Seismic Imaging & Monitoring Systems (SIMS)

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This paper introduces a next-generation miniaturized accelerometer, a sensor measuring acceleration with integrated signal processing, that utilises patented micro-electro-mechanical systems (MEMS) technology inspired by the search for gravitational waves. Immediately we realised that the possible applications of our sensor systems are manifold. This technology offers solutions to the three main challenges currently facing miniaturized accelerometer development: sensitivity, power consumption, and cost. This new sensor will address the needs of the geothermal energy and navigation markets and open up opportunities in entirely new markets where smaller, lighter and cost-effective devices can provide smart sensing.

Sensors; Accelerometer; ASIC; MEMS; Energy; Security

1. INTRODUCTION

Europe is investigating in the Einstein Telescope to enhance its research infrastructure. Around 2030 this facility should be operational to image the universe with gravitational waves with ten-fold improved sensitivity compared to current interferometers. One requires seismic sensor networks to subtract noise caused by the direct gravitational coupling of mass density fluctuations to suspended components of the interferometer to reach this sensitivity. For example, tiny density fluctuations in the earth's crust will couple directly to the suspended mirrors, causing displacement noise that cannot be filtered out by the suspension systems.

To reduce this limiting noise source at low frequencies, Nikhef, the Dutch National Institute for Subatomic Physics has started developing a novel seismic sensor:

- An ultra-sensitive miniaturised accelerometer at low frequencies (1-100 Hz) made in micro-electro-mechanical system (MEMS) technology shown in Fig. 1.
- The MEMS accelerometer has already proven world record sensitivity that is more than an order of magnitude better than the current state-of-the-art. This sensitivity was reached in a laboratory setup where the sensor is read out by bulky discrete electronics.
- We are developing a low-noise, low-power ASIC: an Application Specific Integrated Circuit to reach significantly lower power and cost.

Our main objective is to develop the world's most sensitive and compact accelerometer in the low-frequency regime that can be produced in large quantities. Nikhef and its spin-off company Innoseis have started integrating the MEMS accelerometer with micro-chip prototypes to develop a robust and practical seismic sensor.

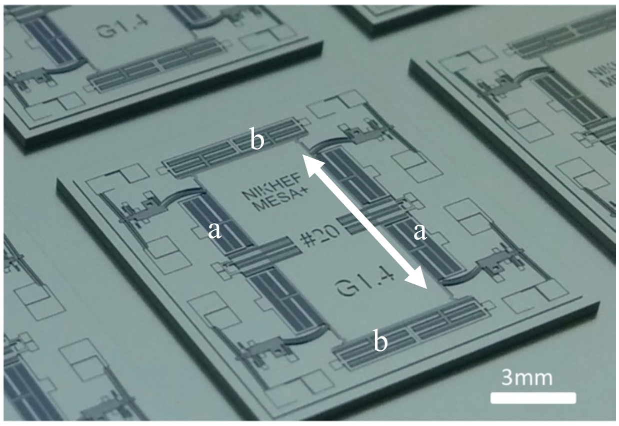

Fig. 1. The MEMS sensor: the central proof mass can move along the arrow's direction and is suspended by adjustable curved springs in the four corners. The variable capacitors on the four sides are used to sense (a) and actuate (b) the proof mass.

ATTRACT Phase I was very productive, and our project high-lights are:

- **A patented MEMS accelerometer:** investigated more robust designs, and developing wafer-scale packaging
- **Developing our 3rd readout chip:** added e.g. a lead filter and Delta-Sigma converter, to eventually place all necessary electronics on-chip
- **A versatile test station is operational**: tested and integrated the different MEMS accelerometer and readout chip prototypes

- **Building a consortium:** established relations on a new application '*inertial navigation in space'*, and improved fabrication techniques in collaboration with our production partners

2. STATE OF THE ART

Many competing attempts have been made to improve the sensitivity of MEMS accelerometers for sub-surface or seismic imaging. For example, Lumedyne produced a prototype sensor that is read-out using an optical system. Although these have seen sensitivity improvements, the devices are currently not commercially available. Commercial MEMS products with reasonable sensitivity (tens of ng/√Hz) also exist but are plagued by high power consumption and high cost, limiting them to niche applications (mainly in oil and gas). The comparison in Table 1 shows the difference between the critical performance criteria of competing MEMS accelerometers. The MEMS presented in this paper has an order of magnitude better sensitivity and is targeted to have significantly lower power and cost.

Tab. 1. Key performance comparison of state-of-the-art accelerometers with our MEMS sensor

Sensor	Sensitivity @ 10 Hz [ng/√Hz]	Power [mW]	Cost (€/unit)
Lumedyne Fabry-Perot	40	TBC	Not on market
INOVA Accuseis	30	85	300
Sercel DSU508	20	85	400
HP/Shell Voyager	15	TBC	Not on market
Nikhef/Innoseis MEMS	<1	25	20 (target)

Hence, we started investigating additional markets. The EU has identified high-performance accelerometers as a crucial technology for navigation grade applications, thrust control, and formation flying (European Space Technology Master Plan). New products with enhanced capabilities are needed for the commercial aerospace sector as well as scientific missions.

Traditionally non-MEMS based devices dominated. However, in the past few years, as MEMS have become more accurate, with the added benefit of lower per-unit cost and size, they have started to gain traction. We will be focusing on the use cases that require the high precision and accuracy where our technology excels, i.e. satellite in-orbit manoeuvres. Currently, there are very few vendors that offer these state-of-the-art MEMS accelerometers. These are integrated into inertial measurement units or sold individually. The Honeywell Q-Flex® QA-3000 series is the current baseline solution for accelerometers, according to industry experts. A European alternative is much sought after, as stated in the European Space Technology Master Plan.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

For an ultra-sensitive MEMS accelerometer, the typically dominant 'flicker' noise must be overcome by several orders of magnitude with a limited power budget. Innovations in both the MEMS design and in the electronics system will target acceleration resolutions in the order of 1 ng/√Hz.

We focus on the development of our patented high sensitivity MEMS accelerometer using geometric anti-spring technology. Geometric anti-spring technology is used in the seismic isolation platforms of gravitational wave detectors and has been successfully miniaturised by Nikhef and implemented in a MEMS accelerometer. Geometric anti-spring technology provides an on-chip mechanical preloading system comprising sets of curved leaf springs that support a proof-mass. Using this preloading mechanism, stiffness reduction by up to a factor 25 in the sensing direction has been achieved. This increases the sensitivity to acceleration by the same factor, resulting in a readout noise floor below 1 ng/√Hz as shown in Fig. 2. Due to its purely mechanical realization, no power is consumed when the accelerometer is operational in a preloaded state.

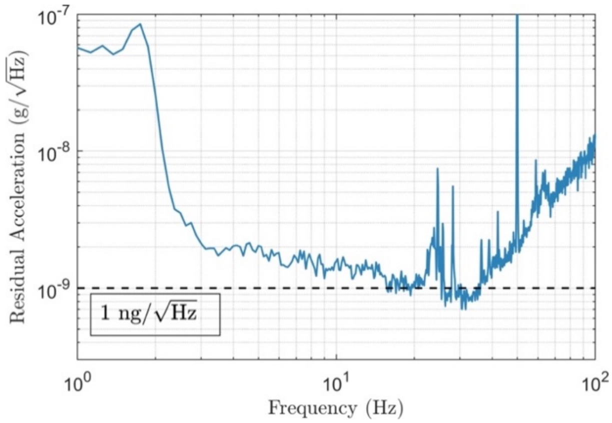

Fig. 2. The measured noise floor of a MEMS accelerometer prototype in a laboratory set-up.

The integration of the MEMS readout electronics into a single integrated circuit (ASIC) has many advantages, including a further reduction of cost and power consumption. The technical challenges include:

a) Further miniaturising the readout electronics without compromising on performance metrics.
b) Correct simulation of the ASIC design as small variations in the circuitry layout can have a significant impact on the overall performance. Nikhef specialists will perform these complex simulations before submitting a design for fabrication.

An important technology step is to replace the discrete readout electronics of our laboratory set-up with ASIC circuitry and integrate the MEMS accelerometer and readout ASIC into a single package. To extend both dynamic range and linearity, the MEMS accelerometer will be operated in a closed-loop fashion.

4. PROJECT RESULTS

A more robust MEMS accelerometer. Due to the narrow cavities inherent to our MEMS production process, stiction of the proof mass is frequently observed. To alleviate this, an improved fabrication procedure is currently being implemented. The fabrication procedure includes processing two separated wafers that are to be joined together using a thermocompression bond. Processing the wafers separately gives complete freedom on cavity features and is a step towards industrial processing flows.
The MEMS sensor needs to be operated in a moderate vacuum to reach the target sensitivity. Prototype MEMS sensors have been individually vacuum-packaged for testing. Still, the process is compatible with an extension to wafer-level vacuum packaging, which is required for large-scale production.

Various readout chip prototypes. In the first step, we've implemented only the front-end circuitry in a prototype chip in AMS 0.35 μm CMOS technology. A test setup has been built where a flexible and programmable loop-filter is implemented in a Field Programmable Gate Array (FPGA). Closed-loop measurements with this system clarified which filter topology and additional circuitry we need to implement in a second prototype chip to reach the sensitivity of 1 ng/√Hz.
However, for the second chip fabrication, we had to move to a new CMOS technology of the X-FAB semiconductor foundry since the CMOS technology used for our first chip became obsolete at AMS. This technology change was a challenge as all components and performances needed to be modelled in new simulation tools. Laboratory tests with the first readout chip showed an unforeseen 'feedthrough' effect that did not appear in the simulations. Besides, there was a mismatch between some of the transistor models in simulation and the fabricated transistors. Extensive characterisation and modelling were needed to understand and solve these issues to prepare our next chip submission.
Understanding the performance and noise characteristics of the readout electronics required comprehensive mathematical models, including the non-linear behavior of the feedback control signals. In addition, the power consumption was analyzed to offer trade-offs between power and performance.

Test station operational to optimize the readout chip. The second readout chip arrived in January 2020, and we've started extensive testing. Fig. 3 shows a prototype readout chip bonded to a MEMS accelerometer. A test setup with partially discrete electronics has seen an expansion to include the feedback control elements of the system since this is not implemented in the chip yet. The chip works as expected, but still has some features we will resolve in the next version. We finished simulations of additional circuitry blocks (a filter and Delta-Sigma ADC). The layout of these blocks is ready and implemented in the third prototype chip that was submitted for fabrication in August 2020.

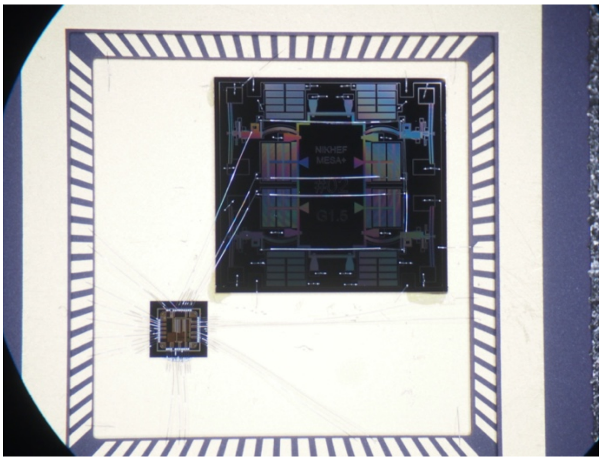

Fig. 3. A readout chip (bottom left) bonded to a MEMS accelerometer (top right) for testing: the metal wire-bonds are visible. The accelerometer shows a similar pattern, with the proof-mass in the middle, as seen in Fig. 1.

5. FUTURE PROJECT VISION

The next phase in our project is to bring the MEMS accelerometer from a lab setting to a realistic environment, depending on the application. This defines our strategy for a potential three year ATTRACT Phase 2 project.

5.1. Technology Scaling

To bring the MEMS accelerometer beyond the current TRL4 level, we have defined three concrete technology steps with accompanying hardware developments. Based on recent manufacturing progress regarding anti-stiction and vacuum packaging of the MEMS sensor, the next fabrication step will result in a more robust device. This will align our production process with industrial requirements while enabling manufacturing scale and yield for mass production.

The readout ASIC prototypes are produced by X-FAB, a leading commercial foundry, in a fully developed 0.35 μm CMOS technology. Hence, scaling will be straightforward as soon as all aspects of the required functionality have been implemented and characterised.

A third area to explore for mass production and out of lab use of the MEMS accelerometer is integrating the MEMS sensor with the readout ASIC in a single package. Such integration is already partially explored during the MEMS fabrication phase and will allow us to release a demonstration kit. This will automatically lift the technical readiness to TRL6 and enable partners to work with the MEMS accelerometer and generate feedback as well as extensive testing. Therefore, we expect that a TRL7 level is in reach at the end of ATTRACT Phase 2.

5.2. Project Synergies and Outreach

Nikhef is used to develop instrumentation for big science infrastructures like the LHC and the future Einstein Telescope, via their engineering departments and close collaboration with European high-tech industry and research institutes. Innoseis' core business is sensor technology development for commercial markets and explores novel industrial applications for our MEMS accelerometer. Nikhef and Innoseis contacted multiple companies in the last year during ATTRACT phase 1. We have investigated various ways forward with manufacturing companies like Teledyne Dalsa, SAES Getters, and LioniX. Nikhef and Innoseis own the IP and designs, and worked e.g. with LioniX to improve our MEMS manufacturing process. Further testing and discussions with providers of customized microsystem solutions (foundries) are needed in Phase 2 to reach a suitable production-ready design. Once the design has been finalized, the production process itself will be developed together with a foundry.
There is currently an active conversation with the European Space Agency (ESA) and V-Kvadrat, a Swedish space engineering company. Together we identified opportunities for commercial applications in space and strengthened the technology based on particular requirements for space applications.
We have identified potential partners funded within ATTRACT Phase 1 with which preliminary conversations are ongoing. For example, a team at the Delft Technical University works on a MEMS accelerometer with optical readout, and a French group works on a magnetometer with potential use for inertial positioning in space.

A team of four students from an honors program at Delft University selected our project for a Summer School at CERN's IdeaSquare in Geneva. They explored various commercial applications of the technology, coming up with out-of-the-box ideas showing the potential of our technology. The cherry on the top was that our students' team won the final pitch competition and a subsequent publication on the case study [1]!

We undertook several other ATTRACT dissemination activities last year to reach out:

- A short pitch video was submitted to explain our project.
- We attended the MEMS 2020 conference in Vancouver and established a number of contacts with MEMS foundries and industrial parties.
- Nikhef organized and hosted an ATTRACT-NL meeting: with pitches of Dutch student teams that participated in CERN's Ideasquare and prepared for phase-2 funding. Nikhef's Communication department and Industrial Contact Coordinator assisted with these activities and will be available for future outreach.

5.3. Technology application and demonstration cases

Inertial navigation. The MEMS accelerometer is well-positioned for use as an inertial sensor for the navigation of satellites. Constellations of satellites will usher in the next era of telecom, earth survey, and space exploration. In a competing market, an increase in satellite performance and operational lifetime are crucial for a profitable business case. High-performance, low power consumption navigation solutions are needed for this, as underlined in the ESA-EU Space Technology Master Plan. Current products can't deliver. Our technology can accelerate it towards a marketable product in the next ATTRACT phase. In 2019 the high-end inertial sensor market was worth $3.24B. Commercial aerospace made-up 25%, with significant growth expected [2].

Geothermal imaging. To address the needs of a growing sustainable energy supply, geothermal energy is gaining popularity as a clean and abundant energy source. It utilizes the heat generated by the Earth, which is extracted to heat houses, power industrial applications, and generate electricity. It requires an excellent knowledge of the underlying geology to plan optimal well locations and extraction rates.

Seismic surveying technology is a crucial link in addressing the challenges of geothermal energy. This technique makes use of sensor networks to image underground structures non-invasively. Innoseis has developed Tremornet, a wireless sensor solution that rids the industry of bulky cabled sensor networks and makes seismic surveying more cost-effective. The MEMS accelerometer will allow these sensors to become even smaller and lighter and offer improved signal performance at low frequencies. The envisaged size of a MEMS Tremornet is that of a small teacup.

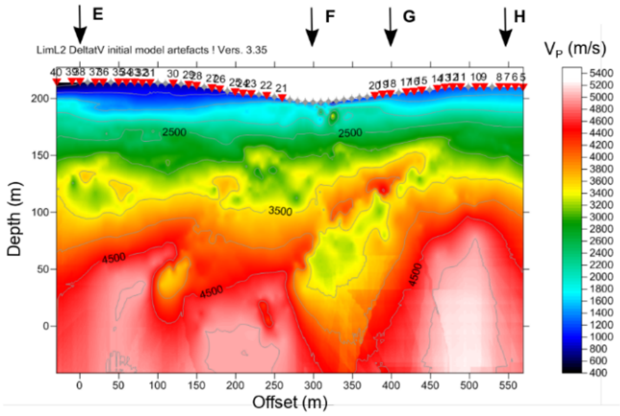

Fig. 4. A Cross-section of the underground of a proposed Einstein Telescope site location made using Innoseis sensors and seismic imaging techniques.

Benefit to European Research Infrastructure. The MEMS accelerometer will enhance the Einstein Telescope infrastructure in two key ways. 1) to improve the sensitivity in the low-frequency range. 2) the sensitivity of a future gravitational wave detector will depend on the local seismic field and geology. It is important for site selection to perform studies with seismic sensor arrays to determine the primary seismic noise sources and the local geology in terms of a subsurface model. Fig. 4 shows the results of a Nikhef-Innoseis project to map the underground structures of a potential Einstein Telescope site in the south of the Netherlands [3].

5.4. Technology commercialization

ATTRACT phase 2 will allow us to fast track the technology into the market. This will be done through the generation of a spin-off company, and demonstrations of the technology in relevant environments in collaboration with launching customers.

The following steps have been taken to initialize the commercialization phase. 1) the new start-up company Innoseis Sensor Technologies has been inaugurated to focus on the MEMS development and marketing, 2) discussions are underway with potential users of the technology, most notably, a collaboration is being drafted with ESA to explore the satellite navigation use case and INOVA Geophysical who has expressed interest in the seismic imaging potential.

5.5. Envisioned risks

The following potential risks have been identified with corresponding mitigation strategies:

Development risk: Hardware R&D can be a risky business, and delays can quickly accumulate when proto-series or test campaigns fail. These risks are reduced by running detailed computational simulations on designs and test results prior to prototype production or validation trials, thus mitigating unexpected outcomes.

Production risk: MEMS and ASIC manufacturing can render poor results or fail altogether. By partnering with the world-class MEMS foundry LioniX, we will leverage their expertise to minimize such errors. Also, fallback scenarios with discrete electronics will mean the project can still progress, even with an unexpected setback.

Commercial risk: Product acceptance and market penetration are key for successful commercialization. These risks will be reduced by partnering with users and securing early launch customers, such as ESA, who will provide feedback on the product as soon as possible.

5.6. Liaison with Student Teams and Socio-Economic Study

Nikhef is a partnership that involves six universities. It is straightforward to include parts of our ATTRACT project in the academic curricula. This exposes students to new technology and various start-up companies, industry, and research organizations and will provide a broader knowledge base. Our successful experience with the honours students (section 5.2) shows that we are open to supervising students.

The author is involved in the Dutch Top sectors. Within nine designated sectors, the collaboration between companies, researchers and the government is being encouraged to find solutions for societal challenges.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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