Self-Assessment 2015-2020

Geoscience and Engineering
Geoscience and Remote Sensing

Summaries and Case Studies

TU Delft

Summary Geoscience and Engineering

The department GSE focuses on surface and sub-surface science and engineering technology for energy, mineral geo-resources, fluvial and shallow marine sediment dynamics, underground construction, soil structure interaction and geotechnical aspects of surface infrastructure. Societal challenges are posed by the energy transition, the urbanization of low-lying deltas, etc. We address these in interdisciplinary research themes: (1) Energy Transition, with sub-themes Geothermal Science and Engineering, Subsurface Storage, and Geo-research for Offshore Renewables, and (2) Consequences of Underground Engineering (theme under construction). These themes build on the different geoscience and engineering disciplines, which are developed in the five research sections Reservoir Engineering, Geo-Engineering, Applied Geology, Applied Geophysics & Petrophysics, and Resource Engineering. The research is supported by experimentation in the Geoscience and Engineering Laboratory (including fieldwork infrastructure).

The interdisciplinary themes have been set up during the review period and are at different stages of development. The most matured theme (Geothermal Science and Engineering) is discussed as a case study.

During the review period, the research of GSE has led to a significant scientific output of 871 journal papers (a growth of 51% w.r.t. the previous period) and 108 PhD dissertations (a growth of 56%). Many staff members and PhD candidates have received international prizes for their research. Successful research worked as a seed for acquiring prestigious grants (one ERC-AdG, three NWO-Vidi grants, two NWO-Veni grants, two Delft Technology Fellowships, one Marie Curie Fellowship).

Open science. The department has made a serious effort to make its research results accessible to the scientific community and the general public. The percentage of journal papers with open access increased from 49% in 2017 to 77% in 2020. Over the whole period, 588 of the 871 papers (68%) were published open access. The facilities and data of EPOS-NL and GEOLAB are made available for other researchers.

PhD policy and training. PhD candidates take part in the Faculty Graduate School. They get assigned two supervisors and their research is monitored in yearly progress meetings. Averaged over the review period, 61% of the PhD candidates finished their thesis in less than 5 years, which is significantly higher than the averages of approximately 40% for Delft University and 39% for the Netherlands.

Academic culture. Department-wide discussions have been held on a range of aspects related to academic culture. In particular, ethical dilemmas related to working with the hydrocarbon industry have been discussed in the light of the Netherlands code of conduct for research integrity. The main outcomes of these discussions have been integrated into our strategy for the coming 6 years.

Human resources policy. The department is moving towards implementing the ideas formulated in the TU Delft perspective on the recognition and rewards of academics. The interdisciplinary themes are led by the rising stars of our mid-career staff, who get the responsibility and freedom to run these themes. Our efforts for attracting more female staff led to an increase from 5% female staff in 2015 to 21% in 2020.

Strategic goals for next six years
- Further development of the interdisciplinary themes.
- Installation of a department council.
- Improving of academic culture, social cohesion and integrity.
- Continue on improving our PhD-strategy.
- Prioritizing Open Science.
- Improving project and financial management.

Summary Geoscience and Remote Sensing

The department Geoscience and Remote Sensing aims to understand the interaction between human activities, the Earth system and our living environment through the combination of observational data science and physical modelling. The GRS program provides fundamental knowledge for improving our society, as is also reflected in the motto of the CEG Faculty: understand, intervene, and improve. It is organized around the themes Atmosphere, Earth System Science, Remote Sensing and Geodesy. Both Geodesy and Remote Sensing contribute to and are inspired by the development of new satellite missions, which provide new data with higher accuracy and space-time resolution. Activities common to all themes are direct numerical simulations, regional modelling, and developing conceptual models, signal processing, the development of retrieval algorithms, sensor synergy and data fusion, calibration and validation. We cover the complete chain from model and sensor development to information products.

GRS has produced a significant scientific output of 655 journal papers and 47 PhD dissertations. Many staff members and PhD candidates have received international prizes for their research. Successful research worked as a seed for acquiring prestigious grants (two ERC Starting Grants, one ERC Consolidator Grant, two NWO-Vidi grants, one NWO-Veni grants, one Branco Weiss Fellowship).

Open science. The department has made a serious effort to make its research results accessible to the scientific community and the general public. The percentage of journal papers with open access increased from 64% in 2017 to 86% in 2020. Over the period 2017 to 2020, 372 of the 466 papers (80%) were published open access. The facilities and data of Ruisdael Observatory and others, are made available for other researchers. In addition, public outreach via social and other media has increased significantly.

PhD policy and training. The PhD candidates are part in the Faculty Graduate School. In addition, the GRS department has developed a dedicated PhD policy based on the input of the PhD students. At the time of writing the report, it was still too early to report on the impact of this policy, but the first signs are positive: progress seems to be faster.

Academic culture. The influx of new staff members, the expected retirement of professors and the opportunities offered by the new internal careering policy of the university necessitated a revisit of departmental governance, organization, and responsibilities. Department-wide discussions have been held on these aspects. The main outcomes of these discussions have been integrated into our strategy for the coming 6 years.

Human resources policy. The department is moving towards implementing the ideas formulated in the TU Delft perspective on the recognition and rewards of academics. Special attention is given to attracting more female staff via scouting and networking.

Strategic goals for next six years.
- A future proof organization.
- Improving the gender balance.
- An open academic culture.
- Timely successful PhD completion.
- Prioritizing Open Science and strategic public outreach
- Reduce workload by increasing support

Geoscience and Engineering: Case study – Geothermal Science and Engineering Theme

Introduction

The Geothermal Science and Engineering theme (hereafter Geothermal theme) was formed in 2017 within the Department of Geoscience and Engineering and is one of the focal points for current and future research and education. As TU Delft is a multi-disciplinary research environment, where strong fundamental science meets societal challenges, a dedicated theme is a focal point where knowledge can be developed and can be recognised as a global player in geothermal research and education.

Why a Geothermal theme?

Worldwide governments, industry and policy makers are looking for solutions for sustainable energy supplies in order to reach their sustainability goals and mitigate climate change. It is generally expected that geothermal energy, as a sustainable georesource, has an important role to play in this process. Geothermal energy has the potential to deliver low-cost thermal energy (for direct use or conversion), and is increasingly considered as a key contributor for urban heat supply, even in areas outside the classical hotspots with high thermal gradients. Sedimentary aquifers provide a large global resource for direct low-enthalpy (<150 °C) geothermal heat. In the Netherlands, for example, the ambition of the geothermal industry is to drill 700 well doublets for low-enthalpy heat production by 2050 (Master Plan Geothermal Energy in the Netherlands, 2018). Currently there are 20 running geothermal projects, and to further and more rapidly upscale is hampered by large uncertainties in subsurface properties and a lack of monitoring tools, along with large required initial capital investments.

In order to increase the use of geothermal energy and to fulfil the high ambitions in the Netherlands and worldwide, it is necessary to better understand the processes involved over the full lifetime of a geothermal project. The processes we target mostly relate to two societal drivers (i) safe use of the subsurface and (ii) sustainable, reliable and affordable energy. The specific scientific questions are related to long term fluid and heat flow behaviour across a range of scales (from the microstructure to field scale), detailed geophysical monitoring in a noisy (i.e., urban) environment, a better understanding of geochemical processes and material testing. At the Department of Geoscience and Engineering we have the relevant subsurface expertise in-house to tackle these challenges and advance the field. This requires knowledge from a number of disciplines and an integrated approach, for example with Geology taking the lead in investigating the sedimentary processes and microstructure influencing fluid and heat flow, Geophysics leading the monitoring, Petrophysics contributing to analysis of properties (at well and sample scale), Reservoir Engineering leading the numerical simulation aspects including upscaling and Geo-Engineering focusing on shallow geothermal technologies. This expertise and knowledge is combined in the Geothermal theme.

TU Delft is working together with industry partners Hydreco Geomec, EBN and Shell Geothermal as Geothermie Delft to implement a geothermal research well on campus, called the DAPwell (Delft Aardwarmte Project well). This fits within the TU Delft ambition to develop a sustainable campus, where electricity is already provided by solar panels on TU buildings and an off-shore wind park. Heating campus buildings with geothermal energy would bring TU Delft a big step towards being CO_2-neutral. The idea for a geothermal research well on campus was first imagined by a group of TU Delft students in 2008. Once implemented, it will add a critical component to the current engagement of TU Delft within the energy transition. We have the vision to further expand this infrastructure to form an Urban Energy

Laboratory including heat storage, cascading heat networks, a smart thermal network and a series of monitoring and exploration wells at different depths (from 100 to 4 500 m depth). The multi-disciplinary research and the development of this large-scale infrastructure requires a central coordination point which is the Geothermal theme.

Strategy

The Geothermal theme aims to become an expertise centre and a global player for geothermal research and development. We want to solve fundamental and applied research questions to contribute to safe and efficient geothermal energy production. Impact is achieved through solid scientific investigation, close connection with industry and full-scale test cases operating in real-world conditions.

Leadership: The theme has a leader with a small leadership team, made up from colleagues with key expertise, a focus on geothermal technology and range of skills. The team provides academic leadership and project management support and communicates activities and outcomes within the theme.

Scientific questions: Form both grand challenges which require large teams to tackle, and focused questions which can be tackled by individual scientists.

HR: Grow the leadership team to approximately 4 FTE to achieve sufficient momentum, and integrate with other academics within the department. There is a gap in skills in geochemistry, which is partly being filled via new recruitment in 2022.

Funding: Acquire funds in collaboration with internal and external collaborators within the Topsector Energy programmes, the NWO Applied and Engineering Sciences domain, the Dutch National Research Agenda programme and the EU framework programmes. Work with a network of industry partners (many current sponsors) to ensure industrial impact.

Education: Continue providing education in the Applied Earth Science BSc programme to ensure students learn about geothermal energy, expand education primarily within the Geo-Energy MSc track, and expand within a newly proposed Heat track in the Sustainable Energy Technology programme of the Dutch 4TU federation.

Atmosphere/culture: Create an open atmosphere where students, researchers and scientific staff are able to openly communicate, propose ideas and discuss challenges.

Theme organisation

The Geothermal theme was conceived and is operated as a knowledge and cooperation group, and it contributes to department policies/implementation. The leadership team of the theme comprises the staff in the department who focus on geothermal energy. The theme is led by Phil Vardon (Associate Professor), who was just promoted to Associate Professor when he started this position. This way full trust and leadership opportunity is given to mid-career staff in the department. The leadership team furthermore includes David Bruhn (Professor of Geothermal Engineering, who expanded his position to 0.6 FTE in 2021), Alexandros Daniilidis (Assistant Professor who joined in December 2021, replacing Maren Brehme who left in July 2021), and Martin Bloemendal (Assistant Professor in the Water Management department of CEG, joined in 2021). David Bruhn focuses on internationalisation and has recently become the coordinator of the Joint Programme on Geothermal Energy in the European Energy Research Alliance (EERA). In 2020, the department deliberately chose to invest in the position of a research/programme manager to support the management and coordination activities in the theme (Susanne Laumann).

Currently the theme comprises about 20 academic staff from various disciplines, ranging from geophysics, petroleum engineering, rock mechanics, geology, hydrology and reservoir modelling, to policy making e.g. in regulation. The group is changing dynamically as projects and interests evolve.

It should be noted that while the theme is hosted in the Department of Geoscience and Engineering, it also includes academics from other departments such as Water Management and Computational Mechanics. The theme therefore stimulates collaboration within the department and across departments.

Achievements

Education

Over the last years we expanded the amount of educational content related to geothermal energy. We did this not only in our own BSc and MSc programmes of Applied Earth Sciences, but also in the context of 4TU (TU Delft, TU Eindhoven, University of Twente, Wageningen University) and LDE (TU Delft, Leiden University, Erasmus University Rotterdam). The MSc track Petroleum Engineering and Geosciences has been replaced by a newly designed MSc track Geo-Energy Engineering with a major geothermal component, and with geothermics playing an increasing role in the BSc programme. Within most MSc programmes, there is the possibility to take part in a Joint Industry Project (JIP), where geothermal energy has played a prominent role. In addition, we contribute to a comprehensive programme on renewable energy (4TU SET MSc course) and a broader view on geo-resources, including societal, environmental and geo-political aspects (LDE Minor). Together, the course work makes TU Delft more attractive and enhances its visibility for (the growing numbers of) students interested in this topic. At PhD level, the Innovative Training Network (ITN)/IDEA league programme EASYGO is the first standardised doctoral education programme focusing on geothermal energy in Europe (see textbox page 8 on *PhD Policy and Training for details).* All of these developments will help to attract students and train future generations of engineers that are able to work in the geo-energy sector.

Internal TU Delft collaboration

- Founding member of the university-wide Urban Energy Initiative, and founding member of Thermo-X (the Thermal energy platform, a sub-group of the Urban Energy Initiative).
- Pioneer in the development of the campus as a living laboratory concept – which has now been adopted as a broad TU Delft ambition.
- Geothermal energy and high-temperature aquifer thermal energy storage (HT-ATES) embedded in the sustainability concept for the university.
- Regular collaborations in teaching cross-programme/faculty and in MSc thesis supervision.

National and International embedding of the theme

National and international embedding is organised through various activities. The Geothermal Get-Together (GGT), for example, is an initiative to bridge the emerging geothermal industry, policy and university research, by the combination of a short seminar followed by informal networking and discussions and therefore reaches the whole knowledge chain. The GGT contributions range from state-of-the-art research to new policy to industry best practices. Since 2018, we held nine GGTs of which the last four were organised as webinars due to the corona pandemic. During these webinars we regularly had more than 70 participants.

We also extensively engage with industry via the Stichting DAP. This organisation, via a network of industry partners, co-funded 5 years of David Bruhn's position and is currently funding a tenure tracker assistant professor (initially Maren Brehme, replaced by Alexandros Daniilidis in December 2021), with a generous start-up fund. Every 2 years, a geothermal symposium co-hosted by TU Delft and Stichting DAP is held at the university, attracting more than 100 attendees.

On an international level, we are closely involved in the EERA Joint Programme on Geothermal Energy (EERA JP Geothemal). David Bruhn has been elected as the new coordinator of the joint programme in July 2021, and with this appointment, also the Programme Office moved to Delft, which is led by Susanne Laumann. Being closely involved in EERA and the joint programme assures our strong position in the European geothermal research and it allows us to be connected to the major EU players and to provide input into agenda-setting procedures, e.g. the roadmap of the EU Strategic Energy Technologies Plan.

In addition, in 2020 the Geothermal theme took over the leadership of the geo-energy community within EPOS from the British Geological Survey. We are currently working on the re-establishment of the community and its embedding in one of the EPOS Thematic Core Services.

The IDEA league is a strategic alliance between five leading European universities of science and technology. Our department has been one of the leaders of the joint Applied Geophysics MSc programme. We proposed to make geothermal a new theme within the IDEA league, with a focus on doctoral education and research collaboration. The first success of this new initiative was the writing and award of the EASYGO ITN, which links large-scale infrastructure available at each of the partner universities and ten industrial partners into a doctoral education programme and funds 13 PhD candidates.

Project highlights

Built on our network and strong track record, we were able to attract research funds from various sources. An overview of our research projects is presented on the theme website. Here we highlight a few:

Geothermal research well on campus, DAPwell

The geothermal well (planned to be drilled in 2022) will offer a unique full scale research infrastructure of international significance, as it provides access to an operating geothermal system. Equipped with a broad range of advanced technologies for monitoring and data acquisition, the geothermal well will deliver essential information on processes affecting deep geothermal energy provision. The DAPwell will additionally provide heat to the TU Delft campus and at a later stage to other buildings within the Municipality of Delft.

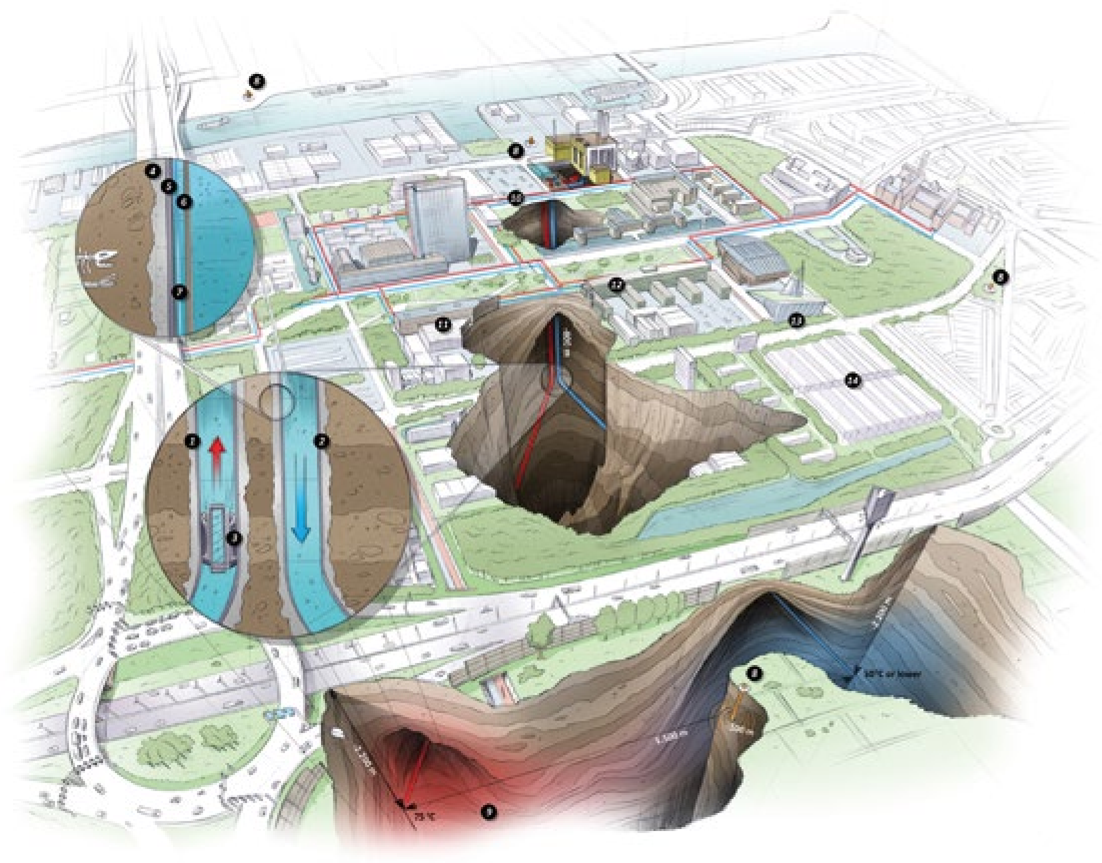

Figure 1. Graphic illustration of the geothermal doublet and the surrounding infrastructure on campus. (1) producer (app. 82 °C), (2) injector (app. 50 °C), (3) submersible pump, (6) fiber optic installation in producer and injector, (8) geophysical monitoring stations, (10) campus heating grid (illustration Stephan Timmers, Total Shot Productions)

The combined aim of heat delivery and research requires collaboration and negotiation internally (with TU Delft Campus Real Estate and the Executive board) as well as with the industry partners of Geothermie Delft. The development of the project was an extensive process, which involved comprehensive decision making processes to ensure the project could address the dual aims, be financially viable and be technically feasible.

Ultimately, this unique infrastructure will make TU Delft a key partner for national and international research cooperation, as access to operating, well-characterised geothermal wells is scarce and thus presents a decisive stepping stone for a major advance in the development and understanding of geothermal systems in sedimentary basins. DAPwell will be complemented by high quality field tests, laboratory and numerical facilities and serve as a reference case for geothermal developments elsewhere.

EPOS-NL

The geothermal research well is part of the Dutch Large Scale Research Infrastructure EPOS-NL that was awarded more than €12 million by NWO. It is a partnership between TU Delft, the Royal Netherlands Meteorological Institute (KNMI) and Utrecht University. The Geothermal theme members contributed significantly in the proposal phase to make this project application successful. EPOS-NL is the Dutch contribution to the European Plate Observing System (EPOS), the Europe-wide infrastructure of geological sciences, geo-hazards and resources (see also text box on open science). EPOS-NL is a cluster of large-scale geophysical facilities for research on georesources which address key geo-societal challenges such as exploration of geo-energy resources, subsurface storage of fluids and CO_2 and hazards such as induced and natural earthquakes. Next to DAPwell, the infrastructure consists of the Earth Simulation Lab in Utrecht, a Multi-scale Imaging and Tomography Facility in Utrecht and Delft, the petrophysics laboratory in Delft and the Orfeus Seismological data centre at KNMI.

Energy Piles in the Netherlands

Energy efficiency of buildings is desirable to reduce costs, greenhouse gas emissions and meet legislative targets. This project aims to tackle a number of outstanding questions for the widespread use of energy piles, an existing technology that has the potential to reduce energy consumption in the heating and cooling of buildings. Energy piles provide both foundation (structural) support to the building and the heating/cooling required. The project aims to address the thermo-hydro-mechanical interaction between the pile and the ground under realistic and extreme conditions, addressing both the short- and long-term behaviours. To achieve these realistic conditions, a 10 meter deep stand-alone experimental pile has been installed in TU Delft's Green Village (~0.7kW), containing detailed instrumentation in the energy pile foundations in order to test and speed up their use on the market. This will help to further standardise the pile technology and help the construction industry move to more sustainable solutions. Following the initial findings and industry collaborations in the project, a novel building on the Green Village has been fitted with 9 energy piles, that are currently being linked to a novel climate control system (~10kW). A development in Zeeland, the Netherlands has been constructed with 500 energy piles (~1MW). See Figure 2 for an impression of the different projects.

Figure 2. Graphic illustration of the different energy pile installations: left – the standalone single pile test, middle – the Co-Creation Centre in the Green Village with 9 energy piles, right – the installation of 500 energy piles in Breskens for a new apartment complex.

WARMINGUP

The WarmingUP collective brings together almost 40 participants from research, industry and government to make collective heating systems reliable, sustainable and affordable for the heat transition. System and process innovations are necessary for improved designs, construction and management. WarmingUP wants to develop these innovations at an increased pace. Acceleration, upscaling and cooperation from the entire heat chain is necessary to realise the heat transition. The Geothermal theme members were closely involved in setting up the consortium and writing the proposal and two PhD candidates have been appointed to work on (i) groundwater monitoring using seismic and electromagnetic methods and (ii) the exploration and efficiency of HT-ATES. In both areas, we are developing techniques and intend to test on real projects during the lifetime of the PhD projects to accelerate adoption into industry. For example, additional measurements for exploration for HT-ATES are being carried out during test borings and drillings for geothermal projects and investigated to gain knowledge on more effective exploration and the impact of heterogeneities.

Highlights of the four Specific Aspects of the Strategy Evaluation Protocol

Open Science: Engagement, outreach and dissemination are a core part of open science, in particular in a societally important topic as geothermal energy. Alongside more traditional methods, the theme stimulates this, for example, through the Geothermal Get-Together where a group of academics (staff and students), industry and government meet in an informal but regular format at TU Delft or online. The research well on campus as a key facility for demonstration of technology as well as an infrastructure for research will further boost these activities.

The ability to offer and maintain open access to data and research facilities/infrastructure are facilitated by the facilities of the European Plate Observing System (EPOS) and EPOS Netherlands (EPOS-NL). EPOS-NL gives national and international researchers the possibility to access its research infrastructures free of charge (which includes laboratory equipment as well as the geothermal research well on campus). Financial support for facility access is provided through the research infrastructure EPOS-NL, which is financed by the Dutch Research Council (NWO). So far, two facility access calls have been launched in 2021 (call 1: access to microscopy infrastructure; call 2: access to petrophysics laboratory equipment) with about 30 applicants. More calls will follow in the upcoming years.

PhD Policy and Training: PhD students are closely involved in the Geothermal theme, with a bi-weekly informal meeting to share news, give informal presentations and stimulate involvement in activities. The group gathering forms an additional support group for early stage researchers outside of their direct supervisors in the section. One major achievement within the theme was the funding of the Innovative Training Network (ITN) EASYGO 'Efficiency & Safety in Geothermal Operations' in 2020 which created 13 PhD positions within the IDEA League universities TU Delft, ETH Zurich, RWTH Aachen University, Politecnico di Milano (PoliMi) and 10 industry partners. The EASYGO ITN is the first standardised doctoral education programme in Europe and it builds on experience and collaboration among the IDEA League universities in various research projects and (since 2006) the joint MSc programme of Applied Geophysics. Within the EASYGO ITN, the PhD students work on a pre-defined project and learn aspects of the entire geothermal operation chain in a specifically designed training programme. The programme includes training weeks on geothermal research related topics as well as on transferable skills, such as team work and communication. In addition, secondments are scheduled at a minimum of one partner university and one industry partner. This way the EASYGO graduates will form a new generation of multidisciplinary experts in geothermal operations trained to achieve standardised efficient and safe operations of geothermal systems to enable the ambitious international expansion plans.

Academic Culture: The theme aims to stimulate academic interactions in an informal and low hierarchy environment. This is complimentary to the formal supervision. There are two main methods to stimulate these interactions: (i) Firstly, we meet and have lunch (pre/post pandemic) on a bi-weekly basis. Usually, 10 to 15 people participate (mostly PhD students and postdoctoral researchers, often with MSc and BSc thesis students, and with professors and industry partners more irregularly). The main parts of the meeting are sharing news/developments/opportunities, an informal presentation and (during non-corona times) the social lunch. Presentations range from BSc project pitches, MSc or PhD thesis plans, updates or final presentation to proposal ideas, granted projects or project updates. The topics include the various disciplines that are represented in the theme and all members broaden their knowledge in the geothermal research field and gain experience of academic presentation/discussion. (ii) Secondly, we meet less regularly (approx. every 2 months) to discuss ongoing projects, project proposals/opportunities, human resources and external communication. This meeting is designed to be focused on permanent academic staff, but all theme participants are invited to also highlight academic activities to more junior members.

Human Resources Policy: Formal human resource management is undertaken via the sections. The leadership team frequently mentors staff within the theme and feeds into the HR process for these staffmembers. This allows clarity of line responsibility for the staff members, while taking advantage of the thematic expertise available.

Future outlook

We will continue developing and contributing research and education in the direction of geothermal energy. In education, geothermal content will be required to be maintained or grown in the Applied Earth Science BSc and MSc programmes and added into the new Environmental Engineering MSc programme. In addition, we foresee that a ‘Heat’ track can be added into the Sustainable Energy Technology programme (SET), which currently focuses on electricity. A proposal has been made via the Thermo-X platform and is currently being discussed at Dean level of the faculties involved in the SET programme.

In research, there are several key challenges. Upscaling from a niche industry to a mainstream industry in low-enthalpy heat is the first; this requires innovations which reduce costs, decrease uncertainties, increase reliability and increase safety. As part of this, it is essential that heat storage and novel subsurface/surface installations are developed and investigated. Secondly, additional resources are needed: (i) hotter resources (which are deeper in most parts of the world) are needed to be exploited for industrial heat; inevitably enhancing systems will be needed, as well as novel exploration and monitoring techniques; (ii) lower temperature (medium depth) resources are more widespread and can be explored, which may reduce financial risks, but have challenges in well stability and required high flowrates; (iii) further integration of shallow geothermal systems into building components and 5th generation heating and cooling networks requires developments in technology, monitoring and smart control. Finally, the majority of geothermal based heating and cooling is low-emission, rather than emission free. Innovations to reduce or eliminate emissions is required.

One of the major infrastructures we are developing is the DAPwell. We intend to develop this infrastructure into a Delft Urban Energy Laboratory on the TU Delft campus. We target (and have undertaken a feasibility study on) a HT-ATES system, and are aiming to develop further projects on heat network control and building integration. As buildings are refurbished and the heat network is extended, different operation modes can take place, which will also affect the subsurface operation. We are also aiming for a deep exploration / monitoring well with a depth of 4.5 km, which will enable testing of novel electromagnetic geophysical monitoring on a real geothermal system, and exploration of both deeper and hotter resources and shallower cooler resources. This infrastructure will be a major asset for the TU Delft research community as a whole and not just for the Geosciences. Scientists from for example Architecture, Process & Energy, and Systems & Control are keen on using such a facility as a living lab which can thus serve as a linking project for campus-wide thermal research.

Geoscience and Remote Sensing: Case Studies

Case study 1: Addressing PhD supervision and completion times

During the previous assessment, one of the main concerns was that the duration of PhD studies often exceeded the nominal four years. GRS installed a working group with both a PhD-representative and 4 staff members to understand why this happens, and to make optimal use of past experience on “best practices” from the full population of PhD students and staff. A questionnaire was distributed to the PhD students asking them to share their experiences and to provide (anonymous) suggestions for improvement. Likewise, academic staff were invited to share ‘best practices’. The outcomes of this survey were distilled into two documents, which are provided below:

The “PhD Memorandum” comprises a list of internal agreements within GRS that add to existing TU Delft policies and facilities offered by the Graduate School. The full memorandum is provided on the next page, but some key points include:

- Before hiring a PhD student, GRS requires that the candidate is tested (IELTS) on English language skills to ensure that they are sufficient to conduct research, publish, and write a thesis. This rule has recently been formalized at the CiTG faculty level.
- It is strongly recommended that the project lead is advised by at least one colleague (e.g. the 2nd (co-)promotor) during the recruitment process to avoid “tunnel vision”.
- It is recommended that the Go/no-go decision is made earlier, at 9 months rather than 12.
- An independent committee member must be present for the 3-month “PhD agreement meeting” where the personal Educational and Developmental Plan is discussed, and the 6-month “PhD progress meeting” where plan adjustments are discussed. The mandate of this independent committee member is to advise.

A list of “Best practices” was also composed by PhD students, with suggestions for advisors.
It is provided overleaf. Key points include:

- Regular, weekly contact is important, even if it is informal.
- Feedback should be constructive and provided promptly (e.g. after 2 weeks)
- Make expectations clear to the PhD candidate. What do you expect and when? When is a thesis complete?
- Step in early when there is a road block.
- In addition to content, focus on the development of soft skills including writing and being a researcher.

These internal GRS agreements complement existing TU Delft policies and facilities offered by the Graduate School. Finally, a list of “tips and tricks” has also been produced by GRS PhD students for GRS PhD students. General recommendations include being proactive, discussing mutual expectations, and seeking help early. Specific suggestions are also made, e.g. guidelines and templates to help prepare efficiently for the 3-, 6- and 9-month meetings. Finally, it includes a list of recommended courses from the TU Delft Graduate School or external providers (e.g. via Coursera).

A representative of the PhD student community attends our weekly staff meeting to keep the PhD students informed on developments within the Department, and to ensure that PhD student voices are heard during decision-making. In addition, PhD students are represented by the GRS student association (Snellius). These connections proved invaluable during the Covid lockdowns as they provided insight into the evolving challenges facing our PhD students and a means to ensure that PhD students stayed connected with each other, and with the Department.

Best practices for advisors/promotors

This is a suggested list of "best practices" to employ throughout your PhD. It is acknowledged that each PhD is unique, with the below intended as a guide based on PhD feedback, and advisor experience.

Guidance:

1. Provide a lot of guidance at the start of the project, gradually reducing oversight during four years
2. Be actively engaged in the research
3. Meet weekly, even if just a "coffee meeting" (short, informal)
4. Provide prompt, constructive feedback; e.g., return drafts within two weeks
5. Provide clear, constructive guidance: i.e. as a constructive coach/mentor and develop ideas together
6. Step in early if there is a roadblock
7. Assist in the planning of the research and in the scheduling of the project
8. Make expectations known

Progress Meetings

1. Schedule all first-year meetings upon entry
2. Go/no go evaluation should be held during the 9^{th} month
3. Guidelines surrounding meetings/expectations should be clear
4. Next to discussing the results, also discuss future research planning

Thesis and Research Planning

1. Discuss ideas and expectations for the "complete" thesis early in the process
1. Aim for peer-reviewed articles as chapters
2. Draft one chapter/article every 1-1.5 years and aim to have 3 by end of 3rd year.
3. It is recommended to draft list of intended topics for each thesis chapter.

Graduate School

1. Encourage PhD student to finish the full 45 credits within the first three years
2. Request a full list of the planned courses (what and when) already at 3-month meeting. New insights later may cause this list to change off course.
3. Graduate School experience should be improved to begin with trough the use of:
    - the list of recommended Graduate School courses [*Appendix B*]. Graduate School representatives of GRS are responsible for updating this list in consultations with the PhDs.
    - courses offered by external organizations (e.g. university, training institutes, research schools etc.

Best practices for PhD candidates

This is a suggested list of "best practices" to employ throughout your PhD. It is acknowledged that each PhD is unique, with the below intended as a guide based on PhD feedback, and advisor experience

General guidance

1. Enjoy it! This is a great time to develop and explore different interests
2. Be proactive. You are ultimately responsible for any planning and issues
3. Seek help early. Make use of the knowledge and experience around you
4. Have a plan, and check it frequently. Update and revise as necessary

Guidance on interactions with your Advisor (incl. Promotor)

1. Aim to meet with your (daily) advisor at least once per week, and your promotor (if different) at least once per month to discuss progress and any current challenges
2. Your advisor should assist in both guiding and planning research
3. Your advisor should not tell you what to work on, but work with you ('advise you').
4. If you have any problems in your advisory relationship, contact your CITG-mentor.
5. Be sure to discuss mutual expectations

Progress Meetings

The current practice is to have `official' progress meetings at 3 and 6 months, the *go/no go* in the 9th month, and annual meetings thereafter.

1. Ensure your meetings are held on time
2. Consult with your advisor(s) on what to prepare
3. Focus on planning, and be sure to discuss advising and other aspects of your PhD.
4. Prepare a short report including research plans, output, and scheduling as appropriate.
5. Send your report to your advisors at least one week in advance so they can prepare.
6. Prepare a short presentation highlighting the key points of the report.
7. Agree with your advisor if it is helpful to define the discussion points beforehand (I.e. agenda) and to follow-up with the key points and agreements.

Thesis and Research Planning

1. Determine with your advisor what is expected and constitutes a "finished" thesis for your specific research.
2. Aim for at least three "research" chapters (excluding introduction and conclusions)
3. Aim to write a (draft) chapter/articles every 1–1.5 years (completed by 3rd year)
4. Decide on the approximate content of your thesis chapters at the 3 month meeting
5. Use the first year meetings to form your thesis introduction or first chapter
6. Start a list of "propositions" early so that you are able to compile a strong list by the end of your thesis

Graduate School

1. By the 3-month meeting: Plan the courses you would like to take
2. Aim to complete at least 15 credits per year such that you are done by the end of year 3 at the latest
3. Seek courses that will truly be of benefit, not just ones to "get points"
4. Look for external course opportunities, not just those at TU Delft

Case study 2: New on- and off-shore vertical reference surfaces for The Netherlands

Summary

The Netherlands lacked accurate realizations of the on- and offshore vertical reference surfaces. Moreover, the relation between both was only established at the onshore tide gauges. Departmental research led to the realisation of the two vertical reference surfaces including the transformations required for the conversion between them. The conceptual framework and part of the methodology were developed before 2015. Between 2015 and 2020 the methodological research was finalized, and the two vertical reference surfaces were computed in collaboration with Deltares, governmental agencies responsible for vertical referencing in the Netherlands, and representatives from the user community. The two vertical reference surfaces, referred to as NLGEO2018 (land) and NLLAT2018 (sea) were provided to the governmental agencies in charge of vertical referencing in the Netherlands in 2018. After a thorough validation, they have been made available to the user community in 2020.

Underpinning research

Novel research on the realization of a mutually consistent set of vertical reference surfaces was undertaken between 2009 and 2020 by Roland Klees (Professor of Physical Geodesy, at TUD since 1994) and his team, primarily Cornelis Slobbe (PhD student at TUD from 2009-2013 and Assistant Professor at TUD since 2013). The conceptual framework and methodology broke new grounds and were well received by the engineering and user community because of their novelty, the improvements over existing methodologies, and the quality of the vertical reference surfaces. The research was communicated in 8 peer-reviewed scientific journal papers and 22 presentations at international conferences. Specific innovations developed over that time period include: the conceptual framework which foresees the combination of gravimetric and altimetric data and water levels at tide gauges with water levels from a hydrodynamic model in a feedback loop [1]; a new functional and stochastic model for satellite radar altimeter data for quasi-geoid modelling [2,3]; a Kalman filter approach to realize a Lowest Astronomical Tide (LAT) based marine vertical reference surface which assimilates tidal water levels at tide gauges into a hydrodynamic model [4]; a methodology for the statistical combination of various terrestrial datasets with a global geopotential model using full noise covariance matrices [5,7,8]; and a methodology to connect the Wadden islands with the Amsterdam ordnance datum (NAP) with cm accuracy [6].

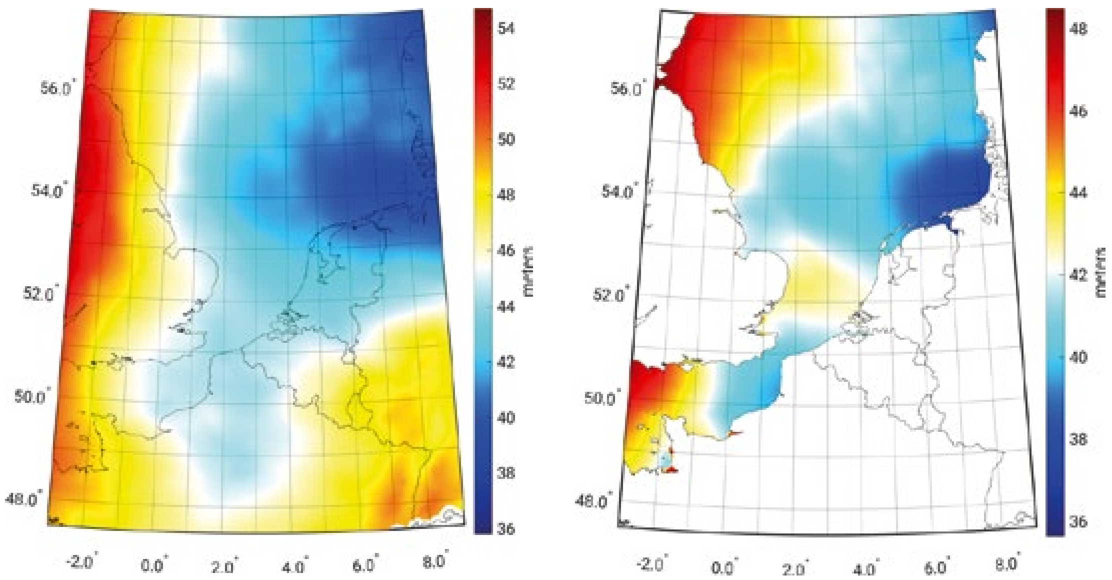

Figure 3. New height (NLGEO2018, left) and depth (NLLAT2018, right) reference surfaces relative to the surface of the GRS80 reference ellipsoid.

Societal impact

The research activities and project deliverables addressed a broad range of problems related to vertical referencing with significant social and economic consequences for the marine and energy sector, including charting and dredging companies and companies offering navigation solutions. The benefits are numerous: faster, cheaper and more accurate hydrographic survey data for nautical charts; more precise navigation in shallow waters; better coastal zone protection by merging of marine and land datasets; more accurate planning of depth maintenance in port approach areas; sea level rise studies, eco-system studies; integrated coastal zone management, and pro-active disaster-mitigation planning; better prevention of vessel grounding. The socio-economic spin-off is substantial: improved charts, which allow for faster transits of ships with deeper draughts which in turn implies a greater amount of goods moving through the shallow Dutch waters such as the ports of Rotterdam and Antwerp; reduced number of groundings by providing more accurate charts, which will reduce insurance rates; improved quality of bathymetric data, which is critical for the selection of routes for pipelines and cables; shorter and more accurate execution of offshore dredging projects and minimized sediment removal with positive impacts on the natural environment; cost benefits for the government due to larger measurement errors in charted depths without effecting the overall error budget; cost savings for the connection of the Wadden islands and off-shore platforms to the height system on land (NAP); reduced uncertainties for hydrographic surveys in the North Sea where GNSS is not available; aiding of offshore dredging projects including large reclamations, pipeline route pre-sweeping, and insulation and stabilization of pipelines in the oil and gas industry.

To maximize societal impact, key users of the project deliverables were involved during project preparation and execution. In fact, a user committee was established with representatives from governmental agencies in charge of vertical referencing (Hydrographic Service of the Royal Netherlands Navy; Ministry of Infrastructure and Environment/Rijkswaterstaat), offshore and dredging industry (e.g., van Oord and Boskalis), surveying companies (Fugro), engineering companies (Allseas Engineering), navigation companies (e.g., QPS), and others (Netherlands Kadaster, oil and gas exploration and production company NAM). In regular meetings, the user committee was informed about the progress and provided feedback, which in turn led to adaptations of the overall plan whenever necessary. Several meetings with the Hydrographic Service of the Royal Netherlands Navy and the Ministry of Infrastructure and Environment/Rijkswaterstaat were organized to guarantee knowledge transfer. Moreover, after finalizing the project a workshop was organized to inform an even broader range of potential users of the new vertical reference surfaces and other related services. About 75 representatives from government and industry participated in the workshop.

The application of the developed conceptual framework and methodology is not confined to the Netherlands. In fact, all coastal countries suffer from similar problems. Collaborations (visits, joint workshops, and knowledge transfer) with institutions in Belgium, Brazil, and Chile, and recently, the Baltic states are on-going. We expect that in the years to come the interest in our approach will steadily increase.

Grants

Some preparatory studies were financially supported in the framework of the EU Interreg IVB North Sea Region Program project “Bringing Land and Sea Together (BLAST)”. The development of the conceptual framework and part of the methodology received financial support from the Netherlands Commission of Geodesy (NCG). Additional methodological research and the computation of the vertical reference surfaces were financially supported by the STW project “Vertical Reference Surfaces for the Netherlands Mainland, Continental Shelf and Wadden Islands (NEVREF)” and a group of governmental and industrial users. The overall financial support was about kE 1,000.

Publications

1. Slobbe, D.C., R. Klees, B.C. Gunter (2014). "Realization of a consistent set of vertical reference surfaces in coastal areas." *Journal of Geodesy* 88(6), 601-615.
2. Slobbe, D.C., R. Klees (2014). "The impact of the dynamic sea surface topography on the quasi-geoid in shallow coastal waters." *Journal of Geodesy* 88(3), 241-261.
3. Farahani H.H., D.C. Slobbe, R. Klees, K. Seitz (2017) "Added value of a proper dealing with coloured noise in radar altimetry data in regional quasi-geoid modelling", *Journal of Geodesy* 91(1), 97-112.
4. Slobbe, D. C., J. Sumihar, T. Frederikse, M. Verlaan, R. Klees, F. Zijl, H.H. Farahani, R. Broekman (2017), "A Kalman filter approach to realize the lowest astronomical tide surface." *Marine Geodesy, 41(1), 44-67.*
5. Klees R., D.C. Slobbe, H.H. Farahani (2017), "A methodology for least-squares local quasi-geoid modelling using a noisy satellite-only gravity field model." *Journal of Geodesy*, 92(4), 431-442.
6. Slobbe, D. C., R. Klees, M. Verlaan, F. Zijl, H.H. Farahani (2018), "Height system connection between island and mainland using a hydrodynamic model: a case study connecting the Dutch Wadden islands to the Amsterdam ordnance datum (NAP)." *Journal of Geodesy*, 92, 1439-1456.
7. Klees R., D.C. Slobbe, H.H. Farahani (2018), "How to deal with an ill-conditioned noise covariance matrix of a satellite-only global gravity field model in local gravity field modelling?" *Journal of Geodesy, 93, 29-44.*
8. Slobbe, D. C., R. Klees, H.H. Farahani, L. Huisman, B. Alberts, P. Voet, F. De Doncker (2018), "The impact of noise in a GRACE/GOCE global gravity model on a local quasi-geoid". J Geophys Res – Solid Earth, 124 (3), 3219-3237.

Knowledge transfer and impact

- Data products: i) Lowest Astronomical Tide reference surface with respect to the GRS80 reference ellipsoid provided to the Hydrographic Service of the Royal Netherlands Navy; ii) quasi-geoid model referenced to the GRS80 reference ellipsoid provided to the Ministry of Infrastructure and the Environment/Rijkswaterstaat.
- Description of the project and deliverables on the website of the NWO-domain TTW.
- Spin-off NWO-TTW project "Versatile Hydrodynamics" (kE 1,100) supported by a broad user community, most of them already involved in the NEVREF project. In this project we intend to develop the water level component of a seamless forecasting system for total water depths in the Dutch North Sea.
- Formalisation of the collaboration with the Hydrographic Service of the Royal Netherlands Navy, the Ministry of Infrastructure and the Environment/Rijkswaterstaat, and the Netherlands Kadaster in the Commission of Geodesy of the Netherlands Center for Geodesy and Geo-Informatics (NCG).
- Invited talks at professional conferences and workshops:
  - Slobbe, D.C., R. Klees, H.H. Farahani, M. Verlaan, F. Zijl, and J. Sumihar (2019). "Roadmap to a Mutually Consistent Set of On- and Offshore Vertical Reference Frames - the Dutch Approach." Oral presentation, IUGG meeting, 8-18 Jul 2019, Montreal, Canada.
  - Slobbe, D.C. (2019). "LAT as chart datum – why actually?" HSB workshop "Hydrografische referentiesystemen en hun toepassingen", September 3, 2019, Aalst, Belgium.
  - Klees, R, DC Slobbe, HH Farahani, M Verlaan, F Zijl, J Sumihar, Developing the geospatial infrastructure to a sustainable management of the coastal zone in a changing climate. II Simposio Brasileiro sobre Praias Arenosas (II SBPA) & XI Cncontro Nacional de Gerenciamento Costeiro (XI ENCOGERCO), Florianopolis (SC), 15 a 20 de Outubro de 2018.
  - Slobbe, D. C. (2018). "Het Normaal Amsterdams Peil anno 2018" interne Expertisenetwerk Waterveiligheid (ENW) dag, May 23, 2018, Den Haag.
  - Klees, R. and Slobbe, D. C. (2018). "Results NEVREF + outlook" 3rd IHO HSSC Tides, Water Level and Currents Working Group Meeting 16-20 April 2018, April 18, 2018, Viña del Mar, Chile.
  - Slobbe, D. C. (2018). "Roadmap to a mutually consistent set of on- and offshore vertical reference frames - the Dutch approach." Norwegian Mapping Authority, March 15, 2018, Stavanger, Norway.
  - Slobbe, D. C. (2017). "Roadmap to a mutually consistent set of on- and offshore vertical reference frames - the Dutch approach." COLACMAR 2017, November 16, 2017, Balneario Camboriu, Brazil.
  - Slobbe, D. C. (2017). "Onshore and offshore vertical reference frames." NCK Theme Day 2017, September 28, 2017, Leiden.
  - Slobbe, D. C. (2015). "Vertical Reference Frame for the Netherlands Mainland, Wadden Islands and Continental Shelf (NEVREF)." 20th NSHC TWG, January 27, 2015, Scheveningen.
  - Slobbe, D. C. (2014). "Satellite radar altimetry and the quasi-geoid." NCG workshop 'Meten en modelleren van zeespiegelvariatie', February 6, 2014, Delft.
  - Slobbe, D. C. (2014). "On the realization of offshore vertical reference surfaces." Hydrografische jaarvergadering, January 20, 2014, Den Helder.
  - Slobbe, D. C. (2013). "Roadmap to a mutually consistent set of offshore vertical reference frames." 38th hydrodynamics & sediment transport & morphology lunch lecture Deltares, October 17, 2013, Delft.
  - Slobbe, D. C. (2013). "A future-proof maritime vertical infrastructure." HSB workshop "Referentievlakken en geodesie in de Noordzee", February 6, 2013, Antwerp, Belgium.

Case study 3: InSAR Geodesy

Research on ***InSAR Geodesy*** addresses the retrieval of reliable estimates of kinematic parameters over areas or objects with time-varying scattering characteristics. Such areas include pastures on drained peat soils, where subsidence and uplift are not reliably measurable. Exacerbated by the effects of climate change, these areas form one of the most demanding challenges for Dutch society, as their continuous drainage causes irreversible land subsidence and significant greenhouse gas emission, forcing choices between agricultural and urban societal interests. In combination with the rising sea levels and elevations already far below sea level, the lack of reliable estimates of irreversible subsidence poses an urgent challenge for the Netherlands and comparable deltaic regions. We addressed this problem in several ways.

***Fundamental research* on InSAR estimation theory** focused on a redefinition of the functional and stochastic models, integer ambiguity estimation, and quality assessment and control. Moreover, we worked on the design, development, and deployment of *new reference stations*, termed integrated geodetic reference stations (IGRS), which can be used to obtain collocated observations from seven different geodetic techniques. The design was patented, tested, manufactured, and deployed. Currently, 35 stations are operational, representing an investment of over 1.5 ME, and the design is currently in production in other countries. Apart from the IGRS, we pioneered the use of *active transponders*, connected to the Dutch tide gauges, to provide a direct reference between sea level variation and unveiling billions of new measurement locations.

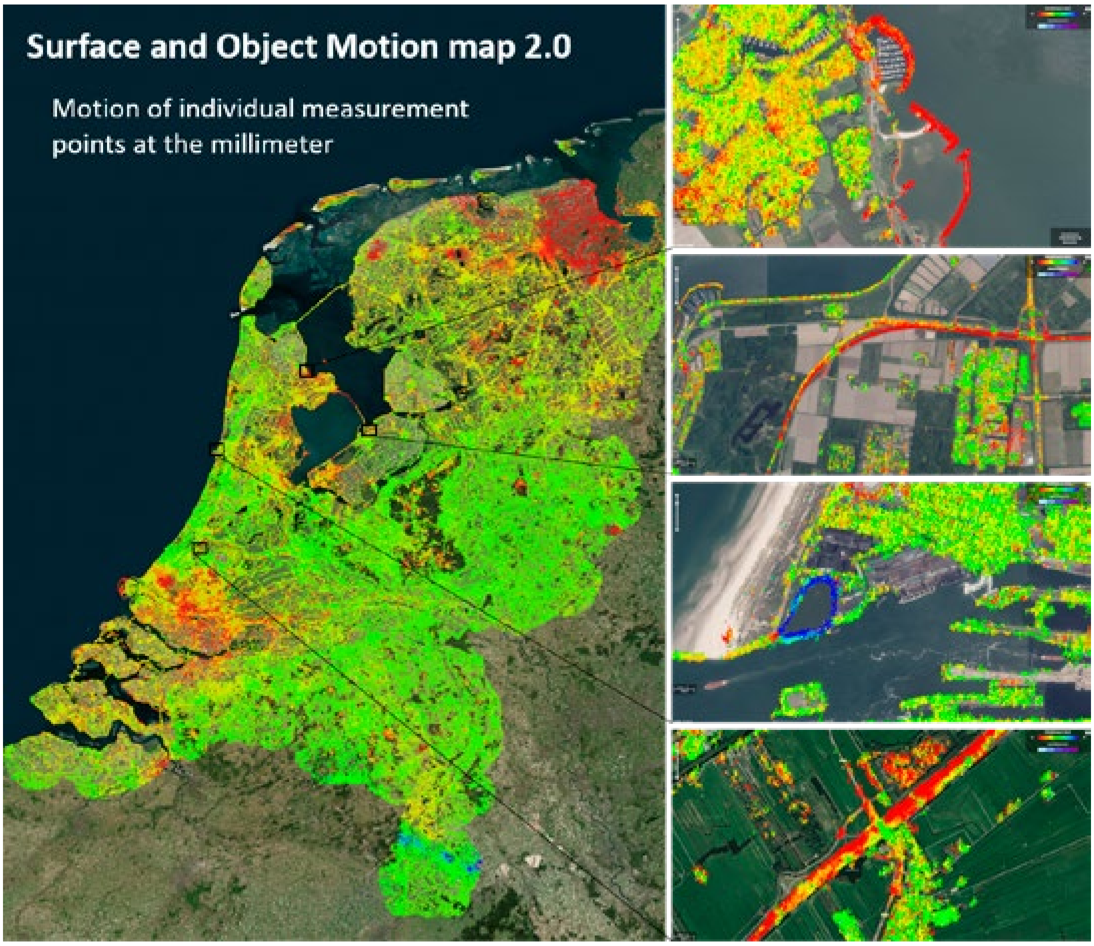

Figure 4. Surface and object motion (SOM) map 2.0. This interactive map allows the user to zoom down to individual measurement sites, and shows the movement of these sites over time. The SOM 2.0 is mostly based on Interferometric Synthetic Aperture Radar (InSAR) data satellites reflections. These reflections are combined to estimate the motion of the earth and objects on it. GPS and gravity data are used to provide references for the data set.

Contextual data processing is a key development initiated by us. The realization that the SAR measurements are as heterogeneous as the earth's surface itself, forced the development of a different philosophy in data processing and kinematic parameter estimation. Contextual information related to the signal of interest, types of land use, disturbance signals such as the atmosphere, the deep and shallow composition of the earth, environmental conditions, and the properties of structures form intelligence that should be included in the estimation algorithms. Additionally, we developed methods for the *integrated processing* of several types of geodetic data.

Aging infrastructure is a societal driver for developing methods for ***structural health monitoring***. General concepts are developed and tuned for railways, highways, tunnels, dikes, dams, embankments, quays, sewer systems, gas, and water utility pipes. Many of these concepts have been quickly adopted by asset managers in industry and are currently operationally deployed.

A special branch of our research activities concerns the ***early-warning detection*** of HILP (High-Impact/Low-Probability) events. Using methods ranging from advanced artificial intelligence to conventional hypothesis testing, methods were developed and deployed to detect impending sinkholes, collapsing quay walls. It is our ambition to build an ***autonomous analysis algorithm*** (CAROLINE) that can demonstrate the philosophy of contextual processing for areas prone to HILP events.

One of the most important societal changes in the Netherlands during the period of evaluation is the increase in *induced seismicity*, the societal and political turmoil, and the successive cessation of the gas production in the Groningen region with its dramatic consequences on the national budget and safety. We were one of the key contributors to the survey schemes and estimation of *methodologies for land subsidence due to gas production*. The current survey philosophy, characterized by a "satellite-unless" approach, is considered optimal from an EHS (environment, health, safety) perspective and follows from direct recommendations given by us. In this philosophy, traditional monitoring using leveling is ceased indefinitely, while required reference benchmarks are maintained. Yet, we are still heavily involved in the disentanglement of the various primary and secondary drivers of vertical and horizontal land motion.

A main challenge during the elapsed and current research period is formed by the extreme numerical and computational demands associated with time series of satellite radar systems, related to data I/O and core processing time. The current data volume reaches 200 TB, and particularly the cumulative inclusion of daily updates in combination with the ambition to develop autonomous near real-time data processing poses strain on the hardware infrastructure needed and possible for a university environment. On the software side, the development is continuous, and algorithms are made available to the public.

During the period of evaluation, we produced two publicly available interactive websites showing the land motion (subsidence and uplift) of the Netherlands, in 2018 and 2020 (https://bodemdalingskaart.nl/en-us/). The Dutch Ground Motion Service, better known as the Bodemdalingskaart in Dutch, is a co-operation between universities, knowledge institutes and companies. Partners include the Netherlands Center for Geodesy and Geo-information (NCG), TU Delft, Hogeschool Utrecht, University of Twente, KNMI, SkyGeo and 06-GPS. The release of both versions of the Bodemdalingskaart triggered front-page coverage in national newspapers and key topics in major television news channels. On an average day, these resources are viewed by approximately 200 users. The datasets have been made available for download.

Case study 4: Antarctica

Our research on Antarctica is a successful example of the feedback between research, funding and communication. Two GRS researchers, Stef Lhermitte & Bert Wouters, are strongly involved in research on Antarctic mass loss and understanding the processes that contribute to it. This has resulted in many publications (including Nature/Science) on ice shelf processes (e.g. KP42, KP43), atmospheric feedbacks over ice sheets and ice sheet mass loss (e.g. KP25, KP26).

At the same time, Lhermitte & Wouters actively share their knowledge with the wider public. By active involvement in open science on Twitter (with > 4900 and >1100 followers respectively), development of interactive websites and a range of lectures for the wider public, they have been able to directly address an extremely wide audience with our scientific results. Likewise, they used their expertise and social media channels to document real-time changes in Antarctica (e.g., calving of icebergs, trajectory of iceberg A68), and to write press releases/reach out to journalists in their network, resulting in emerging news items that were covered by press globally (e.g., calving of Larsen C, Brunt, Amery, Pine Island ice shelves). These tweets have gathered more than 3 Million impressions/viewers since 2017 and have resulted in an extended press coverage with >150 media appearances on radio, tv, written and online press. This coverage, on a variety of topics (e.g. Antarctica, climate change, remote sensing) includes major news outlets such as BBC, The Washington Post, etc.

The combination of high-quality research and strong visibility based on expertise has culminated in a hub of scientific research on ice shelves that was funded by a large investment program of NWO (~2.3M €), GeoForGood by Google, and several other NWO and H2020 initiatives.

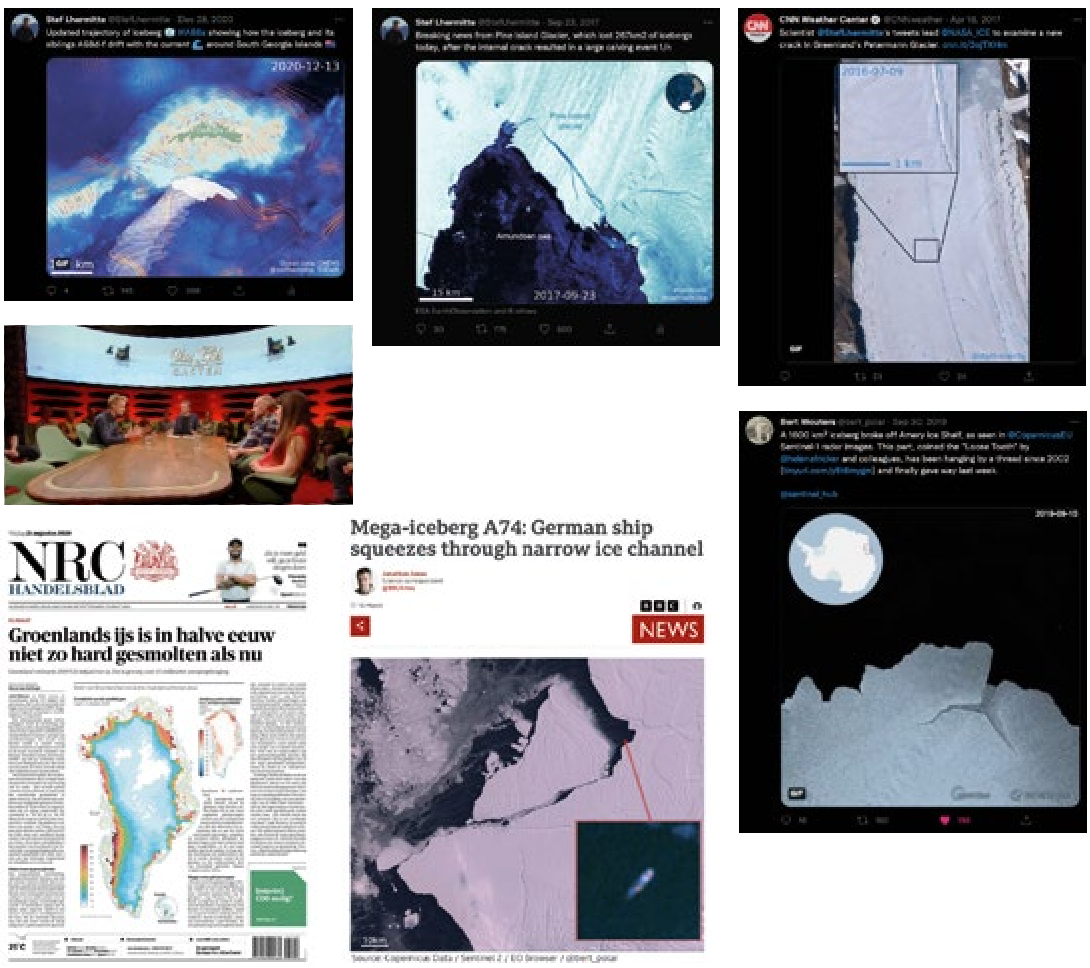

Figure 5. Research on Antarctic mass loss as performed at Dept. GRS, triggers significant media response.

Case study 5: Ruisdael Observatory

GRS took the initiative and is leading the national research infrastructure for atmospheric sciences *Ruisdael Observatory*, a joint enterprise of the universities of Delft, Wageningen, Utrecht, Amsterdam and Groningen, as well as the national institutes KNMI, RIVM and TNO. It was granted with a NWO subsidy of 18 MEuro, and has a total budget of 85 MEuro. It is the Dutch contribution to the European ESFRI research infrastructures ICOS and ACTRIS. The Ruisdael Observatory is good example of how outreach and networking can lead to community and capacity building, and to agenda setting of future national programs: the scientific director of Ruisdael Observatory, Herman Russchenberg, is now chairing the national roadmap committee for infrastructures in the Geosciences.

Scientific background of the Ruisdael Observatory

Since the Industrial Revolution humans have increasingly altered the composition of the atmosphere by emitting carbon dioxide, aerosol particles and trace gases. This has fundamentally changed atmospheric processes on many levels, but we do not yet sufficiently understand how these emissions modify weather patterns, climate and air quality. We have at present no adequate understanding of how the atmosphere might evolve in the future. The weather forecast is limited to days – partly due to the chaotic nature of weather itself – but also because we lack sufficient insight into the physics and chemistry of small-scale processes and how they are coupled to larger scale phenomena in the atmosphere. Apart from the daily weather forecast, we also need to know the long-term trends of the weather, its variability and its extremes. How is the changing atmosphere affecting our climate, and consequently: our living environment? The science to address these issues requires data at different spatial and temporal scales in different environments, ranging from urban centres to forests or grass lands.
With the increasing availability of computational power and observational tools the atmospheric community is now at the brink of a new revolution. With the coupling of large flows of detailed observations to high resolution atmospheric model simulations, we are getting close to the realm of first principles: characterizing and predicting the state of the atmosphere based on the laws of nature with a minimized need for approximations of small-scale phenomena.
Atmospheric science encompasses many different disciplines from weather prediction to climatology, from air quality and greenhouse gas budgets to water cycle research and large-scale circulation. However, important breakthroughs in the most pressing scientific questions in many of these diverse disciplines require similar methodological advances:

- long-term detailed atmospheric and land-surface observations.
- integrating micro- and macroscopic scales using observations (from microphysical observations to large scale measurements) and models (from cloud resolving to global models).

The **Ruisdael Observatory** provides the facilities to meet this goal. It is operational in rural and urban areas to investigate the interaction between the heterogeneous mosaic landscape and the atmosphere. Observations and models will be merged in real time, integrating a wide range of spatial and temporal scales, to form a virtual laboratory for understanding multi-scale processes in atmospheric chemistry and physics, and by doing so improve the accuracy of climate, weather and air quality models on the regional scale.

The concept of the Ruisdael Observatory

The backbone of the observatory is formed by four advanced stations: the urban area of Rotterdam, Cabauw in flat grass land, Loobos in a forest and Lutjewad at the Wadden Sea coast to cover different backgrounds. These stations are embedded in national networks for the observation of meteorological parameters, radiation and air quality. Included in the observatory are also a suit of mobile stations for turbulence, atmospheric chemistry and clouds, as well as computational and data facilities for running LES models. The location of Ruisdael Observatory – in a coastal climate and amidst major European industrial areas and cities – makes that a large variety of air masses and weather types can be observed and studied. The Dutch landscape and human activities in it are well documented and also intensively monitored. This unique combination makes the Ruisdael Observatory particularly attractive to international researchers working on improvement of both observational capabilities and modelling tools for climate change predictions for regions around the world. The figures on the next page show the layout of the observatory.

Figure 6. Layout of the stations of Ruisdael Observatory. Also shown are the locations of the KNMI and RIVM operational networks of automatic weather stations AWS, radiation, air quality, cloud cover and height. Not shown are the mobile facilities.

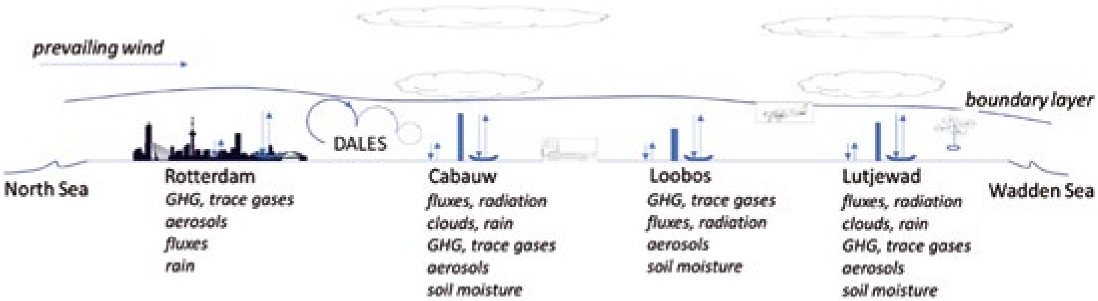

Figure 7. Transect from Rotterdam to Lutjewad: 220 km, from the urban dome across agriculture land and forests to the sea

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