FIRST BREAK

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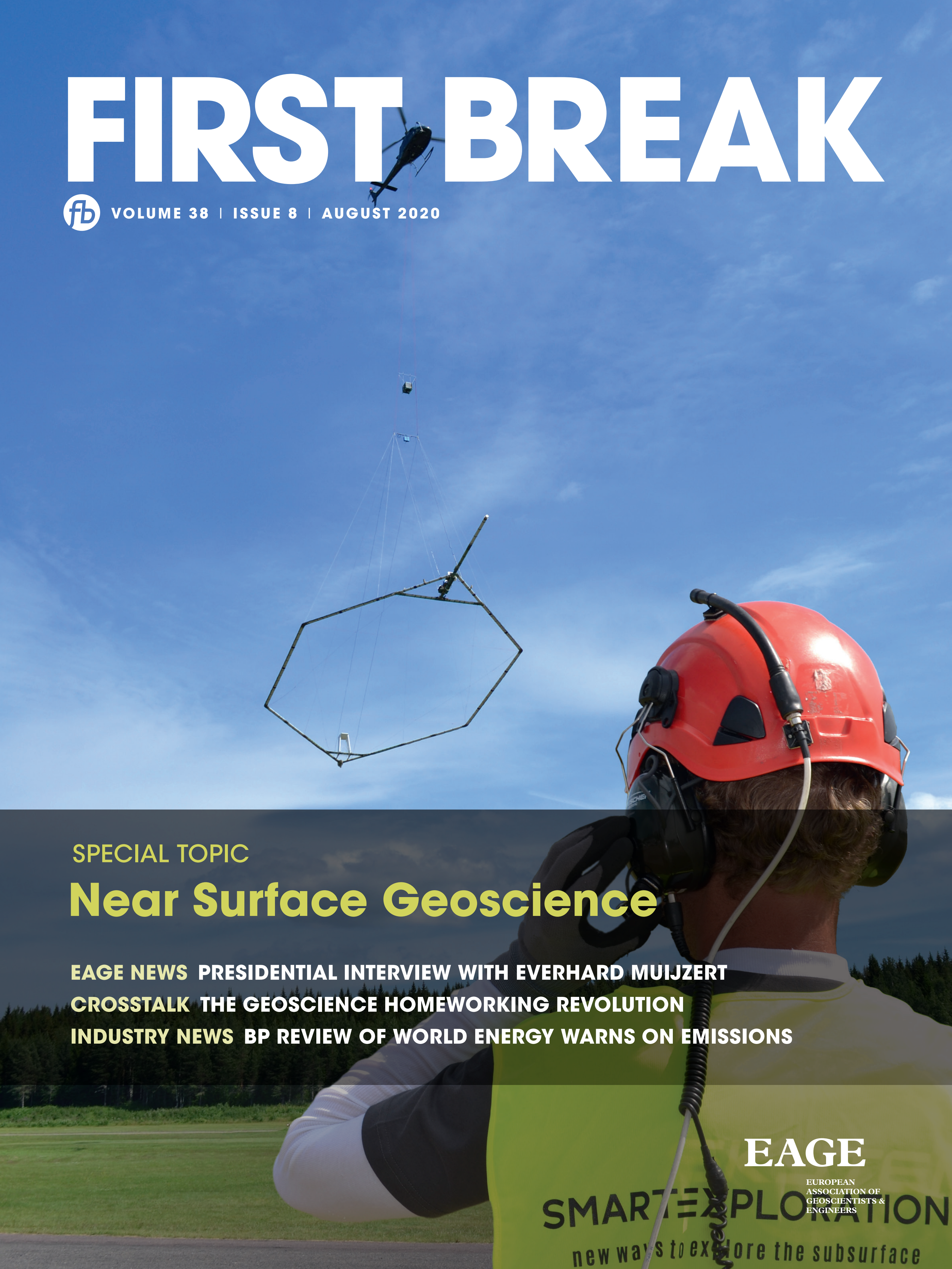

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New ways of exploring subsurface with Smart Exploration Solutions

Alireza Malehmir (Uppsala University), Per Gisselø (SkyTEM Surveys), Valentina Laura Socco (Politecnico di Torino), João Carvalho (LNEG), Paul Marsden (Nordic Iron Ore), Asli Onar-Verboon (EAGE) and Marcin Loska (Proxis)

Smart Exploration is an ambitious project, funded under the EU's Horizon2020 Research and Innovation Programme, responding to the call for 'New solutions for sustainable production of raw materials – New sensitive exploration technologies'. The project's main objective is 'developing cost-effective, environmentally-friendly geophysical solutions for mineral exploration'. With a budget of €5.2 million ($5.9 million), Smart Exploration kicked off on 1 December 2017 and will be completed in November 2020.

Partners from 27 organizations and 9 EU countries with different specialisations are gathered to improve exploration techniques to help sustain raw materails critical for green technologies and smooth transistion towards decarbonization. Of these 27 partners, 11 are SMEs, 11 are academic and research institutions, 4 are mining companies, and 1 is a municipality (Figure 1). Both SMEs and academic experts are working together to ensure that research and innovation go hand-in-hand in a practical and market-oriented manner. This combination allows a smooth transition from research to innovation, innovation to development, which is important for product realization and competitive growth.

The work is centred on the development of five prototypes and six new/improved methodologies for 3D imaging and modelling. Project partners have also used improved algorithms to successfully recover and reprocess a number of legacy data sets (see *First Break* August 2019 issue).

The five prototypes have been developed using a dedicated work package "WP2: New Instruments" and covering different types of solutions for specific needs and exploration conditions.

UAV: A modular-based, multi-functional and less sensitive to the system noise unmanned aerial vehicle (UAV) and ground-based geophysical system capable of acquiring magnetic, radio- and controlled-source electromagnetic (EM) data.

HTEM: A deep-penetrating TEM helicopter-based system providing higher resolution subsurfcae models in a faster and more cost-effective manner. It works like a big 3D-scanner of the ground using the same physical concepts as the MRI-scanner at the hospitals.

Slimhole: A slimhole modular-based digital seismic-magnetic-temperature system insensitive to electric noise to allow deeper penetration around boreholes.

E-Vib: Broadband electrically-driven seismic source. It is used to vibrate the ground and thus enables the mapping of the subsurface using broadband frequency signal to create sound waves, in a similar manner to a cinema's sound system.

GPS-Time Transmitter: Mobile GPS-time system for time synchronization of in-mine–surface explorations and new processing approaches for full-scale active- and passive-seismic data recording to maximize their value along with higher-resolution exploration.

Thanks to the mining partners, the project has access to six test sites to conduct surveys and validate these new technologies in brownfield and greenfield areas; (a) Gerolekas Bauxite Exploration Site, Greece, (b) Skouries-Fisoka Copper-Porphyry District Exploration Site, Greece, (c) Neves-Corvo Base-Metal Mining Site, Portugal, (d) Ludvika Iron-Oxide Mines, Sweden, (e) Siilinjärvi Phosphate Mine, Finland, (f) Kosovo Chromite Greenfield Sites.

The newly acquired data through the prototypes at the test sites, combined with the new methodologie, have proven to provide better targets and geological characterisations at greater depths.

In this special issue of *First Break*, the partners will reveal the details of these prototypes, how they are expected to make a difference for mineral exploration and at the same time how these prototypes can be beneficial for other applications.

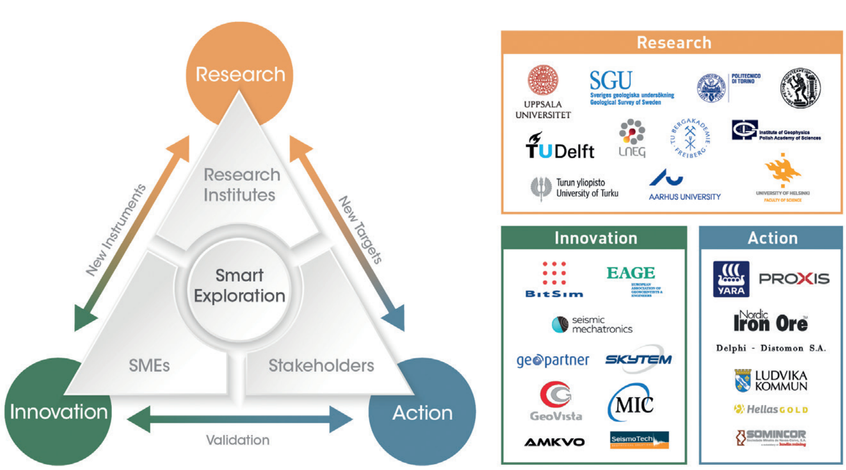

Figure 1 Key components of the Smart Exploration project are Research-Innovation-Action covering tasks related to New Instruments, New Targets and Validation of the solutions developed in the project. A combination of SMEs (small and medium-sized enterprises), research institutions and mining companies as well civil society makes the group very well positioned for the envisaged tasks.

Slimhole System

Anders Sivard (BitSim), Niclas Jansson (BitSim), Christopher Juhlin (Uppsala University) and Alireza Malehmir (Uppsala University)

Can you tell us about yourself and your company?

I am Anders Sivard, co-founder of BitSim, a Swedish SME company. I have worked in the electronics industry for many years holding various positions in R&D, sales and management in Europe and the US for companies such as Ericsson and Sun Microsystems. BitSim is an electronics design house founded in 2000 and based in Stockholm, Sweden. We focus on imaging and data acquisition applications of big data and streaming.

What role do you play in Smart Exploration?

Within the project, we have developed new downhole exploration equipment for water-filled slim boreholes of NQ sizes.

We previously developed an advanced system for deepwater exploration and have had a long relationship with the excellent group of geophysicists at Uppsala University. During the discussions with the Uppsala geophysicists, we realized that we could utilize our knowledge into new leading-edge technology for the mineral exploration industry.

What are the unique characters or advantages of this new system?

The potential of deep exploration, with several thousands of metres-deep slim boreholes, together with designing a low power solution and our existing data communication blocks in a smart way, is a unique combination for creating a new exploration product. This prototype provides a much simpler system that can be frequently used by mineral explorationists.

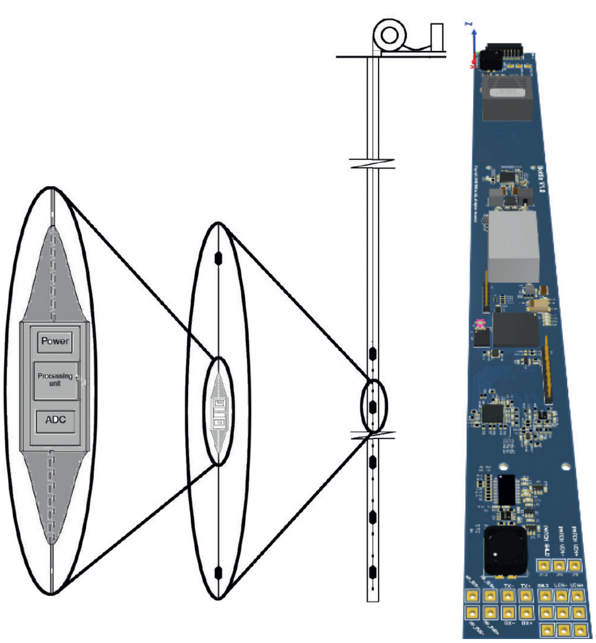

Figure 1 Small diameter (approximately 35 mm) circuit and acquisition designs of the slimhole system.

The slimhole geophysical system (Figure 1), currently mainly seismic, is easy to handle and can be expanded to 100s of hydrophone sensors sampling at 4 KHz. Measurements can be recorded 'live' and even be run together with similar equipment in neighbouring boreholes for multi- and cross-hole measurements. There is a lot of bandwidth to handle the measured data, and the sensor data should be synchronized to under a microsecond accuracy and precision.

From the environmental and safety point of view, thanks to our low power solutions, we have developed a system that have fewer safety requirements in terms of the electrical environment and EU regulations, using only a sub-75 volt power feed.

What is the main difference of this prototype compared to other systems available in the market?

There is currently no existing exploration system for slimholes that we know of that allows measurements in deep holes with low noise digitized data transfer and that are modular. While there are sophisticated systems available, they are often for wide-diameter boreholes and any available for slimholes are limited in the

Figure 2 Field photo taken during the so-called backyard test in a known hydrological borehole near the city of Uppsala, Sweden (June, 2020).

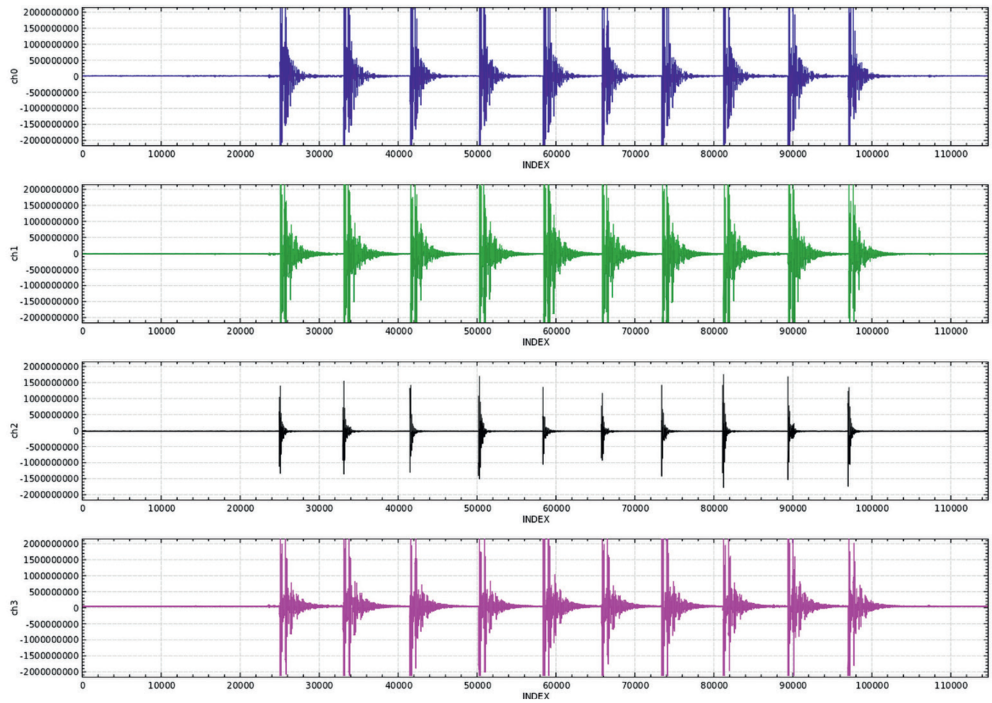

Figure 3 Examples of repeated hits recorded on four of the hydrophones during the backyard test in Uppsala.

number of sensors they can handle. Our development work is also light and easy to transport and does not require heavy tower installation for operation.

Can you elaborate on the collaboration?

We had to understand the typical needs while developing the prototype for this specific usage of mineral exploration. We have teamed up with Uppsala University because of their knowledge in the field, data scrutinization and applications in particular. This collaboration of an academic expert group and our engineering team worked very well to ensure that the system we develop fits the mineral exploration purpose.

Have you experienced any challenges during this development?

Development of such a system cannot be done without extensive planning and proper understanding of the main motive. We have spent a considerable amount of time to find and develop the best methods for downwards and upwards data communications. The data transfers are done in a new, inventive way that took some time to get working with minimal power consumption. The high pressure, mechanical bottles and assemblies also took some time to complete. Having a diverse team working from different technical backgrounds helped us to overcome these challenges.

What would you describe as breakthrough of this system?

Thanks to the modularity, the end user can select the number of nodes in a borehole (multiple of 4 sensors, up to 100 sensors per hole) and in addition simultaneously measure nearby holes. The system can record in real-time, with near noise free data recorded and transferred, with excellent synchronization and large data capacity.

The system is developed to serve the mineral exploration industry market but it could potentially be used in geothermal and geotechnical applications. Waste-storage site characterization and CO_2 sequestration are among other potential applications.

Has the system proven to be successful?

We aim to complete the validation phase by the end of this year. The current version of the system goes down to 500 m. So called backyard tests of the boreholes at Uppsala University (Figure 2) have been completed with promising results (Figure 3). Further tests are planned at our partner Nordic Iron Ore's mine in Ludvika. In the autumn 2020, the system will be fully validated at the exploration boreholes in the Blötberget mine of Ludvika given prior knowledge and all the surface data available from this site thanks to Nordic Iron Ore.

Will the system be available for others to use or designed only for the project?

We are looking forward to the validation stage of the project to get first-hand market feedback from the work. This will be important for us to show that the system can be used in the mineral exploration industry and will help us to enhance our TRL (Technology Readiness Level). We have taken measures to protect the IPs generated from this work. Future marketing work will rely on new services and manufacturing the system for purchasing and possibly making a more robust version of the system to be delivered to mining and exploration companies. We are looking for investment and business partners for this stage.

There have been some early contacts with interested companies. There are number of companies awaiting the outcome of the validation work. Besides these contacts, we also have a market strategy which we are keeping updated as we progress. We are looking at hiring and selling equipment and also providing services through our partnership with Uppsala University.

Deep-probing time-domain electromagnetic helicopter-based system (HTEM)

Per Gisselø (SkyTEM Surveys)

Can you tell us about yourself and your company?

SkyTEM Surveys ApS (SkyTEM) was established in 2004 as a spin-off company from the University of Aarhus, Denmark. The company was established with the purpose of commercializing the helicopter-borne electromagnetic system developed for mapping the groundwater resources and their protection. Since the beginning SkyTEM has maintained a close collaboration with partners in the academic world. SkyTEM has continued the development of the airborne electromagnetic system and has entered the world of mineral exploration. Over the years SkyTEM has collected more than 1,000,000 km of airborne data on all seven continents of the world.

I joined SkyTEM in 2007 with a background in geology. I started out as a field operator of the SkyTEM system and went on to work on data processing, interpretation and project management. Since 2012 I have been head of operations overseeing all the SkyTEM operations around the world.

Figure 1 The SkyTEM system was flown for the validation survey at the Blötberget Mine Site, Ludvika, Sweden.

What is the main task of SkyTEM within the Smart Exploration project?

SkyTEM was happy to join the Smart Exploration project. Most of our involvement with academia had been within the hydrogeophysical community. We did see this project to improve our interaction with the mineral exploration community in Europe. The purpose of the developments made on the SkyTEM system was to enhance the depth of penetration of the airborne EM system. In addition, I have been a member of the executive board and the leader of work package 2 that is concerned with the development of the prototypes within Smart Exploration. The development work started at the onset of the Smart Exploration project. The first version of the prototype was ready for validation 18 months into the project.

What is the main drive behind this development work?

With the vast majority of near surface deposits having being discovered there is a need to explore deeper. To improve the SkyTEM systems' ability to look deeper has been the main motive.

Can you please tell us more about this new HTEM system?

Within the Smart Exploration project SkyTEM has focused on the development of their airborne EM systems to increase their maximum depth of investigation. In order to bring the developments to the market within a short timeframe they have been implemented on the SkyTEM312HP platform. The high power TEM transmitter delivers a maximum current of 250 Ampere in each transmitter turn. The 12 turns mounted on the SkyTEM300-series compact frame, with an area of 342 m^2, deliver a combined magnetic dipole moment of approximately 1,000,000 Am^2.

Developments on the transmitter side have focused on lowering the operational base frequency to 6.25 Hz. This has two benefits. Firstly, the on-time duration can be increased which results in a higher signal response from the ground, especially at late times. Secondly, it allows for later off-time measurements to be recorded (~60 ms) which typically relate to even deeper features in the ground. A new design of the receiver coil suspension system has been implemented, which reduces the effect of the motion induced noise at the base frequency of 6.25 Hz and thereby allows for a good signal-to-noise ratio.

Has the HTEM prototype made a distinct difference for the industry vs current systems?

The ability to operate the SkyTEM system at 6.25 Hz is a unique operating capability.

The validation survey with the SkyTEM system operating at 6.25 Hz base frequency was flown in June 2019 at the

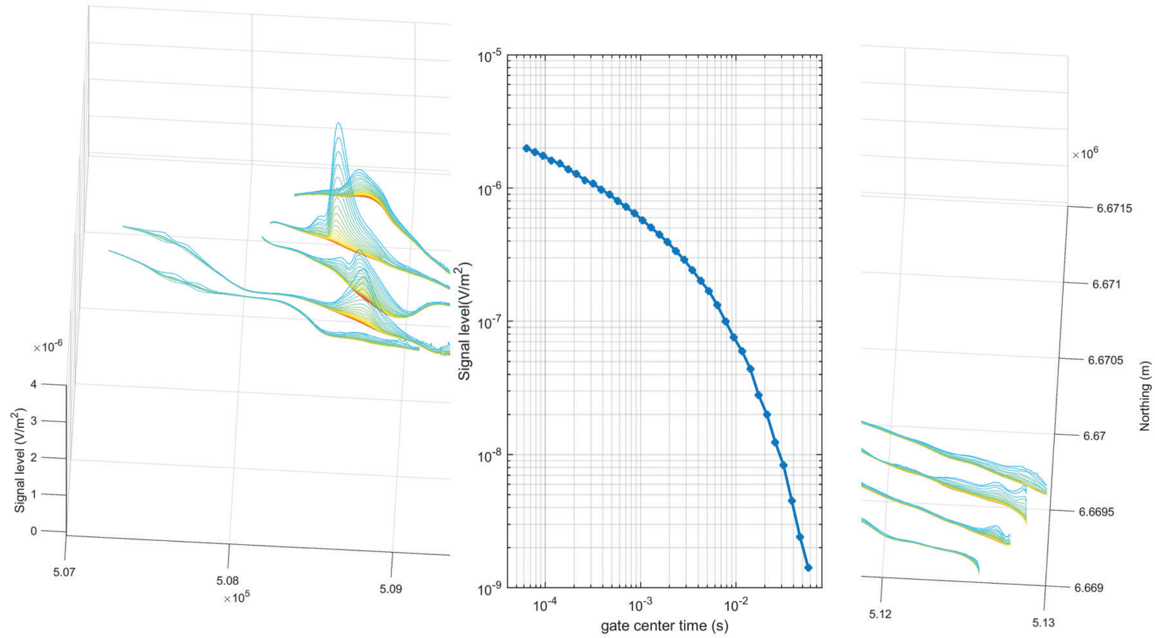

Figure 2 The dB/dt Z-component data plotted along the flight lines overlain with the decay curve at the peak anomaly.

Blötberget Mine Site (Figure 1) of project partner Nordic Iron Ore in Sweden. Figure 2 shows the gate plots of the Z-component plotted along the flight lines overlain with the decay curve above the peak anomaly. The anomaly has a clear signal well above the noise signal all the way to the latest gate time at 60 ms only obtained through the 6.25 base frequency operation.

After the successful Blötberget test flights, adjustments were made and the prototype has also flown on one of the INFACT (another EU funded project) test sites. The system will be further validated at two of the Smart Exploration validation sites in Greece (brownfield) and Kosovo (greenfield) with the support of local project partners by the end of the year.

What difference can this system bring and to which industries?

The possibility of operating the SkyTEM system at 6.25 Hz brings two advantages to deep-seated mineral exploration. Firstly, there will be an ability to explore deeper than previously possible with airborne EM systems. Secondly the resolution of partially known deep-seated exploration targets can be enhanced.

Moreover, all industries that use the difference in the resistivity of the geological materials will have the potential to use the system. In addition to the mining industry, the industries with the need for deep exploration such as the oil and gas and geothermal industries can benefit from this system besides mapping of host rocks for CO_2 storage, and deep seated groundwater resources.

What has been the main challenge for this development work?

A Bench Test has been developed to provide both a platform to test the firmware and hardware for operating 6.25Hz. As the transmitter was initially designed for 25 Hz operation, critically different components needed to be tested. The bench test has allowed us to begin these investigations and test single components to get endurance data from the monitored operation.

Due to lack of design specifications from the supplier of the components, it has been necessary to make these tests on our own.

One of the results of the bench tests did emphasize the need of a more efficient cooling system for the transmitter. The updated cooling system has been designed and produced to overcome this challenge.

Are there any environmental or safety risks of this system?

One of the major benefits with airborne surveys is that they are non-invasive and do not impact on the local environment. The methodology works in the same way as an MRI-scanner in hospitals. The strength of the electromagnetic field is well below the public health recommendation and in the same range as that of an electrified train.

Can you please elaborate on the collaboration in this work?

SkyTEM has solely developed this new HTEM system, but it has being tested at the mine sites of the project partners. The possibility to validate the prototype on a dedicated validation site with a large amount of background information has been very important in order to complete the prototype development.

What are your future plans with this prototype?

With the addition of this new capability of the SkyTEM system we expect to raise our market share for the mineral exploration industry. After the validation survey in Sweden we have flown two commercial surveys in the same region for both public and private clients. The prototype is being marketed through our sales team, that already has a large network in the worldwide mineral exploration industry. SkyTEM is a geophysical service provider and we are ready to sell surveys with the new system, while the system itself is not for sale.

Electric Seismic Source with broadband frequency (E-Vib)

Richard de Kunder (Seismic Mechatronics)

Can you tell us about yourself and your company?

I am the CEO of Seismic Mechatronics. The company originated from a collaboration between TU Delft, Magnetic Innovations and MI-Partners in the Netherlands. The project has developed the Electric Seismic Source, E-Vib. In 2016, Seismic Mechatronics decided to further commercialize the E-Vib technology and operate worldwide. Our expertise lies in direct drive motor development and mechanical/electrical engineering.

What is your main task in the Smart Exploration?

We are one of the technology providers within the Smart Exploration project. Our task was to bring E-Vib to a higher Technology Readiness Level (TRL) and for hard rock seismic applications by improving its operational capabilities. Smart Exploration enabled us to do extensive testing and fine-tuning while raising awareness in the seismic acquisition industry concerning the advantages that E-Vib brings. For the prototype, the lead time for the development from concept, order, building and testing took approximately 12 months.

The mechanical/electrical development of the E-Vib has been done solely by Seismic Mechatronics. However, other project partners such as TU Delft, Uppsala University, Lundin Mining/Somincor and Nordic Iron Ore played critical roles in testing and validation. The collaboration with the Smart Exploration project has been fantastic, resulting in shorter time-to-market for the E-Vib than we earlier envisaged.

What was the motive to develop such a system?

The mineral exploration industry is challenged to supply critical raw materials for the long term and also to come. To improve this supply, cost-effective, sustainable, zero-carbon emission innovations are necessary. A key aspect is finding these critical raw materials using seismic methods that have a great resolution at depth. As a result, Seismic Mechatronics develops electric seismic sources to radically impact seismic data acquisition by doing it sustainably with higher quality and lower costs in comparison with the other hydraulic systems available in the market and for an exploration depth generally economically minable worldwide (e.g., 500-2500 m).

Can you please elaborate on the prototype?

Instead of conventional ways of generating seismic signal for data acquisition, such as explosives and hydraulic vibrators, the E-Vib uses electric motors. One of the main technologies in the E-Vib is the linear synchronous motor. The design of the motor is based on a frictionless or contact-free movement. As a result, we are able to generate signal with low distortion, high controllability and repeatability as well as high forces at the low frequencies. This in turn results in higher seismic data quality at lower costs. Moreover, the frictionless design and high forces at the low frequencies also enable us to the build compact electric sources, while achieving a great depth of penetration. Finally, acquiring the seismic data is done much safer and is more environmentally friendly compared to conventional seismic sources.

Since the E-Vib does not use any fluids, is high pressure and is based on a frictionless design, there are no environmental risks or danger to human life. In Australia, our Lightning E-Vib was granted a 'non-environmental impact' status, implying its use does not require environmental permits, which saves time and money.

Figure 1 E-Vib validation at a geologically and geophysically known site in the Netherlands (December, 2018).

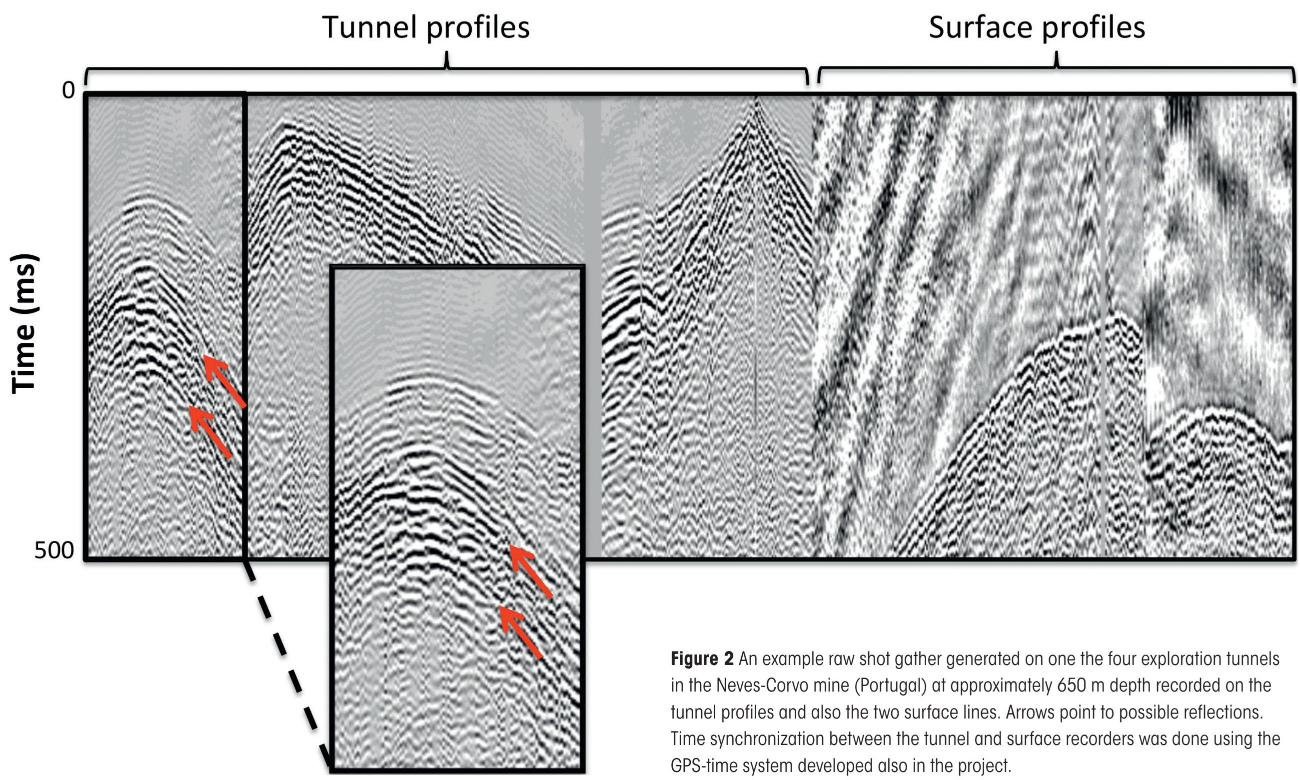

Figure 2 An example raw shot gather generated on one the four exploration tunnels in the Neves-Corvo mine (Portugal) at approximately 650 m depth recorded on the tunnel profiles and also the two surface lines. Arrows point to possible reflections. Time synchronization between the tunnel and surface recorders was done using the GPS-time system developed also in the project.

Has the prototyope been proven to work successfully as expected?

The prototype was tested at three different set-ups and environments in the Netherlands, Portugal and Sweden.

In the Netherlands (Figure 1) and Sweden, the prototype (branded as Storm seismic source) was tested at the surface level against known geological structures and existing seismic data. Results proved to be promising and helped to image key geological units down to even 2000 m depth at the Dutch site (Brodic et al., 2019) and 1500 m in the Swedish site (Pertuz et al., 2020).

In Portugal, the E-Vib was tested inside the Neves-Corvo exploration tunnels. Figure 2 shows an example shot gather after cross-correlation and vertical stacking of three repeated shot records. The data quality is reasonable given the noisy condition of the mine with clear first arrivals on both tunnel and surface profiles but also possible reflections as marked. Time synchronization between the tunnel and surface recorders was done using the GPS-time transmitter system developed also in the project. After finishing the survey, we realized that conventional seismic sources, such as vibrators, would probably not have been permitted in such a mine as they do not meet standards assigned for permitted vehicles in an underground mine. While the conditions inside the tunnels (at 650 m depth) were extreme due to high temperatures and humidity, which greatly affect the electronics, the source performed well and clear reflections were imaged in the raw shot gathers, opening up possibilities for similar surveys inside mining tunnels (Malehmir et al., 2019).

Thanks to the robust design of the machine, we were able to conduct all three test surveys successfully and the interpretation of collected data against legacy data has proved that E-Vib adds value to seismic data acquisition.

What does the future hold for E-Vib technology?

The E-Vib has been proven to be effective for mineral exploration purposes. It can operate safely and effectively in the mine tunnels at greater depths with high-resolution results, where any other commercial seismic sources could not operate to the best of our knowledge. Even though this prototype has been designed specifically for mineral exploration, the E-Vib technology can be used in all industries requiring an onshore seismic source.

We aim to bring a range of E-Vibs to the market for different purposes and for this reason we have started the Full Force Geophysical joint venture with industry partners to enable an efficient time-to-market. The E-Vibs can be both hired and bought and we also offer the total seismic service package from acquisition to processing to interpretation.

References

Brodic, B., de Kunder, R., Ras, P., van den Berg, J. and Malehmir, A. [2019]. Seismic imaging using electromagnetic vibrators: Storm versus Lightning. *EAGE-NSG Annual Meeting*, Extended Abstracts.

Malehmir, A., Donoso, G., Markovic, M., Maries, G., Dynesius, L., Brodic, B., Pecheco, N., Marsden, P., Bäckström, E., Penney, M. and Araujo, V. [2019]. Smart Exploration: from legacy data to state-of-the-art data acquisition and imaging. First Break, 37(8), 71–74.

Pertuz, T., Malehmir, A., Brodic, B., Bäckström, E., Marsden, P., de Kunder, R. and Bos, J. [2020]. Broadband seismic data acquisition using an E-vib source for enhanced imaging of iron-oxide deposits, Sweden. *SEG Annual Meeting*, Expanded Abstracts.

GPS Time Transmitter

Alireza Malehmir (Uppsala University), Lars Dynesius (Uppsala University) and Tord Sjölund (Mic Nordic AB)

Can you tell us about yourself and your team?

I am Alireza Malehmir, the scientific coordinator of Smart Exploration. I am also the task leader for providing the GPS-time transmitter system in GPS denied environments. My specific role is to develop solutions and formulize them with other partners. For some time, I have been calling for such a solution to be applied in the mineral exploration and tunneling industry.

Uppsala University and Mic Nordic have collaborated to develop the prototype. For the validation work we are working with partners such as Somincor-Lundin Mining and LNEG (Portugal). Three individuals form the team developing the prototype: Lars Dynesius and myself from Uppsala University and Tord Sjölund from Mic Nordic. We bring a wide range of expertise in electronics, design and manufacturing. For example, Mic Nordic specializes in indoor mobile signal technologies for hospitals, exhibition halls, shopping malls and tunnels. Their products include FM, Tetra/Rakel, GPS, 1G, 2G, 3G and 4G solutions. Uppsala University specializes in hardrock seismics and came up with the idea of this invention.

What was the motive of developing such a GPS time transmitter for time denied environments?

Many experts in the mineral exploration industry regard the future of exploration to be deeper mining at depths of 800-2500 m. It is believed that the majority of shallow and giant deposits have already been explored and exploited. To sustain operating mines, avoid new environmental footprints and for financial reasons, brownfield and near-mine exploration is where exploration expenditure will be focused. Technical challenges (e.g., logistics and infrastructure and operational noise) around an operating mine limit the exploration techniques that can be used. For this reason, in-mine exploration becomes in most cases limited to mainly drilling and based on drill core observations. To improve exploration at depth and in operating mines, improved geophysical solutions are needed. Exploration should also help exploitation to be done effectively to avoid ore block loss and possible geological surprises during the mining operation. Mining and exploration infrastructure such as tunnels and boreholes can be used to partly tackle these issues.

As an example, most underground mining operations in Scandinavia are carried out using the block (sub-level) caving or cut and paste (or cut and filled) mining methods requiring many parallel mining and exploration tunnels (usually 50-100 m apart at the same level as 'drift') and also at different levels (50-100 m connected through access tunnels or ramps). Such tunnel layouts are ideal to set up a network of seismic sensors for an underground 3D seismic survey that can image structures and geology under the mining tunnels, or between them or between different levels as well as the hanging-wall. When combined with surface seismic recorders that are synchronized in time, this can allow us to capture the seismic wavefield between the tunnels and the surface and what happens to the seismic wave (e.g., amplitude and velocity) as it travels between the surface and the tunnels and vice-versa. In such circumstances, imaging vertical or very steep dipping structures would be possible (like half MRI scanning) by utilizing the underground space where synchronized receivers and sources are used.

When a full-scale experiment is conducted, for example using 100-1000s sensors on the surface and similarly in the underground space (simultaneous recording) one can (1) delineate the extension of existing ore bodies, (2) map fracture and fault systems, (3) study seismicity in deep stressed mines, (4) time calibrate existing mine seismometers, (5) study anisotropy due

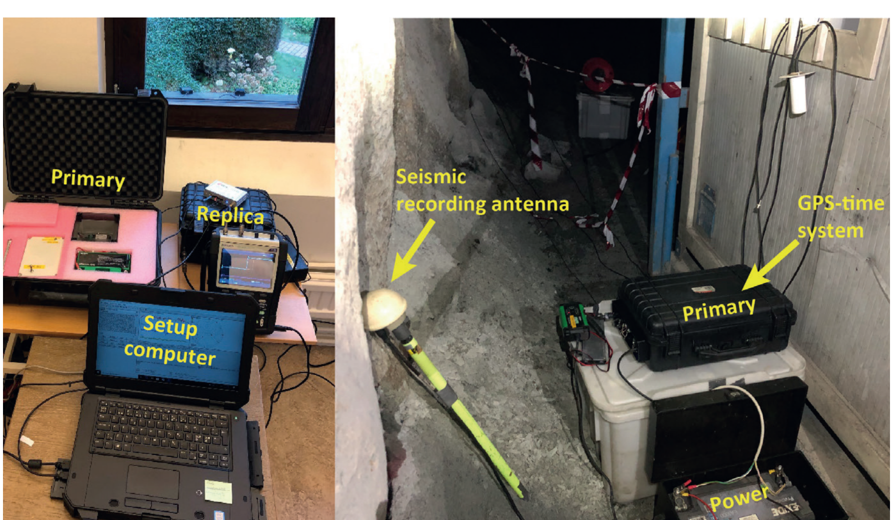

Figure 1 (left) GPS-time system including the primary and replica units. (right) The set-up at the Neves-Corvo providing a time signal to a portion of the survey layout using a system of cabals (using the primary unit). Replica unit was used to feed 30 wireless recorders.

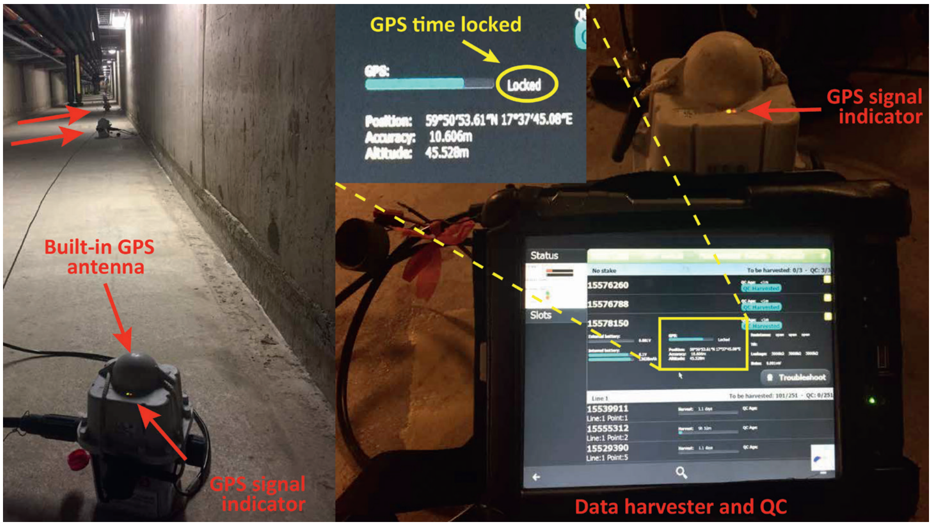

Figure 2 Simulating a tunnel seismic survey using commonly used (RAU from Sercel company) wireless seismic recorders/sensors (20 used here) in a pilot test examining the performance of the GPS-time system. Flashing green-red light indicator on the recorder means locking to GPS-time signal. The test was conducted in December 2018 in Uppsala using a long basement facility corridor. An accuracy of 10 microseconds was observed already at this stage.

to mining-induced fracturing (unloading), (6) characterize ore quality, (7) optimize blasting, (8) explore ahead of mining and tunnelling and (9) perform 4D imaging and characterization (e.g., time-evolution of various mining blocks).

How long did it take the team develop this prototype?

We had the idea for this development work from an earlier survey where we were able to transmit GPS-time signals using cables (see Brodic et al., 2017). However, we knew this would not be possible everywhere hence a mobile system had to be developed to work at different depth levels or connecting one tunnel to another. It took 12 months before our first in-house test was successful. Within 14 months we were able to validate the system for an upscaling survey set-up at the Neves-Corvo mine in Portugal.

The task team met and worked together from the planning stage, design and tests. We made the system for the Neves-Corvo survey more robust, which was essential given the humidity and extreme conditions at 650 m depth.

Can you explain how the system works?

The GPS-time system developed here (Figure 1) is a hardware solution (physical prototype) that comes with a number of expert-knowledge experiments/surveys (how-to solutions). The system can transmit relative or real simulated GPS-time signals in closed spaces (e.g., tunnels) for several (10-1000s) readily available in the market sensors (e.g., within 1-3 days) in an easy and practical manner (1-2 persons and no requirement for extensive cabling from surface to the underground spaces).

As part of the development work, we also demonstrated why such experiments should be done and expanded to a different dimension than in the today's exploration and underground mining/construction industries.

The solution is based on off-the-shelf components that are readily available in the market but not assembled as a whole for such a purpose. There are components in the development that are unique such as the ability to provide time signal for a distributed array of sensors (not only for a single point), practical in the sense that it does not need extensive cabling. Combined with fibre-optic technologies, attenuations of the GPS-time signal are considerably reduced for longer sensor arrays or going from one level of depth to another. If needed, multiple systems can be used in different depth levels independently without a cabling requirement at depth.

A great benefit of the system is that one does not need to modify existing recording sensors, which is a substantial saving.

Are there any environmental or safety risks?

Simplicity of the set-up and the lack of harmful components such as high-power electricity makes the system suitable for in-mine applications; limited set-up time and no need to stop any mine operation or access the mine communication or other cabling systems are other advantages in terms of safety. The system does no harm to the environment and is safe.

Are there any other comparable systems available in the market?

There are none available that provide a GPS-time signal in a modular manner to the same extent. Other GPS-time systems are only clock-based and in most cases can only feed one recording unit with true GPS-time or only relative time.

Has the system proven to be successful?

Laboratory tests (in Uppsala and using basement facility corridors/culverts) were first done (Figure 2), allowing us to GPS-time lock more than 20 wireless recorders and check the potential drift of the system over a day of experimentation. However, a full-scale test in a real conditions was required and was carried out in the Neves-Corvo massive sulphide underground mine in Portugal during January-February 2019 (Figure 3). The GPS-time system enabled the time-synchronization of 30 wireless recorders in an exploration tunnel at approximately 650 m depth, and a 400-plus unit cabled system set-up in four exploration tunnels as well as more than 350 wireless recorders on the surface. Such an experiment to allow high-resolution imaging between surface-tunnels and deeper tunnels would not have been possible without the GPS-time system developed in this project.

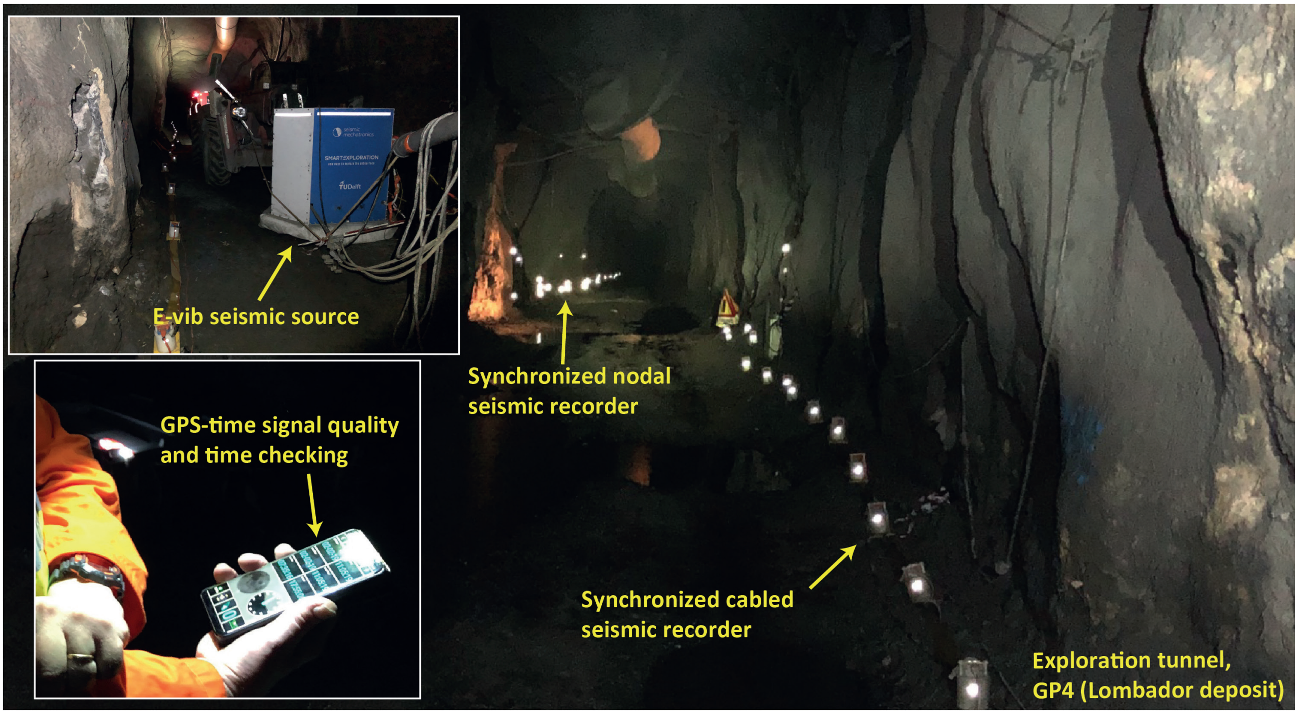

Figure 3 Validating the performance of the GPS-time system at the Neves-Corvo mine (approximately 650 m below ground surface) and checking signal quality using common GPS time signal quality applications (inset figure). More than 1000 wireless recorders and the cabled system units inside four exploration tunnels and two profiles on the surface were synchronized in time and surveyed together in this up-scaling experiment. The E-Vib prototype seismic source developed in the project was also used in this experiment.

What was the main challenge you faced during the development of this system?

Our main challenges were mostly technical in the sense that we did not know whether the signal strength and sensitivity would be sufficient. We worked quite a bit around this and made sure that we can adjust the signal level when needed using amplifiers. However, we had to make sure that the receiving units would not saturate if too strong a signal was transmitted. Other challenges were in obtaining parts and assembling them on time. The discussions among the partners were very useful in foreseeing risks and mitigating them as early as possible.

What difference can this solution make to the industry?

We think using a couple of case studies like the Neves-Corvo, more mining companies will realize how to use the system effectively for their exploration challenges. In fact, we recently leased the system for a survey using a simpler set-up than the Neves-Corvo but at greater depth for a deep underground mine survey in Sweden.

This system can be used anywhere where GPS-time for time-series analysis is required. We think besides the mining and mineral exploration industry, tunneling projects in urban settings, waste-storage monitoring and characterization can also benefit from this development work.

What is next step for this prototype? Will it be available in the market?

Given the broad application of the system and its commercial aspects in the mineral exploration and mining industry and for sensor manufacturers, through UU Innovation-Uppsala University and financial support, we were granted a Swedish patent for both the prototype and methods that the technology can cover. However, we feel that the system should be protected beyond Sweden and for this additional financial and market analyses are needed. During the patent application extensive search and review of existing technologies were carried out together with patent lawyers and UU innovation patent and IP experts to help us to better understand how to get the solution to the market.

The system has been leased for one commercial application so far and we hope for more. We have also met a few consultants and service providers. We have a market strategy and in the short term we are focusing on case studies and demonstration work.

Companies can rent, use our how-to solutions, but also buy. We have protected the IP through our patent application and PCT so this should be an incentive to people wishing to negotiate with us for various applications.

References

Brodic, B., Malehmir, A. and Juhlin, C. [2017]. Delineating fracture zones using surface-tunnel-surface seismic data, P-S and S-P mode conversions. *Journal of Geophysical Research-Solid Earth*, 122.

Malehmir, A., Dynesius, L. and Sjölund, T. [2018] *Mining and mineral exploration system and method for performing time-accurate measurements in a mine.* Swedish patent application, number 1851332-5, 26-October 2018.

Unmanned Aerial Vehicles (UAV) and ground-based electromagnetic (EM) systems

Mehrdad Bastani (Geological Survey of Sweden), Henrik Johansson (Geological Survey of Sweden), Alex Paulusson (AMKVO AB), Kent Paulusson (AMKVO AB), Lars Dynesius (Uppsala University)

Can you tell us about yourself and your team?

I am Mehrdad Bastani. I have a PhD in geophysics in the field of electromagnetic. I've been a senior geophysicist at the Geological Survey of Sweden (SGU) since 2000, working with processing, modelling and interpretation of large ground and airborne geophysical datasets. The team developing UAV prototypes also involves some other experts and has worked earlier on testing UAV-magnetic surveys (Malehmir et al., 2017)..

Henrik Johansson, who holds a PhD in physics, is the manager of the airborne geophysics group at SGU and works with data processing, software development, hardware development and maintenance.

Alex Paulusson and Kent Paulusson are from AMKVO AB based in Uppsala, Sweden, an SME company specializing in Unmanned Aerial Vehicles (UAV). They were founded in 2014 and are experts in photography, thermography and 3D scanning/modelling using UAV.

Lars Dynesius is a senior research engineer from Uppsala University (UU) with more than 40 years of experience working on and developing geophysical equipment.

Can you tell us about your team's task in Smart Exploration?

SGU is the expert agency for matters relating to bedrock, soil and groundwater in Sweden. One main task is supporting the development of the mining, rock and mineral industry and promoting the use of geological information in societal planning. Therefore, we became involved in Smart Exploration to further develop new systems for drone measurements.

SGU is responsible for leading the development work in WP2, including hardware and software development of the geophysical measurement system and data processing software. The geophysical development work is done in collaboration with Uppsala University. AMKVO AB is responsible for development of the UAV, including the birds that house the geophysical instruments, as well as operating the UAV.

SGU and Uppsala University have been in close collaboration to design and construct the data acquisition systems for both drone and ground surface measurements. We have been collaborating with AMKVO AB to construct a drone with optimal efficiency and minimum EM noise (Figure 1, left frame). We

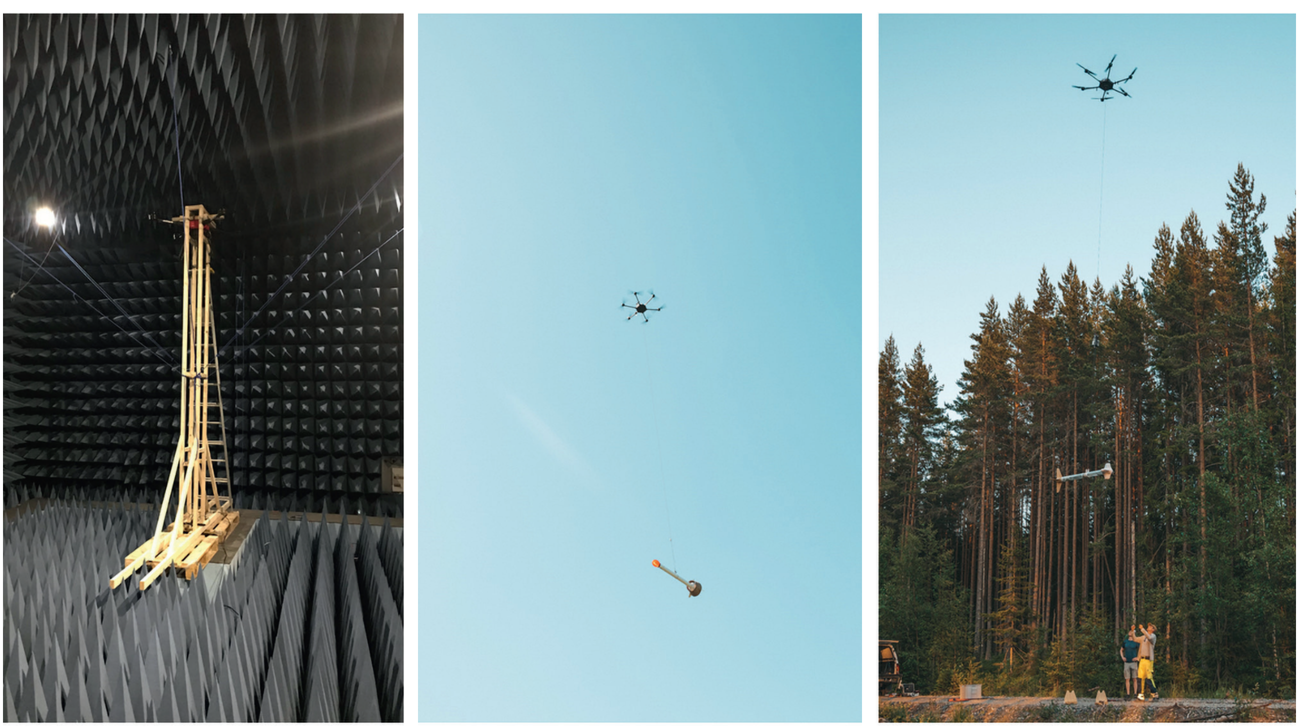

Figure 1 EM noise tests carried out in the shielded room at Ångström laboratory, Uppsala (left). UAV with the bird housing the system for magnetic field measurements (middle). All the electronics are mounted in the bird. UAV with the EM system hanging below (right). The data acquisition system is between the UAV and the bird. Photos are taken by AMKVO AB.

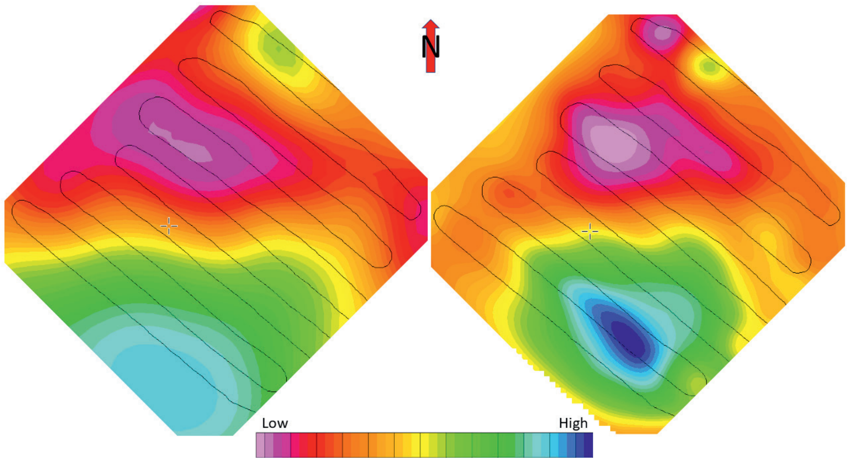

Figure 2 Preliminary results of the test measurements carried out on 24 June in an area in Sweden. Apparent resistivity map from SGU's fixed-wing VLF measurements carried out in 2016 with a flight-line separation of 200 m (left). Apparent resistivity map from the UAV measurements with a flight-line separation of 100 m (right). UAV flight-lines are shown in both figures for reference.

have also selected a test site in close contact with Nordic Iron Ore (NIO) and Uppsala University.

What is the main motive of developing such prototype?

Geophysical surveys are routinely conducted in a wide range of scales to image underground structures and resources in 3D. The surveys cover a wide spectrum of methods and techniques ranging from borehole to airborne measurements. For the latter, large data acquisition systems are mounted on aircrafts flying over areas extended to several hundreds of kilometres and acquire data in a reasonably short period of time. Airborne surveys are cost-effective if the areas covered are large enough so that the cost per data point is effectively low. Moreover, in many applications the airborne data lack spatial resolution and a more detailed survey, for example ground measurements, is inevitable. Ground surveys, on the other hand, are conducted over much smaller areas and usually focus on the targets selected by analysis of airborne data. Such surveys are rather slow and demand extensive manpower in the field. There are even cases where the ground surveys are not feasible because of existing obstacles, for example waterbodies or harsh topographical variations.

Considering such circumstances, a need for development of measurements systems that acquire data as fast as airborne and as accurate as ground systems is necessary. Unmanned Aerial Vehicles (UAV) are good alternatives for such purposes. There are already many geophysical data acquisition systems in the market mounted on UAVs, for example the UAV system developed by GEM Ltd in Canada that measured the earth magnetic field.

One very popular geophysical method is frequency domain electromagnetics (EM) where the electric and magnetic field components of EM fields are measured to map and model the earth electrical resistivity. There are plenty of applications showing the importance of the models of electrical resistivity. Example applications are: mapping conductive man-made pollutions from a wide range of activities such as mining, agriculture, sea water intrusion caused by uncontrolled pumping etc; modelling conductive orebodies such as iron or copper sulphides, graphite horizons and imaging fracture zones in infrastructure projects.

Can you describe the system?

We have developed three geophysical systems.

The first is a UAV-borne system for measuring the Earth's total magnetic field. It is based on GEM Systems GSMP-35U sensor. The platform features a laser altimeter, Inertial Measurement Unit (IMU) and Global Navigation Satellite Systems (GNSS) receiver (Figure 1, middle frame).

The second is a UAV-borne system for the so-called extended-VLF band measurement. It is based on three orthogonally mounted induction coil sensors and a data acquisition system with up to 1 MHz continuous data sampling of the EM magnetic field components. The effective bandwidth is 1 to 350 kHz, and the data sampling is synchronized to the GPS Pulse Per Second (PPS) to facilitate timing synchronization with other equipment. This platform also features a laser altimeter, IMU and GNSS receiver (Figure 1, right frame).

The third system is a ground-based electromagnetic (EM) system capable of measuring both the magnetic and the electric field in the bandwidth 10 Hz to 250 kHz. The data recording of all channels is synchronous and continuous with GPS PPS synchronized sampling.

All three systems were assembled within the project. The UAV was built for the purpose of minimizing its EM noise signature and provides at least 20 min flight time with payload. In addition, we have developed a MATLAB-based data processing software for in-field visualization and processing of EM data.

Can you define the process of this development?

It took 18 months to complete the hardware and software. The systems were ready for the test that was planned for May 2020. Because of some delays caused by the Corona pandemic we anticipate that the field tests will be completed by the end of September 2020.

Are there any risks to the environment or safety concerns with this system?

With UAV operations there is always risk of in-flight failure or loss of payload during flight. We have implemented several features to minimize these risks, including securing payload with double connections, a UAV with six motors to cope with one engine failure, and a return-to-home function in case of signal loss between ground and UAV.

What is the main difference between this prototype and other UAV systems?

Although there are reported attempts on mounting EM data acquisition systems on UAVs, there are no available commercial system of this type in the market. This might be because: a) The noise figure is not properly modelled and compensated for b) The data processing is not well-developed and established c) The data acquisition systems used are heavy and not designed properly for the UAV-based measurements.

Our team has long experience in development and construction of both ground as well as fixed-wing EM systems. We are familiar with the problem and have solutions for noise identification and reduction. We have also developed dedicated software for data processing and noise manipulation.

Has the system been validated?

We are currently conducting our validation tests. Our backyard tests have been very promising and at the end of June we carried out survey flights over a known magnetic anomaly outside of Ludvika in Sweden. We are currently processing this data and plan to have it ready at the end of the summer or early fall. Then we will also carry out measurements with a controlled source for the ground system, as well as for the UAV-borne system. Hopefully, depending on how the pandemic situation develops, we will also carry out additional survey flights at a site in Finland.

What have been the main challenges throughout this development work?

The main challenges were:

- Selection of suitable components for an electrical drone with a reasonable payload and flight time,
- Noise from the drone,
- Choice of proper EM sensors that cover a large bandwidth,
- Power consumption,
- Design and production of a bird that houses all the sensors and is light and stable,
- Reducing the weight of the UAV systems.

We made a lot of effort to construct a solution that meets our expectations.

Can you elaborate on the difference this solution is expected to bring to the industry?

The EM system is fitted for small-to-medium size surveys at the so-called brownfield and even smaller greenfield areas where the surveys with larger systems mounted on a fixed-wing and helicopter are currently utilized commercially. The system is easy to mount and operate in areas with a proper visual site. Such a system provides sufficient depth penetration (500 m at 1 kHz in areas with average 1000 Ohmm resistivity).

Besides the mineral exploration purposes, the system can be used for geological surveys, infrastructure corporations, universities and research centres, water management organizations and to some extent military.

What is the future for this prototype?

We are considering applying for a patent that might cover the entire measurement set up; the data acquisition, the UAV including the birds, and the software solution. After the tests within the Smart Exploration we will showcase our results in the international conferences and publish them in the relevant journals.

In general, SGU does not involve in any commercial work but we are interested in taking up services. Our project partner AMKVO AB is interested to commercially take it to the next level, where we can benefit by providing our services. We are certainly planning to utilize the UAV system in the SGU's routine work where more detailed surveys are demanded and that will promote our products for both industry and society.

References

Malehmir, A., Dynesius, L., Paulusson, K., Paulusson, A., Johansson, H., Bastani, M., Wedmark, M. and Marsden, P. [2017]. The potential of rotary-wing UAV-based magnetic surveys for mineral exploration: A case study from central Sweden. *The Leading Edge*, **36**(7), 552–557.

Smart Exploration Team, Siilinjärvi Mine Site, Finland (2019)