NTNU SFI Centre for Geophysical Forecasting

Annual Report 2020

RCN # 309960.

CGF SFI Centre for Geophysical Forecasting

NTNU

sfi Centre for Research-based Innovation

The Research Council of Norway

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Foreword

Late afternoon on 11th June 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.

Director CGF, Martin Landrø

Together with 12 partners and four NTNU departments, we were asked to build a new centre, where research and innovation are in 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 is not made easier by the Covid-19 pandemic which 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 a 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.

This annual report covers only one month (December) in 2020. Hence it focuses more on plans and intentions than results. So this report offers a short overview of the Centre, the team and major objectives, with some early activities and developments. I hope you find it interesting and please do contact us if you have suggestions related to our CGF centre.

Summary

The new SFI "Centre for Geophysical Forecasting" (CGF) started up on 1st December 2020 and was officially opened by NTNU rector Anne Borg and state secretary Tony Christian Tiller on the 14th December 2020.

Figure 1: Rector Anne Borg, cutting the ribbon at the CGF opening ceremony.

The fundamental theme for the CGF is "Geophysical Forecasting". This concept anticipates exploring not only new sensing technologies and analyses, such as Distributed Acoustic Sensing (DAS) through Fibre-Optic (FO) cables, but also making better use of the seismic bandwidth as well as natural acoustic and electromagnetic noise spectra, and then assimilating all this information for predictive purposes and for decision support. Developing and optimising DAS for Norwegian needs and conditions is a major focus of research, with its own Work Package (WP). There are also dedicated WP on CO_2 and gas storage, effective monitoring and forecasting systems and geohazard prediction and deep mapping, including 4D earth models, rapid updating of geomodels and the use of AI. Connected to all of these are two WP specifically dealing with the development of statistical digital signal processing and data management development and harnessing the computational power of emerging Heterogenous & Parallel Computing (HPC) architectures, including cloud and edge computing and storage. But our goals are not simply to generate new research results and methods. It is vital that the value created by this research and development cross over into innovative products and services that generate value for our industrial partners and for Norwegian society, including new spin-off companies where our innovations are not a good fit with existing partners' portfolios.

Our progress to date has been mainly in setting up the organisational structure of the CGF, aligning Partners and signing agreements, establishing our governing board, as well as research and innovation advisory boards, and in creating a physical space for the CGF to operate. An initial teambuilding workshop was held and a series of online meetings have been established to create the all-important communication and collaboration channels between CGF team members, partners and advisors. A CGF website and LinkedIn presence has been created, in addition to a MS Teams CGF environment, providing both internal and external communication channels and repositories for materials. A total of 11 PhD positions have been advertised and we are now evaluating over 155 received applications. The Centre has also engaged with other SFI's to coordinate communication and innovation strategies.

The CGF has already begun to generate interest in the wider community, evidenced by several inquiries from potential new partners who are interested to join forces, and in interest from a local community who would like the CGF to be involved in monitoring a civil engineering project that involves geotechnical stability issues with quick clay.

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 onshore and offshore 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.
- Publish 40 market-targeted publications 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 will break new ground in applying leading-edge wave propagation methods, advances in Distributed Acoustic Sensing (DAS) using FO backscattering 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. The core innovation potentials and financial impacts within each of the three focus areas are:

- CO_2-storage management; Carbon Capture and Storage (CCS) is estimated to have a potential total annual business volume of 100 Billion NOK, based on 10 new CCS-projects similar to the planned CCS-project offshore Norway (7-12 Bn NOK; Northern Lights, 2018). A 7% share, derived from site surveying and identification, sequestration processing and subsequent leakage monitoring, would generate 7 Bn NOK, creating a valuable new industry in Norway based on geophysical services for CCS.
- Hydrocarbon production monitoring (30 Bn NOK, Meld. St. 28, 2011); Create new business opportunities for partners based on new geophysical monitoring methods exploiting the value of huge "continuous" digital data, with an estimated business value of 3 Bn NOK.
- Geohazard monitoring and forecasting (4 Bn NOK, Aftenposten, 05.08.2019); Apply offshore hydrocarbon methods together with innovative technologies such as satellite remote sensing and the use of FO cables for DAS to generate new products and services in the interests of society and industry, with an estimated value of 1 Bn NOK.

Research plan/strategy

The CGF research is organised into 6 coupled Work Packages (WP)

WP1: Distributed Acoustic Sensing (DAS)

DAS is based on rapidly repeated measurements of the back-scattered laser light from Rayleigh scattering at impurities within a FO cable. By extracting the phase of the backscattered light as a function of position in the FO cable by time-gating, one can monitor dynamic strain at many discrete points along the cable. Acoustic and seismic waves that stress the cable will induce strain, which modulates the backscattered phase. The sensitivity depends on the inherent DAS interrogation noise, the DAS cable design and its coupling to the environment, all of which require further research to understand and optimise.

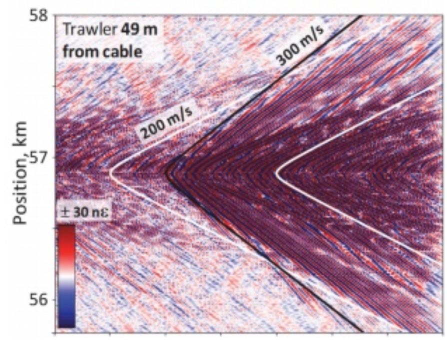

Figure 2. DAS data recorded in a telecom cable crossing the North Sea showing seabed wave modes originating from a trawler.

Recent development work performed by CGF partner ASN Norway has shown that FO cable strain can be precisely monitored over far longer distances and with higher sensitivity compared to present state of the art. Based on these achievements ASN is now targeting to commercialise DAS equipment for submarine cable protection, monitoring long cable length in excess of 100 kilometers, see Fig. 2 for an example of seabed contact by a nearby trawler. These improvements in range and sensitivity open the way for new applications of DAS technology. We envision a huge potential for listening to the earth's crust by connecting DAS equipment to only a tiny fraction of the vast network of FO cables deployed both subsea and onshore for telecommunications.

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

The primary tasks and activities for WP1 are:

- Define geophysical models and DAS measurement system specifications for applications of interest.
- Develop signal processing techniques to map recorded FO strain into geophysical observations.
- Design and conduct field trials acquiring DAS recordings from FO cables close to geological structures of interest.
- Analyse field trial data to establish the coupling between the environment and the FO cable.
- Develop DAS equipment and data processing techniques suited for the geological applications of interest.

This work package is highly relevant for all three innovation areas (CO_2, hydrocarbons and geohazards).

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.

Norway already has two CO_2 storage projects (Sleipner and Snøhvit) and one in development, Northern Lights, which forms the storage component of a much bigger national CCS project, Longship. In addition to storage of CO_2 there is also a growing demand for the storage of Hydrogen and compressed air in support of renewable energy systems. Smart geophysical and mathematical methods are needed for such projects, both to determine optimal storage sites and for monitoring the operations.

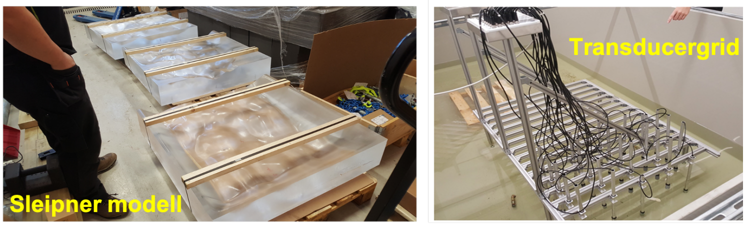

Figure 3. The CO_2-storage test tank at NTNU (2x4x1,1m). Left: The Sleipner model (1x3x0,4m). Right: the ultrasonic array, capable of handling 1024 channels.

A crucial risk associated with all subsurface CO_2 storage projects is leakage through the overburden. It is obviously important to establish the natural seismicity in storage areas and to be able to identify induced seismicity and possible fracturing. We must therefore improve passive seismic methods, developing smart and cost-effective methods to monitor broadband background noise. Subsurface gas storage projects are multi-disciplinary and require a strong background spanning passive seismic, active seismic, conventional and DAS technology, mathematical and signal analysis techniques, fluid flow simulation and geological mapping. There will be a strong focus on overburden characterisation and monitoring including use of high frequency methods (via FWI), use of controlled source electromagnetics and time-lapse gravity.

CGF has completed construction of a dedicated CO_2 test tank (Fig. 3) which allows 1:1000 models of real geophysical domains to be investigated with controlled gas flow injection and an array of ultrasonic hydrophones. The plan is to model a typical CO_2 storage volume simulating a sand layer beneath a caprock surface and then to inject a fluid similar to supercritical CO_2, acquiring ultrasonic time lapse "field data" during injection.

EU has stated that 30% of its budget will be devoted to clean energy and climate action, and the European demand for CCS and gas/energy storage will most likely expand significantly in the next decades.

This primary tasks and activities for WP2 are:

- Design and perform scaled laboratory experiments simulating slow and rapid migration and leakage in/from CO_2-storage sites.
- Develop methods for detecting lateral migration and vertical leakage when monitoring CO_2 plumes, exploiting HPC & AI-methods combining fluid dynamics with 4D seismic processing and novel use of FO DAS technology.
- Develop multi-scale stress and strain models of key geological storage domain to give an improved basis for rock failure prediction and seismicity forecasting.
- 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 (conventional 4D and 4D FWI).
- Assessment of a range of seabed and downhole FO DAS cable layouts for both near-well (early-phase) and far-field (later phase) site monitoring, as a complement or substitute to conventional marine 4D seismic monitoring.

WP3: Effective monitoring and forecasting systems, offshore, coastal and onshore

There are now several Permanent Reservoir Monitoring (PRM) systems installed on the Norwegian continental shelf. AkerBP (a CGF partner) will provide data from one of the first PRM systems offshore Norway, the Valhall Field. The enormous amount of data generated by such systems opens up many new possibilities. We will focus on computational geophysics and developing novel ways of analysing and bringing such data directly into field management. We propose that smart fusion of the half-yearly active source acquisitions performed at such fields with sparse spatial source coverage (but dense in calendar time) and continuous passive data will generate innovative and useful data products to support field management. This multi-use of heterogeneous spatial and temporal data requires a systematic statistical approach (WP6) to optimally exploit the data diversity. Furthermore, the need for intense computational geophysics (WP5) and advanced FWI modelling (WP2) is obvious. Such PRM systems are of particular interest to detect early leaks and avoid unwanted pressure build ups at the field.

CGF are developing and testing approaches to map and monitor transition zones close to Norwegian harbors and coastal areas. To map and monitor pressure and salt variations in such areas is crucial, and we believe that our experiences from seismic time-lapse monitoring are well-suited for developing new systems for this. Seismic monitoring of the ground conditions close to roads and other infrastructures is another application area, where we will collaborate closely with our partner NPRA. CGF has already engaged with a project to build a new road (717) near Rissa, the site of the disastrous quick clay slide of 1978, with plans to install two observation wells and a FO cable during construction.

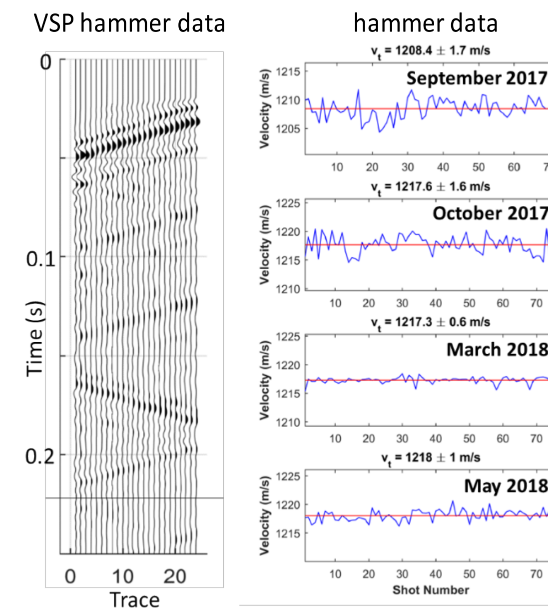

Figure 4. VSP-experiment in the 30 m deep test well at NTNU using a hammer source. Low pass filtered data (left) and estimated tube wave velocities from 72 hammer shots for 4 different calendar months (right) are shown.

NTNU has a 30m deep well, instrumented with a conventinal hydrophone array and a FO cable provided by ASN. Fig. 4 shows results from a series of active tests, where the tube wave dominates, strongly influenced by the shear wave velocity in the formation. 72 shots were acquired, and the repeatability was surprisingly good, showing a standard deviation ~ 0.1 %. This demonstrates a clear potential for using shallow wells to monitor subtle changes in shear properties close to the surface. The major learnings from this experiment are two-fold: Massive amounts of data improve accuracy, and simple experimental setups can be exploited to monitor and forecast important parameters like shear stiffness of the near surface. We also estimated the tube wave velocity by using backrgound ambient noise. While posible, the accuracy decreased significantly, indicating a clear gap that should be investigated: How to improve the accuracy of passive measurements and assign the corresponding uncertainty estimates (WP6) taking random and systematic noise into account. A recent paper (Mainsant et. al., 2021) successfully estimated the Rayleigh wave velocity of sediments in a landslide-prone area from traffic noise on a nearby road and were able to show a significant decrease a few days prior to a landslide event.

The primary tasks and activities for WP3 are:

- Develop new 4D seismic analysis methods exploiting full-waveform inversion and refracted waves to the full extent, leveraging cutting-edge HPC technologies.
- Combine regular 4D PRM-seismic data with sparse surveys using a fixed source and passive data.
- Combine 4D seismic with gravity and EM-data to improve the accuracy of estimated saturation and pressure changes in a reservoir or CO_2-storage site.
- Improve use of instrumented shallow observation wells for monitoring changes in shear stiffness.
- Test existing simple tools for acquiring seismic data in coastal areas and combine this with on-shore data (GPR, EM and seismic on shore).

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.

Offshore examples for geohazards include, for example, an induced M_w = 4.2 earthquake at the Ekofisk field, North Sea caused by unintended water injection into the overburden. Since the start of production, the Ekofisk field has compacted more than 10 meters, and we need to study seismic data, compaction and stretching effects at different depths. Today, the Ekofisk field is instrumented by a large receiver array that is trenched into the seabed, and 3D seismic data is acquired twice a year. In addition, a subset of continuous passive seismic data is processed in near-real time by NORSAR to provide immediate feedback in case of any larger seismic event.

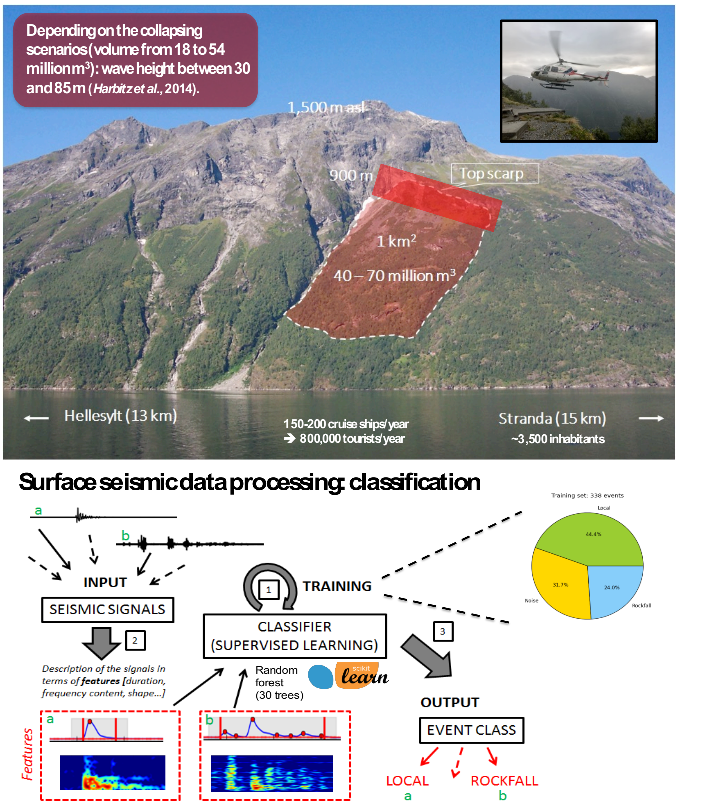

Figure 5. Upper panel: picture of the Aaknes rock slope with, in red, the moving area that might slip into the fjord, generating a major flood wave. Lower panel: Schematic showing how the seismic data are automatically processed, analysed and classified into e.g. local seismic events and rock falls.

Further improvements towards combining active and passive seismic methods and including complementary methods like seabed bathymetry, pressure gauges in wells and instrumented wells will be investigated. This type of monitoring (using for instance FO cables) might be extremely valuable for gaining greater understanding of earthquake source mechanisms. 3D seismic mapping of deep ocean areas has not yet been applied in any systematic way. We plan to take advantage of our partners' NORSAR and JAMSTEC's knowledge to develop strategies for such monitoring. We propose to use repeated seismic data swaths acquired prior to and after an earthquake and then map 3D movements to gain new insights. In addition, we propose to use electromagnetic data (EM) from comparable geological settings. Johansen et al. (2019) collected EM data across the Mohns Ridge to better understand the link between deep and shallow melt migration, earthquake occurrence and deposition of deep-sea minerals. By such combinations of data sets we foresee a better understanding of the connection between the position of earthquakes and deep-sea minerals.

Onshore geohazards in Norway include the danger for rock slopes. One of the world's best monitored sites is the Aaknes rock slope in Romsdal (Fig. 5). NVE (a CGF partner) is monitoring the site, including acquiring passive seismic data. NORSAR has a real-time data link to the site and processes the data using machine-learning methods to provide online event classification. This activity directly links geophysical data with machine learning and we have seen very good success rates with the classification. However, including better models and new insights in machine learning at CGF will lead to further improvements on event classification and location and hence an improved forecasting of rockslide geohazards, also applicable to other sites. A related challenge is the monitoring of railways and roads. Bane NOR (a partner in CGF) has FO cables along tracks, providing opportunities for monitoring rock fall and gradual changes in subsurface properties related to geohazards. Automated warnings of rock falls, landslides and avalanches using dedicated radar, geophones or infrasound systems are already available but can be usefully complimented by broader spatial monitoring of general geohazard activity with the goal of improving our understanding of mechanisms and building a more effective and accurate decision basis. In addition, these data could be closer connected to traffic monitoring to avoid accidents and delays. An overall goal for this activity is to improve current warning and decision systems for when to close a road, and when to open again, providing more precise and timely information to both decision makers and public road users.

The primary tasks and activities for WP4 are:

- Investigate novel instrumentation and monitoring system for landslide and avalanche detection including FO sensing tools. This includes understanding of physical coupling of installed FO cables (soil/gravel/cement) at the NORFROST test site.
- Field trial and testing of installed FO cables and geophones for geohazard monitoring in collaboration with partners.
- Analysis and interpretation of 15 years of time series data at Aaknes, in collaboration with WP6 using ML methods.
- Collection and interpretation of new seismic and EM offshore data.

WP5: HPC tools and techniques for model fitting the subsurface

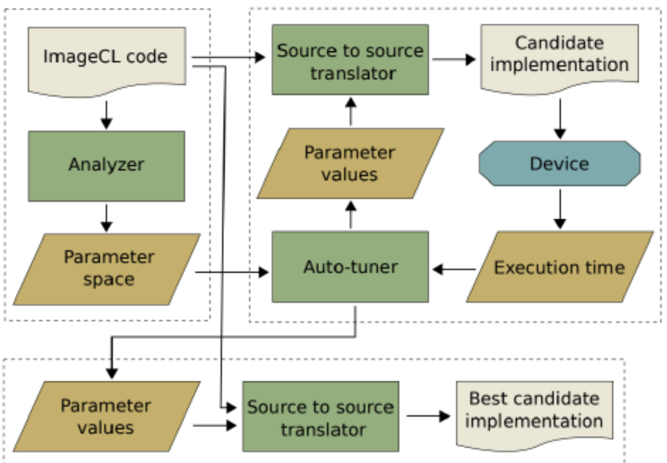

Figure 6: Principles of ImageCL compiler workflow for Autotuning for HPC.

The largest problem in many geophysical simulations is the large computational demand of the numerical model. The accuracy and resolution of the results scale with computational cost and the volume of the model. This WP will develop methods and tools to harness the computational power of HPC to efficiently model and simulate relevant geophysical behaviours.

Graphical Processing Units (GPUs) power many of the world´s top supercomputers since their simpler computational cores offer a lot of computational power for significantly less energy. Unfortunately, GPUs remain challenging to program, and with newer models coming out about every 6 months it is an intractable task to update codes manually for each new generation. An appealing approach is to develop parameterised codes that can be autotuned. Even so, with many parameters such as the size of a thread block, amount of work per thread, thread access pattern, use of texture or constant memory or shared memory for arrays as well as how much to unroll loops, one quickly ends up with tens of thousands of parameter combinations to test. HPC-Lab has developed the ImageCL language that can autotune several stencil-based image processing algorithms for a given GPU device. In order to reduce the autotuning work, we apply Machine Learning (ML) to find a near-optimal configuration for a given GPU/CPU. A natural next step is to extend this work and look into how similar techniques can be applied to compute-intensive geophysics.

Geophysical measurements typically generate inverse problems which cannot be solved directly. A common approach is to apply matched-field optimisation methods based on a parameterized model. The procedure can be fully automated and is limited only by numerical complexity and available computer resources. This method is often called Full Waveform Inversion (FWI) and has been used for some time for Controlled Source Electromagnetic Measurements (CSEM), Magneto Telluric Measurements (MT) and for seismic data. Our ML-based automated optimisation promises to be a powerful tool to apply to this class of computational problems.

This work also ties into the HPC-Lab NFR FRIPRO project on computational X-ray microscopy, where we have improved performance of the PaxPro application, a C++ library focused on solving the paraxial wave equation in 2D and 3D. 4D CT includes processing a lot of image data to increase the area of focus, and also here we may consider applying AI to reduce the amount of data that we need to store.

The primary tasks and activities for WP5 are:

- Building a framework that includes an extended ImageCL-like tool that can autotune chosen geophysics kernels that are performance-critical for model-fitting computations for geophysics.
- Develop methods for reducing the numerical requirements for model-fitting.
- Extend the framework to explore, via AI-based optimisation methods, emerging CPUs/GPUs/TPUs.
- Explore how to use emerging computer systems to process data gathered at the sensor rather than having to move it all to a central location for processing which takes both time and energy.

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.

The adaptive feedback loop is illustrated in Fig 7. First, probabilistic state-space models are required to realistically represent the complex physical relations that are only exact in calibrated laboratories and to process data for tailored tasks. Second, Bayes' theorem tells us how to correctly assimilate different kinds of data, where observations are weighted according to their associated uncertainties. Third, uncertainty quantification is the only way to gauge the strength of monitoring results, and express concern about significant anomalies or flag an alarm when there is substantial surprise in the measurement as compared with the forecast available from the model description. Finally, a probabilistic model facilitates the evaluation of survey designs and monitoring schemes, where one can evaluate and compare different approaches for what, when and where to sample observations to improve predictions and make better decisions.

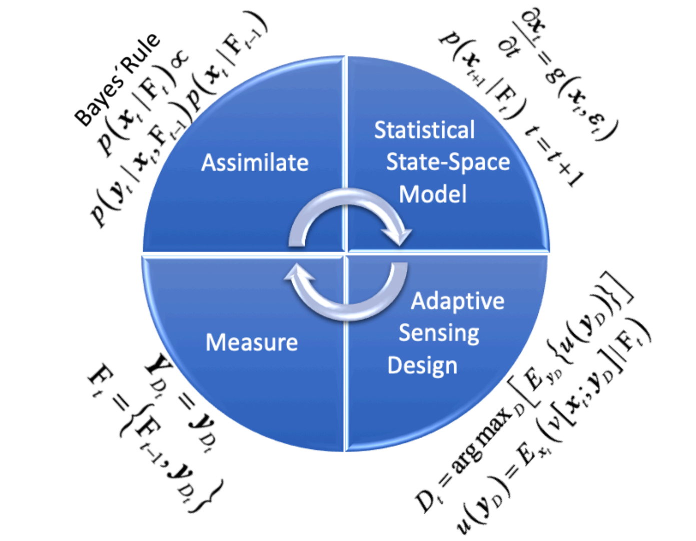

Figure 7. Probabilistic modelling enables adaptive planning and model updating.

Within the Bayesian approach, the model will be updated as and when new data become available. The updated model combines physical principles and calibration with in-situ data, generating our best estimates to use for geophysical forecasting. Going beyond the current practice of looking at correlations in AI and ML, we will use a combination of geophysical models and data to facilitate learning from data. This involves developing novel statistical machine learning approaches to develop new workflows for embedded system of sensors that conduct effective geophysical monitoring for targeted applications. This work will lay the foundations for an Internet-of-Things (IoT) system for effective geophysical monitoring, as well as for societal use in e.g. maintenance, warning systems, strategic decision support and intelligent transport systems. Decisions regarding geohazards, Earth resources and CO_2 storage involve enormous costs, and by phrasing the problems in a framework of statistical decision analysis, one can reduce costs and gain substantial value.

The primary tasks and activities for WP6 are:

- Real-world measurement and synthetic data pre-processing in order to provide datasets suitable for detection, estimation, localisation and prediction based on statistical machine learning.
- Optimisation of available communication/computational resources.
- Identification of effective data gathering schemes and cooperative strategies in sensor networks, using probabilistic sensor management and validation methods.
- Develop Bayesian framework for dynamic risk analysis in space-time applications.

Innovation plan/strategy

The primary innovation objectives for the center 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.

To address the three innovation areas (CO_2, hydrocarbons and Geohazards), the center is organised in 6 research WPs and a separate one for management, innovation, and communication. This work package will ensure that innovation is harvested from the research results.

In 2018 a joint NTNU and SINTEF FME innovation task force presented 5 guidelines on how a research centre may develop a culture and capability to support innovation output. Among several recommendations from the work were to allocate dedicated resources targeting innovation in a centre, and to share experience and competence across different centres.

In 2020 NTNU and SINTEF were selected by the Research Council of Norway as hosts for several new national centres for research-based innovation (SFIs and FME).

The research council, centre partners and the hosts have high ambitions for the Centres' ability to contribute to innovations for the benefit of the partners and the society.

Therefore, dedicated innovation resources from 5 of the new research centres hosted by NTNU and SINTEF,

- SFI Autoship, hosted by NTNU (Kjell Olav Skjølsvik, Jan Onarheim)
- SFI Harvest, hosted by SINTEF (Asgeir J. Sørensen)
- SFI CGF, hosted by NTNU (Ståle Emil Johansen, Reinold Ellingsen)
- SFI SWIPA, hosted by SINTEF (Trine Marie Stene)
- FME Northwind, hosted by SINTEF (Inger Marie Malvik)

have decided to cooperate 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.

The purpose of the document is to:

- Align innovation goals, awareness, and commitment
- Provide high level support and guidance for innovation management
- Facilitate knowledge management, and ensure contract compliance
- Serve as a normative reference for PhD training

For use in a specific centre, the document will be adapted and amended based on the contract, project description and in compliance with the principles defined by the consortium agreement between the centre participants.

In addition to starting this cooperation with NTNU and SINTEF centres we have also initiated the following CGF activities:

- Started discussion with partners for definition of *use-cases* defined by partners in cooperation with CGF wp-leaders.
- Introduced the *Innovation-prospect* concept internally in CGF. Each prospect will describe research results and how they will be turned into innovation cases.
- Initiated processes for common understanding of innovation and innovation strategy in CGF. This will result in a *roadmap for innovation* which will be a common and very simplified document both describing and motivating for innovation in the center.
- Established our Innovation Advisory Board for CGF.

Organisation

Figure 8. The historic Gamle Elektro building on Gløshaugen campus.

The CGF is organised as a physical centre, housed in the historic Gamle Elektro building on Gløshaugen campus (Fig. 8) built in 1910 and designed by architect Bredo Greve. 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 (Fig. 9).

Organisational structure

The CGF organisational structure is based on 6 research WP and a management WP, governed and guided by a management team with the support of Innovation and Research Advisory Boards, overseen by the governing CGF board. The structure is illustrated in Fig. 10, where the WP leaders and management team are also shown.

Figure 9. The CGF meeting room in Gamle Elektro.

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.

Martin Landrø is currently also leading the GAMES (Geophysics and Applied Mathematics for Exploration and Safe Production, No. 294404) consortium at NTNU. This is a 5-year project with a budget of 39.9 MNOK. Landrø has received several awards: the ENI Award (2011), the Conrad Schlumberger award (2012) and the Norwegian IOR-prize (2014). 70-80 researchers attend the yearly 4-day GAMES-meetings. We will use the GAMES network to establish a yearly CGF-seminar including international scientists.

A major organisational effort in these initial months has been to select and appoint the members of the boards, who obviously play critical roles in the management and leadership of the Centre.

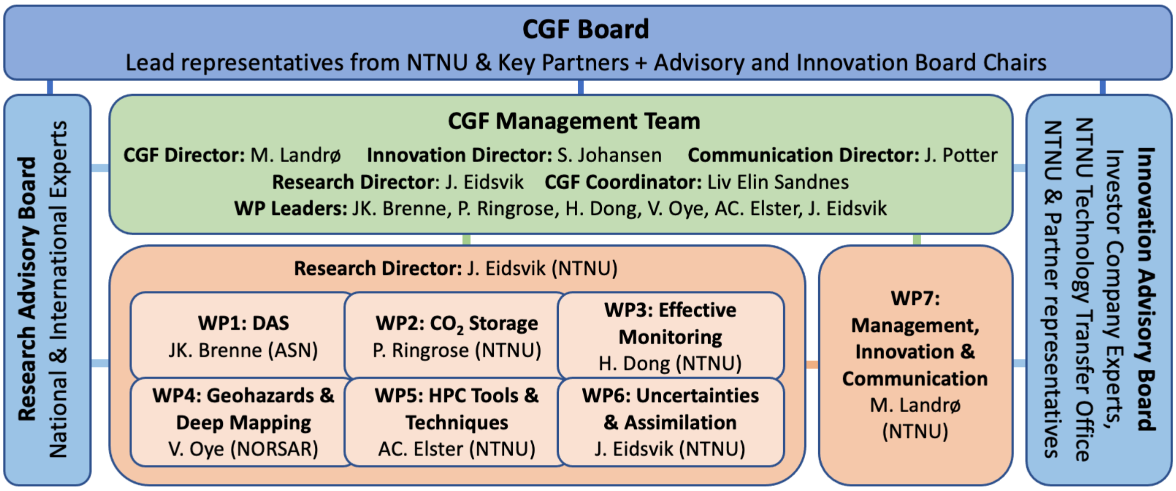

Figure 10. CGF organisation chart.

These board members have now been appointed and the composition is as follows:

Dario Grana	Uni Wyoming	
Jo Eidsvik	NTNU	
Karin Andreassen	Uni Tromsø	
Serge Shapiro	Berlin	Scientific Advisory Board
Shuichi Kodaira	JAMSTEC	
Steven Constable	SIO	
Vera Schlindwein	Alfred Wegener	

Camilla J Larsen	TTO/NTNU	
Duncan Irving	TietoEVRY	
Kent Andorsen	AkerBP	Innovation Advisory Board
Olaf Schjelderup	Uninett	
Solveig Christensen	Exero Tech	
Ståle Emil Johansen	NTNU	
Mark Thompson	Equinor	

Arve Mjelva	NORSAR	
Hilde Nakstad	ASN	
Kari-Lise Rørvik	GASSNOVA	
Odd Pettersen	NTNU	CGF Board
Steinar Bjørnstad	Tampnet	
Tina Ek	Equinor	
Tom Røtting	UniNett	
Martin Landrø	NTNU	Secretary
Kjell Sand	NTNU	Deputy

Partners

The CGF 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 initial CGF partners come from a wide range of fields, spanning the CGF vision landscape and complementing each other with very little overlap or competition. There are 12 founding partners:

- AkerBP
- Alcatel Submarine Networks (ASN)
- Bane Nor
- Digital Geologi
- Equinor
- JAMSTEC
- NORSAR
- Statens Vegvesen (NPRA)
- Tampnet
- TietoEVRY
- Uninett

In addition to these founding partners, several additional organisations have since approached CGF with proposals to join as additional partners. These proposals are currently under review by management and the governing board and, in the event a recommendation is made to accept their proposals, will need to be approved by the founding partners.

Cooperation between the Centre's partners

By exposing PhD students and post docs to a mixture of academic and industrial working environments with open and regular communication among all players, we will 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

While it is difficult to produce scientific results within the first month, some experiments that were performed in anticipation of the start up in December 2020 and which we work on as a part of CGF activities can be presented here.

WP1 - Distributed Acoustic Sensing (DAS)

In March 2020 we acquired DAS and conventional seismic data in the Trondheimsfjord, close to Munkholmen, using NTNU's research vessel "Gunnerus". Fig. 11 shows the track of Gunnerus (green) during the experiment and the FO cable trenched into the seabed (red) with (inset) an image of the DAS interrogator. Fig. 12 shows a comparison between the conventional seismic data and DAS data measured from the FO cable. The purpose of this fjord experiment was to investigate the extent to which it is possible to achieve similar seismic images using a high frequency electric source (bubble gun) and recorded signals in the FO cable compared to conventional seismic. Fig. 12 confirms that this is indeed possible, and

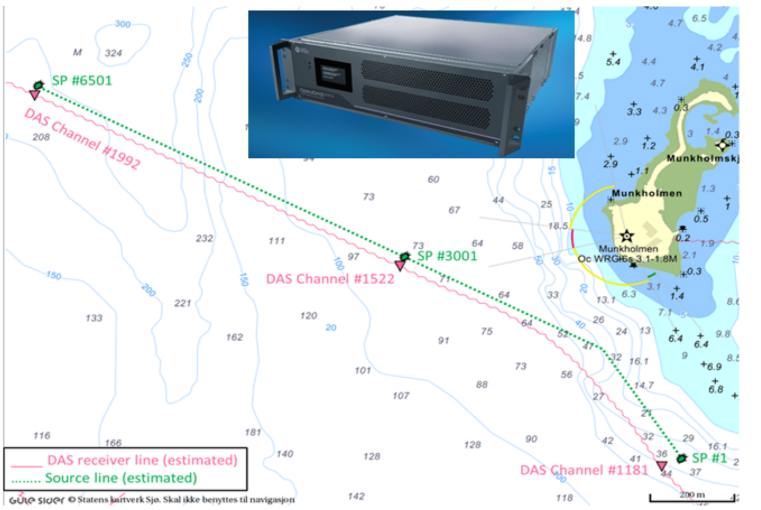

Figure 11: DAS interrogator (inset) and a depth map of the Trondheim fjord, close to the island Munkholmen. Green dotted line shows the vessel sail line, and the red line shows the FO cable that is trenched into the seabed.

although the signal to noise ratio is weaker for the DAS data, these results are very encouraging and give a strong indication that there is a huge potential in using FO cables for acoustic measurements. In CGF we plan to purchase a DAS interrogator in 2021 and this purchase is now underway. The work from the Trondheim fjord experiment has been submitted to Geophysics for publication.

We have started to prepare for the PhD project on "Embedding geophysical sensor systems in optical data communication systems". The preparations have comprised some brief exchanges with Google and the Simula Metropolitan Center for Digital Engineering that both have activities in this field. Together with Simula and Google, Tampnet is exploring how the State of Polarization information from optical transmission systems can be utilized for monitoring. Lab-trials are currently being conducted for characterising sensitivity and frequency response of the detection capabilities. The PhD candidate will be involved in further work within this field. Further collaboration with these centers will be considered. The PhD student will start in August.

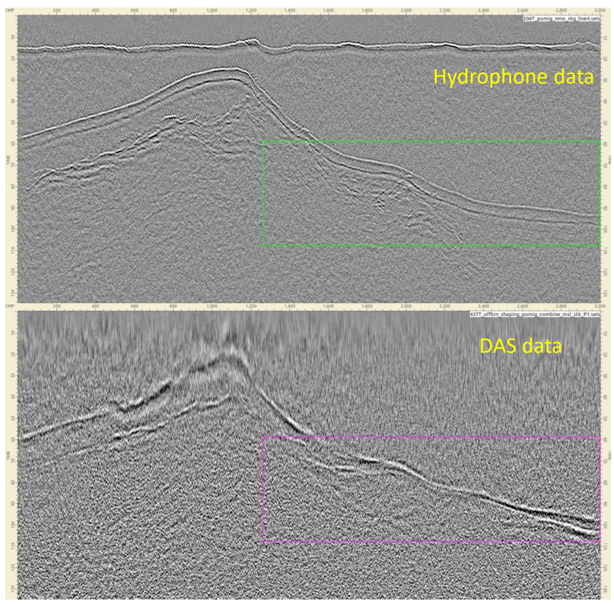

Figure 12. Traditional seismic acoustic data image (upper panel) compared to DAS data (lower panel) derived from a vibro-acoustic source towed in shallow water in Trondheimsfjord.

The partners ASN and Uninett have discussed how to assess the potential of DAS measurements multiplexed with telecom traffic signals in telecom FO cables. Based on inputs from Uninett, ASN has started to source components to build a DAS interrogator for operation in the L-band within 2021. The next steps will comprise of lab trials in a telecom test bed.

The long-term trial campaign with ASN DAS measurements in a dark FO fibre of a Tampnet telecom cable in the North Sea has been offered as an infrastructure for the CGF. DAS data from 4 timeslots with earthquakes in January and February 2021 has been transferred by WP1 from this Tampnet/ASN infrastructure to WP4 for analysis by Norsar.

WP2 - CO2 and gas/energy storage

This WP has been developing the CO_2-storage test tank at NTNU and preparing for initial experiments, as well as developing the digital test datasets to be used for flow simulations. The Smeaheia Dataset was recently released on the co2datashare.org website – an international platform for data sharing, led by Sintef, Equinor and NTNU.

Detailed plans for two PhD topics have been developed (part of the 11 advertised PhD positions) in discussion with industry Partners. One Journal paper has been published on the use of Noble gas tracers for monitoring CCS projects, based on an ongoing PhD project (Uli Weber at Univ. Olso) co-supervised by Philip Ringrose from the CGF SFI. Profs. Ringrose and Landrø have also been contributing to a major review paper on CO_2 storage expected to be published in May 2021.

WP3 - Effective monitoring and forecasting systems, offshore, coastal and onshore

This WP has started with existing Master and PhD students and some results have been submitted to scientific journals in 2020 and published in early 2021, as listed in the publications section of this report. The project on determining soil saturation by seismic velocities for near-surface characterisation using DAS data has begun by collaborating with WP4 on using the NOR-FROST test site and designing a configuration for a geophone array for the test site to obtain reference/benchmark solutions to be used for comparing the analysis of DAS data.

Another work that is highly relevant for CGF is the tube wave clay experiment that was conducted in 2017 at the experimental hall at Valgrinda (NTNU). Two observation wells were drilled through marine clay. The deepest well was 93 m and the shallower well was 30 m. We used a steel plate and a hammer as a source and measured the tube wave velocity several times (repeated experiments). The results from this experiment are described in a full paper published in Geophysics this year. Our plan is to use similar techniques in future CGF-experiments.

WP4 - Geohazard prediction and deep mapping of earth's crust

MT data from two locations at the Mid-Atlantic Ridge (Mohns Ridge and Kinpovich Ridge) have previously been acquired and inverted with respect to resistivity. At the Mohms Ridge inverted resistivity have been used to identify partial melt. (See Johansen et. al, Nature 2019)

The MT measurements have further been correlated to a global tomographic sear-wave velocity model based on earthquake data. Although spatial resolution of the MT resistivity and the seismic velocity model is quite different it is still possible to correlate areas interpreted as partial melt on the MT data with corresponding areas with anomalously low shear wave velocity. Using laboratory measurements of resistivity versus partial melt content and shear velocity versus partial melt content it is concluded that seismic tomography and MT inversion leads to roughly the same quantitative estimates for melt content.

In cooperation with JAMSTEC in Yokohama, we have started analysis of a regional Ocean Bottom Seismic survey along a 500km line extending across the Japan Trench subduction zone. The primary objective is to estimate the water content of the subducting lithosphere using P-wave and S-Wave velocities down to about 15-20 km depth. Our first technical goal is to apply Full Waveform Inversion of this data set to estimate P-wave and S-wave velocities and also to estimate sensitivity to acquisition geometry and water content. At the moment, we have estimated an initial P-wave velocity model using conventional first-arrival tomography. This will serve as part of the initial model for the Full Waveform Inversion.

Looking towards monitoring geohazards, we have started to investigate how to test different FO cables deployed at the NOR-FROST test site at NORSAR with different types of sources and how to best deploy FO cables later in field tests towards rock fall and avalanche monitoring using DAS.

WP5 - HPC tools and techniques for model fitting the subsurface

This WP has begun with existing Master and PhD students. Our work includes creating a parameterised dataset, LS-CAT, consisting of all open CUDA source codes from github that we are cleaning up and will be using as training data for autotuning. We have also written articles on current parallel architectures stemming from Europe and how to improve benchmarking new architechtures, all work which we will build on for this project.

An important fundamental problem in geophysics is the seismic inverse problem where internal mechanical properties of the earth are estimated from measurements at the surface. Modern approaches to the solution of this problem rely on the ability to numerically simulate seismic wave propagation accurately and efficiently. While the physics of seismic waves are well known, the computational cost of the numerical solution is high and this holds back progress on mapping the details of the structure of the earth. Research into implementing and optimising existing methods onto new hardware is one possible way forward. Currently, working together with Anne C. Elster and a MSc. student (Maren Wessel-Berg) we are in the process of analysing a well-known OpenSource Spectral Element package (SPECFEM) with the objective of increasing computational speed by effective use of GPU and/or Tensor processors. SPECFEM is a central code for seismic simulations, including FWI. Maren is also an applicant for one of the 11 advertised PhD positions. She is currently analysing the codes using NVIDIA Nsight Systems and Nsight Compute. These are the tools also used by Ingvild Høstøyl, an Elster´s Master student doing her masters thesis at CERN aalysing larger code for CERN. Ingvild´s co-advisor is Dr. Maria Girone, CTO CERN OpenLab. This project thus gains insights both from HPC-Lab and CERN re. analysing physics-based codes.

In addition, we will be hiring a Post Doc on the 4D-CT project Elster has with NTNU Physics, that should also support this work package.

Elster also gave an IEEE Computer Society DVP Webinar in March 2021 that referenced CGF.

WP6 - Data assimilation and uncertainty quantification

This WP has started a weekly discussion forum where Centre participants present and discuss ongoing work and ideas. So far, the focus has been on understanding the core application challenges in data assimilation and uncertainty quantification. Persons from other WPs have presented cases from their domains to gain insight in the application and to spark interest in the WP6 participants in ways to approach these kinds of data and case studies.

Work relevant for the Centre was submitted with current MSc and PhD students, and some of this has been accepted for publication as listed in the publication list attached to this report.

International cooperation

One of the partners in the CGF (JAMSTEC) is international and based in Yokohama, Japan. We cooperate with this research institute for marine geodynamics, led by director Shuichi Kodaira. In addition to this we have established close relationships to the following highly reputed organisations: Stanford University (USA), TU Delft (Netherlands), Colorado School of Mines (USA) and CNRS (France). In addition to these we have established research cooperation with individuals (one to one cooperation) at several other universities (Table 2). All universities listed in Table 2 are excellent collaborators for exchange of PhD students, post docs and researchers. Prof. Elster´s group has strong ties to the University of Texas at Austin where Elster spends each summer hosted by Prof. Pingali, known for the parallel graph algorithm framework Galois. She also plans to increase her collaborations with a former student, now an upcoming MIT PhD graduate, Fredrik Kjølstad, who will be joining the CS department at Stanford in 2020.

Key Persons	Expertise	University/Institution	Cooperation
Kees Wapenaar	Seismic interferometry and	TU Delft (Netherland)	SE+JP+O
Johan	Acquisition and wave	ETH Zurich (Switzerland)	SE+JP+O
Tariq A.	Inversion theory and seismic	KAUST (Saudi Arabia)	SE+JP+O
Mirko van der	AVO, passive seismic,	University of Alberta	SE+JP+O+SB
Nathalie F.-	Physical model tank	LMA (Marseille, France)	SE+JP+O
Tip Meckel	CO_2 storage	University of Texas, Austin	SE+JP+P+SB
Don Lawton	Time lapse seismic, CO_2	University of Calgary	SE+JP+P
Manika Prasad	Experimental rock physics	CSM (Colorado, USA)	EV+JP+P
José Carcione	Wave propagation, rock	OGS (Trieste, Italy)	EV+JP+P
Mark	Sea bottom seismometers	Scripps (USA)	EV+JP
Shuichi Kodaira	Earthquake seismology	JAMSTEC (Japan)	EV+JP+P
Tapan Mukerji	Rock physics, Geophysical	Stanford University (USA)	EV+JP+P
Gavin Taylor	Machine Learning	US Naval Academy (USA)	SB+O
Keshav Pingali	Performance Engineering	University of Texas, Austin	SE+EV+JP+P
Stan Dosso	Underwater acoustics &	University of Victoria,	SE+JP+EV

Table 2: International scientists with established relations to NTNU. (SE= Student Exchange, JP= Joint Publications, O = Ongoing, P= planned, EV= Expert visits, SB=Sabbatical stay at NTNU, P=Project).

Recruitment

In addition to bonding the key researchers at NTNU and the CGF partners into a team, we have recruited a Centre Coordinator and Administrative staff member, in addition to launching a call to select 11 PhD candidates, covering a variety of projects, for which we have received over 155 applications which are now being evaluated.

The 11 announced PhD positions include the following topics:

1. High performance computing for geophysical inversion and forecasting.
2. Artificial intelligence and machine learning methods for interpretable analysis of cause and effect in geoscience.
3. Machine learning methods for feature extraction in massive geoscience sensor measurements

4. Geophysical activity monitoring methods which are integrated or embedded with long-distance data-communication optical transmission systems
5. Determining soil saturation by seismic velocities for near-surface characterization using DAS data
6. Using geophysical methods with DAS for geohazards monitoring.
7. Multiphysics modeling for in-well monitoring of production/injection wells using FO data.
8. Leading-edge detection of lateral migration of CO_2 plumes using plume-dynamics models and 4D seismic processing
9. Detection and forecasting of vertical migration of CO_2 using high-resolution models of overburden sequences.
10. Seismic wave propagation and inversion in fractured anisotropy media.
11. Bayesian statistical methods for geophone and DAS monitoring of geohazards risk

The successful PhD candidates will be directed to explore new methods that have a broad scope and innovative potential. By exposing young professionals to a dedicated geophysical monitoring center with extensive international collaboration and an innovation focus, our ambition is to develop a strong core of interdisciplinary excellence for tomorrow's leading researchers and innovators.

Communication and dissemination strategy and activities

The CGF has a strong focus on internal communication and alignment in the team, with regular management board oversight and reporting lines from each WP leader. We are also very aware of the value that our partners bring to the enterprise, contributing not only resources and datasets, but crucial research ideas and perspectives, facilitating the all-important diversity in training the 24 PhD's that the Centre will support and providing bridges to transition new research tools and results into innovative products and services in the marketplace. While constraints on physical meetings due to the Covid-10 pandemic have inevitably made teambuilding more difficult, regular weekly meetings are held online to facilitate interaction to ensure, as far as possible, that key personnel are able to align their activities and that issues arising are transparent and open to discussion and resolution.

A CGF logo and visual identity has been designed and is now in use throughout CGF materials (see header of this report for a version of the logo with text). Negotiations are in progress with an external media design company with the view to exploring the professional development of a visual landscape for the CGF that could include standard images and materials for use in presentations and publications.

An MS Teams environment has been set up with channels for each WP and advisory board, within an overarching General channel to which all CGF affiliated personnel are invited to participate. It is here that all the documentation, announcements, minutes of meetings, presentations, etc., are to be stored as a common resource to those authorized at each level.

A series of webinars has been organised by the Director of Research to provide a means to better connect the WP and for each WP leader to better understand the needs and capabilities of the other WP and how they might best fit together.

The other major facet in the communication and dissemination strategy is outward-looking, external communication. This includes dissemination to peers and communication to the wider public. To this end a CGF website has been constructed in compliance with NTNU guidelines and populated with information from the WP leaders and partners. The website serves not only as an outreach tool to the public and potential staff but also provides a repository for written and graphic materials that partners and NTNU management may draw on to promote the Centre in their media interaction materials. In addition, a CGF LinkedIn profile has been established, with all CGF staff invited to connect, through which announcements and job opportunities may be effectively promulgated through the joint network of all our key personnel. At present this profile has 75 connections and has been successfully used to promote the availability of 11 PhD positions.

There are good indications that the CGF website and LinkedIn profile are creating value. The companies that have contacted us to explore becoming CGF partners have told us that they had visited our CGF website and got information that gave them a good impression. The CGF userid on LinkedIn is also getting requests to connect with professionals in related fields, who are not part of CGF, indicating that it is reaching the geophysics community and is of sufficient interest to create requests to connect and be updated about CGF news and events.

Annex 1 – Personnnel

Key Researchers		Main research Area(s)					
Name	**Affiliation**	**WP1**	**WP2**	**WP3**	**WP4**	**WP5**	**WP6**
Aksel Haukanes	ASN	1					
Alan Baird	NORSAR				1		
Alexey Stovas	NTNU			1			
Andreas Wuestefeld	NORSAR				1		
Anne Cathrine Elster	NTNU					1	
Børge Arntsen	NTNU					1	
Dag Roar Hjelme	NTNU	1					
Duncan Irving	TietoEVRY					1	1
Emil Solbakken	NPRA				1		
Erling Siggerud	Digital Geologi				1		
Espen B.Raknes	NTNU/Aker BP			1			
Fredrik Hansteen	Equinor			1			
Frode Storevik	Uninett	1					
Giampiero Salvi	NTNU					1	1
Håkon Tjelmeland	NTNU						1
Hamed Amini	Aker BP		1				
Hefeng Dong	NTNU			1			
Hilde Nakstad	ASN	1					
Ismael Rodriguez	NORSAR				1		
Jan Gerhardsen Formanek	BaneNOR				1		
Jan Kristoffer Brenne	ASN	1					
Jo Eidsvik	NTNU						1
Johan-Fredrik Synnevåg	Equinor	1					
John Potter	NTNU	1					
Kenneth Duffaut	NTNU		1		1		
Kent Andorsen	Aker BP				1		
Kjetil Haavik	Equinor	1		1			
Kurosh Bozorgebrahimi	Uninett	1					

Lars Edward Rygg Kjellesvik	Digital Geologi				1		
Lars Harald Blikra	NVE				1		
Lasse Amundsen	NTNU			1			
Liv Elin Sandnes	NTNU coordinator						
Martin Iandrø	NTNU		1	1	1		
Mathias Alerini	Equinor						1
Nadege Langet	NORSAR				1		
Ola-Petter Normann Munkvold	Equinor					1	
Olaf Schjelderup	Uninett	1					
Ole Jakob Mengshoel	NTNU					1	
Per Åge Avseth			1	1			
Phil Ringrose	NTNU/Equinor		1				
Pierluigi Salvo Rossi	NTNU					1	1
Ragnar Woldseth	NTNU finance						
Rune Martin Holt	NTNU		1	1			
Rune Mittet	NTNU				1		
Shuichi Kodaira	JAMSTEC				1		
Ståle Emil Johansen	NTNU				1		
Stein-Are Strand	NVE				1		
Steinar Bjørnstad	Tampnet	1					
Susann Wienecke	ASN	1					
Svend Østmo	Equinor		1				
Tore Humstad	NPRA				1		
Volker Oye	NORSAR				1		

Visiting Researchers

Name	Funding	Affiliation	Nationality	Sex M/F	Duration
Jakob Rødsgaard Jørgensen				M	

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

Name	Funding	Affiliation	Nationality	Sex M/F	Duration
Shunguo Wang	NRC		PRC	M	

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

Name	Funding	Affiliation	Nationality	Sex M/F	Duration
Hannah Joy Kriesell	NRC	NTNU	DEU	F	
Lea Bouffaut	NRC	NTNU	FRA	F	

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

Name	Funding	Affiliation	Nationality	Sex M/F	Duration
Robin Andre Rørstadbotnen	NRC	NTNU	NOR	M	
Kittinat Taweesintananon	NRC	NTNU	THA	M	
Mohammed Ettayebi	NRC	NTNU	NOR	M	
Lukas Thiem	NRC	NTNU	DEU	M	
Håkon Gryvill	NRC	NTNU	NOR	M	

Mina Spremic	NRC	NTNU	NOR	F	
Uhmedzhon Kakhkhorov	NRC	NTNU	RUS	M	
Jiaxin Yu	NRC	NTNU	PRC	F	
Samira Pakdel					
Jacob Ødgård Tørring					
Zawadi Berg Svela					
Master degrees					
Name	**Funding**	**Affiliation**	**Nationality**	**Sex M/F**	**Duration**
Maren Wessel-Berg				F	

Annex 2 – Accounts

Funding	**Amount (NOK)**
The Research Council	264 763
The Host Institution (NTNU)	85 722
Research Partners*	
Enterprise partners*	
Equinor	117 966
Tampnet	27 500
Aker BP	7 700
NVE	19 861
ASN	180 025
Public partners*	
StatensVegvesen	19 860
Total funding	**723 397**

Costs	**Amount (NOK)**	**WP1**	**WP2**	**WP3**	**WP4**	**WP5**	**WP6**	**WP7**
Host Institution NTNU	452 769	62 562	62 563			14 214		313 430
Research Partners	0							
Enterprise partners								
Equinor	55 403	4 400	43 450			2 750	1 100	3 703
Tampnet	27 500	27 500						
Aker BP	7 700		7 700					
NVE	0							
ASN	180 025	180 025						
Public partners								
StatensVegvesen	0							
Total costs	**723 397**	**274 487**	**113 713**	**0**	**0**	**16 964**	**1 100**	**317 133**

Annex 3 - Publications

Journal Papers

Anne C: Elster: “The European Factor: From ARM to ATOS”, *Computing in Science & Engineering*, Vol, 23, 102-105, IEEE

Anyosa, S., Bunting, S., Eidsvik, J., Romdhane, A., & Bergmo, P. (2021). Assessing the value of seismic monitoring of CO2 storage using simulations and statistical analysis. *International Journal of Greenhouse Gas Control*, *105*, 103219.

Jin, S., and A. Stovas, 2021, Reflection and transmission approximations for P, S1 and S2 waves in triclinic media, Geophysical Journal International 224(1), 558-580.

Gineste, M., & Eidsvik, J. (2021). Batch seismic inversion using the iterative ensemble Kalman smoother. *Computational Geosciences*, 1-17.

Paglia, J., Eidsvik, J., & Cerasi, P. (2020). Workflow for Sensitivity Analysis and Decision Making on the Lower Limit of the Mud-Weight Window in an Overpressured Formation. *SPE Journal*.

Stovas, A., Roganov, Yu., and V. Roganov, 2021, Geometrical characteristics of P and S wave phase and group velocity surfaces in anisotropic media, Geophysical Prospecting 68, no.1, 53-69.

Stovas, A., 2021, On parameterization in monoclinic media with a horizontal symmetry plane, Geophysics 86, no.1, C37-C49.

Weber, U.W., Kipfer, R., Horstmann, E., Ringrose, P., Kampman, N., Tomonaga, Y., Brennwald, M.S. and Sundal, A., 2021. Noble gas tracers in gas streams at Norwegian CO2 capture plants. *International Journal of Greenhouse Gas Control*, *106*, p.103238.

Xu, S., Stovas A., Mikada, H., and J. Takekawa, 2021, On-axis triplications in ORT medium, GeophysicalJournal International 224(1), 449-467

Zeng, J., A, Stovas, H. Huang, L. Ren, and T. Tang, 2021, Prediction of shale gas reservoirs using fluid mobility attribute driven by post-stack seismic data: A case study from Southern China, Advances in Applied Geophysics, 11, 219, 1-18.

Zeng, J., A. Stovas, and H. Huang, 2021, Anisotropic attenuation of stratified viscoelastic media, Geophysical Prospecting 68, no.1, 180-203.

Published Conference Papers

Lars Bjertnes, Jacob O. Tørring and Anne C. Elster:” LS-CAT: A Large-Scale CUDA AutoTuning Dataset, to be presented at International Conference on Applied Artificial Intelligence (ICAPAI 2021) and published by IEEE