible leakage out of the storage complex. A tentative PhD thesis title is: Improved geophysical detection and forecasting of vertical migration and leakage of CO2 (dense phase and gas phase) into realistic high-resolution models of overburden sequences'.

Kristina Skarvang: I am Norwegian/Japanese and have B.Eng. from Waseda University in Japan and a MSc in Physics from NTNU. My PhD research will be on using long-distance optical cable as a seismic sensor. This will include DAS data and optical state of polarisation (SOP) which is susceptible to mechanical disturbances of the FO cable and is a promising parameter to be used for sensing over long distances. A tentative PhD thesis title is: 'Embedding geophysical sensor systems in long-distance optical data communication systems'

The Tien Mai, post doc: I have a background in statistical machine learning with a PhD in statistics from France. Prior to joining CGF, I was using and developing machine learning algorithms and proposing novel statistical models for genomic data as a postdoc in statistical genetics at the University of Oslo. As a postdoc at CGF, I am working on statistical models for DAS data, and new learning algorithms for handling this kind of data.

In addition, after more than a year of tumultuous growth and development, we are both sad to say goodbye to Liv Elin Sandnes as our coordinator, but also delighted to congratulate her on taking up her new role as Organisation and Communications manager at the Museum of South Trøndelag (Museene i Sør-Trøndelag – MiST). Liv Elin was instrumental in overcoming many of the initial teething troubles of setting up the new Centre and managing the many liaison tasks with our partners. Fortunately, we have been able to recruit Helene Alnes Vedlog as our new Coordinator. Helene first came to us on a 'temporary attachment' of a few weeks in March 2021, but was very quickly enticed to continue working with the CGF part-time, shared with the IES administrative office. We are now very happy that Helene has accepted the position of full-time coordinator and look forward to working with her for many years to come. Helene comes to us with a degree in Psychology and a Masters' in Organisational Psychology, so is unusually well-qualified for building bridges across our pool of academics and industry partners.

Innovation

One of the primary innovation objectives for the Centre is to bring geophysical monitoring and forecasting services to markets by establishing spin off companies. In 2021 CGF has focused its research on how to use DAS in various applications. As a consequence of this, innovation efforts have focused on this topic, and it has therefore been decided to establish the first spin off company to commercialise research results from the center within DAS. This has been the main focus for the innovation work in 2021.

The new company is based on a strong innovation prospect in the application of DAS to a range of source detection, classification and tracking applications. Initially, the most technically advanced applications are likely to be land-based, in the detection of animals, vehicles, unusual events, etc., in and around sensitive areas (roads, railways, protected installations, etc.). The CGF is working with its partners and NTNU to protect the intellectual assets identified in this domain and to take them forward to innovative products and services. To strengthen innovation in the center and to improve CGF's opportunities to innovate through start-up companies, we will hire a new employee who in addition to working with innovation in general in the center, will focus on commercialising results through spin-off companies. We have also coordinated with 5 of the new Centres hosted by NTNU and SINTEF to define and implement a best practice for innovation in a centre for research-based innovation that facilitates and stimulates the transformation of knowledge to value, starting with a general strategy document. A key element in the strategy is that innovation must be initiated and worked on in the work packages and then be coordinated and implemented by work package 7, which has the overall responsibility also for innovation.

Communication

The communication strategy is comprised of both internal and external communication initiatives.

Internally, we have established three seminar series and a social event, each of which occurs monthly, to draw team members together for synergistic exchange. The seminar series are:

- SASHIMI – Held on the first Thursday of every month, offering an opportunity for partners to present their interests and needs
- SUSHI – Held on the second Thursday of every month for WP project results presentations to find valuable applications
- LAKS – Held on the third Thursday of every month for students to air their nascent research to gather feedback and support.

In addition, there is a Pizza Party (now with a regular Kahoot game!) every fourth Thursday.

For external (inward) communication, we are planning a 'TEMPURA' ad-hoc seminar option in which guest speakers from outside the CGF are invited to present relevant research.

Most of the external communication strategy is aimed at disseminating CGF results and activities to the outside world. For this we have developed a comprehensive CGF website in the NTNU format (https://www.ntnu.edu/web/cgf) in addition to a CGF LinkedIn account.

External communication spans peer-to-peer exchange with research colleagues, all the way to public outreach and school interactions. Peer-to-peer communication is mainly delivered by publications (of which there were ~50 in 2021 alone), books, workshops participation etc. A CGF workshop was organised as part of the NIKT conference this year, co-chaired by our WP leader Anne Elster, entitled "AI and HPC in Geophysical Forecasting".

Public outreach is accomplished by a combination of popular science articles in magazines and newspapers (of which there are 4 or 5 this year), science fairs, public interest talks, etc. As an example of the latter, CGF contributed to a public outreach and education event called 'Researchers' Night'. This is an important dissemination event that brings together students and teachers from upper secondary schools and high schools in Trøndelag. This presented an excellent opportunity for CGF to connect with young minds and communicate our research. A CGF team designed, prepared and delivered a multi-media stand activity that included video, hands-on props, posters and a Kahoot competition on the subject of 'Listen to the Ocean', featuring FO DAS results and in-situ acoustic/video whale tags (Fig. 24). The stand attracted many groups of students over three hours of display time and we even got a request for our preprint DAS paper from one student, who thought it should be published in Nature!

Figure 24. Students at the CGF booth during 'Listen to the Ocean'

Finally, the plan is to develop and convene periodic workshops and seminar series on topics central to CGF interests where both CGF and external organisations will present, creating collaborative opportunities. The first of these is a planned 'State of the Art of DAS' seminar series to be organized by NTNU and NORSAR, held jointly with the US Air Force research Laboratory (AFRL).

International cooperation and activities

EU-applications submitted:

- SAMBA (ITN project, M. Landrø, NTNU, European universities and industry)
- SMILE (ITN project, P. Ringrose, NTNU, European universities and industry)
- BIODAS (Biodiversa EU call, H. Kriesell, NTNU, European universities)

CGF has one international research partner, JAMSTEC (Japan). Due to the Covid-situation there has been no scientific visits during 2021. Shuichi Kodaira (JAMSTEC) gave a digital talk as a part of the SASHIMI seminar series.

Jo Eidsvik (CGF), Phil Ringrose (CGF) and Martin Landrø (CGF) gave international digital courses arranged by EAGE. The CO_2-course given by Ringrose and Landrø was a cooperation with Heriot Watt University in Edinburgh. Anne Elster (CGF) and several students did manage to attend a computer conference in US and John Potter visited the University of Pisa during 2021. Several senior CGF researchers gave plenary and invited talks, both virtually and in person/hybrid, during the year. More details are available on the CGF 'news and events' page.

Gender equality

Women are currently highly underrepresented at all levels in science and engineering, creating a lack of role models for female students. The host department for CGF (Electronic Systems) currently has only 12% female professors, and in computer science only 22% of the 5th year master students are women. Our ambition is that CGF will contribute to a positive change. We have two female professors acting as WP leaders (Anne Elster and Hefeng Dong) and two women as international collaborating professors.

So far we have recruited 7 PhD students, of which 2 are women (29 %). In the CGF board there are 3 women and 5 men. In the innovation board there are 2 women and 4 men, and in the research board there are 2 women and 4 men.

Covid-19

The start-up of the center has clearly been characterised by Covid-19, perhaps especially because we have chosen a physical centre model where our common meeting room functions as a hub in the center. In the first half of 2021, we had a home office, and this has clearly affected PhD students and the research activity in the center, because one loses the informal communication and spontaneous conversations that occur in hallways and around the lunch table. Laboratory work has gone quite well but is also characterised by major delivery problems. Special equipment has often had a delay in delivery of 3-12 months during Covid-19, and this has affected the construction of laboratory equipment.

Measures taken

We have prioritised students who have limited opportunity to work from home (networks, facilities etc.) and allowed them access to campus and their workspaces. We have also prioritised laboratory and fieldwork as far as it has been practically possible. In the fall we have arranged monthly pizza-gatherings for students, while the End of the year-celebration was unfortunately cancelled because of Covid-19.

PERSONNEL

Key Researchers

Martin Landrø	NTNU	Andreas Wuestefeld	NORSAR
Håkon Tjelmeland	NTNU	Steinar Bjørnstad	Tampnet
Jo Eidsvik	NTNU	Duncan Irving	TietoEVRY
John Potter	NTNU	Shuichi Kodaira	JAMSTEC
Anne Elster	NTNU	Lars Harald Blikra	NVE
Børge Arntsen	NTNU	Kent Andorsen	AkerBP
Hefeng Dong	NTNU	Tore Humstad	NPRA
Alexey Stovas	NTNU	Emil Solbakken	NPRA
Kenneth Duffaut	NTNU	Jan Gerhardsen Formanek	BaneNOR
Ståle Johansen	NTNU	Kurosh Bozorgebrahimi	Uninett
Giampiero Salvi	NTNU	Frode Storvik	Uninett
Dag Roar Hjelme	NTNU	Olaf Schjelderup	Uninett
Shunguo Wang	NTNU	Erling Siggerud	Digital Geologi
Ole Jakob Mengshoel	NTNU	Svein Arne Frivik	Shearwater
Phil Ringrose	Equinor/NTNU	Tone Trudeng	MagseisFairfield
Jan Kristoffer Brenne	ASN	Thomas Elboth	Shearwater
Susann Wienecke	ASN	Lasse Amundsen	Equinor
Volker Oye	NORSAR		

Visiting Researchers

Name	Affiliation	Nationality	Sex M/F	Duration	Topic
Jakob Rødsgaard Jørgensen	Århus University	Denmark	M	1/1-31/8	Computing

Postdoctoral researchers working on projects in the Centre with financial support from other sources

Name	Funding	Nationality	Sex M/F	Duration	Topic
Hannah Joy Kriesell	NRC	Germany	F	1/1-31/12	Bioacoustic
Lea Bouffaut	NRC	France	F	1/1-31/10	Bioacoustic

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Sex M/F	Duration	Topic
The Tien Mai	Vietnam	M	1/8-31/12	Mathematics

PhD students with financial support from the Centre budget

Name	Nationality	Sex M/F	Topic
Kristoffer Tesdal Galtung	Norway	M	Seismic wave propagation and inversion in fractu-red anisotropy media
Franz Kleine	Germany	M	DAS for geohazards monitoring
Andrea Callioli Santi	Brazil	F	Detection and forecasting of vertical migration of CO_2 using high-resolution models of overburden sequences.
Ricardo Martinez Guzman	Venezuela	M	Leading-edge detection of lateral migration of CO_2 plumes using plume-dynamics models and 4D seismic processing
Kristina Shizuka Yamase Skarvang	Norway	F	Geophysical activity monitoring methods whichare integrated or embedded with long-distance data-communication optical transmission systems
Kevin Growe	Germany	M	Near-surface characterization using DAS data
Nicholas Bradley	Great Britain	M	Fibre optics and wells

PhD students working on projects in the Centre with financial support from other sources

Name	Funding	Nationality	Sex M/F	Topic
Robin Andre Rørstadbotnen	NRC	Norway	M	Seismology, DAS, earthquakes, seismic data
Kittinat Taweesintananon	NRC	Thailand	M	Petroleum Geophysics and DAS
Mohammed Ettayebi	NRC	Norway	M	CSEM (electromagnetics)
Lukas Thiem	NRC	Germany	M	CO_2-monitoring and DAS
Håkon Gryvill	NRC	Norway	M	Statistical analysis
Mina Spremic	NRC		F	Statistical analysis

Name	Funding	Nationality	Sex M/F	Topic
Uhmedzhon Kakhkhorov	NRC	Russia	M	Seismic imaging
Jiaxin Yu	NRC	China	F	Rock Physics
Samira Pakdel				
Jacob Ødgård Tørring	NTNU	Norway	M	Computing
Ole Edvard Aker			M	Computing
Zawadi Berg Svela		Norway	M	Computing

Master students

Name	Sex M/F	Topic
Maren Wessel-Berg	F	Optimizing Spectral FEM and related methods used for FWI on newer GPUs
Tobias Dyngeland	M	Computation and machine learning methods applied to solve the problem of estimating pressure trends in multiple rock compartments.
Tor Haughdahl	M	Autontuning techniques for geophysical simulations
Lars Sørlie	M	ML and GPU optimization techniques for large physics codes
Jacob Simonsen	M	Quantum computing with Franz Fuchs
Øystein Rognebakke Krogstie	M	Dynamic Task Parallelism in FPM and Related Methods
Lars Bjertnes	M	Applying Natural-Language-Processing-Based Machine-Learning techniques to our large scale CUDA autotuning dataset
Andreas Hammer	M	Analyzing Halo Computations on Multicore CPUs
Ivar Sandvik	M	Adding GPU-accelerated Real-time SPH-based Avalanche Simulations to the NTNU HPC-Lab Snow Simulator
Ingvild Høgstøy	F	Exploring NVIDIA Ampere Tensor Cores for an Event Generator Code for High-Energy Physics
Konstantin Mathisen	M	Towards Photon Mapping in Vulkan
Nandito Davy	M	Velocity depth trends prediction on the Norwegian Continental Shelf (NCS) wells using the bounding average method
Oscar Ovanger	M	Graph Gaussian process classifier with anchor graph and label propagation
Eline Nybråten	F	Large-scale CO_2 injection: Pressure increase in multiple compartments and optimization of the geomechanical limit
Tian Guo	F	Large-scale CO_2 injection: Pressure decay in multiple compartments and optimization of long-term basin pressure
Ujjwal Shekhar	M	Effective seismic model from fractured rock

ANNEXES

CGF PUBLICATIONS IN 2021

Aaker, Ole Edvard; Raknes, Espen Birger; Arntsen, Børge. (2021) "Elastodynamic full waveform inversion on GPUs with time-space tiling and wavefield recon struction". 77, 2021.Journal of Supercomputing, 77, 2416-2457.

Abedi, Mohammad Mahdi; Pardo, David; Stovas, Alexey. "Approximations for traveltime, slope, curvature, and geometrical spreading of elastic waves in layered transversely isotropic media". Geophysics 86(6) C173-C184, 2021.

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Amundsen, Lasse; Landrø, Martin. "From Arrhenius to CO Storage XI: How Earth's IR Photons are Transfer red in the Atmosphere in the Presence of CO". GeoExpro 18.(1) 48-51, 2021.

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bin Waheed, Umair; Alkhalifah, Tariq; Haghighat, Friborz; Stovas, Alexey; Virieux, Jean. "Traveltime computation for qSV waves in TI media using physics-informed neural networks". EAGE; 10-17, 2021.

Bjertnes, Lars; Tørring, Jacob Odgård; Elster, Anne C. "Autotuning CUDA: Applying NLP Techniques to LS-CAT". NIKT: Norsk IKT-konferanse for forskning og utdanning, 1, 72-85, 2021.

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Reyes Ortega, Valeria; Constable, S.; Wang, Shunguo. "Investigation of the lithosphere-asthenosphere boundary across the Mendocino Fracture Zone using marine Magnetotelluric method". Marine Seismology Symposium; 2021-03-08 - 2021-03-19, 2021.

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Roganov, Yuriy; Stovas, Alexey; Roganov, Vyacheslav. "Use of perturbation theory in computation of phase velocities and polarization vectors in weakly anisotropic media". Geofizicheskiy zhurnal, 43(3) 64-81, 2021.

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Stovas, Alexey. "Perturbation in monoclinic medium with a horizontal symmetry plane". Geophysical Journal International 226(1), 692-708, 2021.

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Stovas, Alexey; Roganov, Yuriy; Roganov, Vyacheslav. "Geometrical characteristics of phase and group velocity surfaces in anisotropic media". Geophysical Prospecting 69(1) 53-69, 2021.

Stovas, Alexey; Roganov, Yuriy; Roganov, Vyacheslav. "Perturbation of phase velocities in elastic orthorhombic media". Geophysics 86(4) C101-C118, 2021.

Stovas, Alexey; Roganov, Yuriy; Roganov, Vyacheslav. "Pure mode P and S wave equations in elastic orthorhombic media". Geophysics 86(5) C143-C156, 2021.

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Zhu, Xiaoyu; Dong, Hefeng; Salvo Rossi, Pierluigi; Landrø, Martin. "Feature Selection Based on Principal Component Regression for Underwater Source Localization by Deep Learning". Remote Sensing 13(8), 2021.

FINANCES

Funding (1000 NOK)	Amount
Research Council	5 268
Host Institution (NTNU)	6 833
Research Partners*	1 685
Industry Partners**	4 555
Total	**18 341**

Costs (1000 NOK)	Amount
Host Institution (NTNU)	10 246
Research Partners*	1 685
Industry Partners**	2 927
Equipment	3 483
Total	**18 341**

The Total budget for SFI CGF is 233 mill NOK and all partners have a substantial in-kind contribution to the Centre. The financing of SFI Centre for Geophysical Forecasting are based on contribution from Research Council of Norway and cash and in-kind contribution from the Industry Partners, NTNU and the Research Partners.

* Jamstec and Norsar

** Aker BP, ASN, BaneNOR, Digital Geology, Equinor, Magseis Fairfield, NVE, Shearwater, Statens Vegvesen, Tampnet, TietoEvry and Uninett