Indholdsfortegnelse

Introduction

This report contains a short overview of the status of tTEM mapping in Denmark and abroad. It has been prepared within the framework of GeoFysikSamarbejdet and aims to provide an overview of the width of uses for tTEM and the total volume of mapping carried out in Denmark as well as abroad.

This report will be followed by a Part 2, where tTEM, PACES and ERT/MEP will be compared.

The report has been written by Jesper Pedersen and Anders Vest Christiansen.

The tTEM-system

Development

The development of the system that has since become the tTEM system, began i 2015 with a number of experiments with transmitting in a very small transmitter loop attached to poles driven into the ground. The motivation was that we needed a geophysical system that could produce 3D images of the near surface underground (0-70 m) cheaply and quickly. SkyTEM does not have sufficient resolution that close to the surface and the system is too costly to use in smaller areas. MEP can provide the necessary resolution, but it is too costly to use for anything other than short 2D profiles. GCM is not able to penetrate further than 5-8 m below the surface.

In 2015, GCM had proved that pulling a system after an ATV could be quite effective, and the results were good in relation to area coverage. This led to a long row of thoughts on how to build a TEM system that could be pulled. We met with many challenges, not least with the transmitter technology, since, for practical reasons, the transmitter coil is only 2 x 4 m, which makes for a weak signal. Thus, it is necessary to repeat the measuring a large number of times and to use a heavy current. However, this generates a lot of heat around the electronic parts and creates other problems as well. It took several years to solve these problems. We experimented with a receiver coil in what is called the 0-position as known from the SkyTEM system. For several reasons this did not work, but it took more than two years to reach that conclusion. Now the transmitter coils are placed ca. 8 m behind the transmitter in an offset position.

Production with tTEM began in September 2017, and the system has been running practically continuously ever since. Development did not stop there and we have developed several new generations of the transmitter and receiver platform as well as new versions of the electronic parts. In 2019, these developments are converging towards the present system as shown in figure 1. This is a very strong production system, built of fiberglass and composite materials.3D printed carbon strengthened parts have been used extensively. A navigation system, crucial to the system’s effectiveness in the field, was developed as well.

Figure 1. The tTEM system in action.

The new platform is very flexible, and variations of the system have been created for use on snow (SnowTEM, see figure 2) and on water (FloaTEM, see figure 3). FloaTEM has been used extensively in the Mississippi delta in the US and it has produced satisfactory results. The SnowTEM system has been used in Switzerland and is right now being used in Greenland.

Figure 2. The FloaTEM system. The transmitter coil is mounted on two SUP-boards and the receiver is dragged after a small rubber boat. The system as a whole is pulled by a small motor boat.

Figure 3. The SnowTEM system. The runners of the sledge have been widened to act as skis and the system is pulled by a snow scooter.

The method

tTEM is a transient electromagnetic method like the TEM and the SkyTEM methods. The system has been developed with the aim of achieving a three dimensional geological mapping of the upper 30-70 m of the subsurface. The tTEM system consists of sledges pulled by an ATV (All-Terrain Vehicle) (Figure 1).

All instruments are mounted at the back of the ATV, and a tablet is fixed in front for observing where and what is being measured in real time. The front sledge carries a 2x4 m transmitter coil that generates a heavy current creating a strong primary magnetic field. When the current is turned off abruptly in the coil, the primary magnetic field will decay and create an eddy in the ground. The eddy creates a secondary magnetic field that will decay slowly over time. The decay rate of the second magnetic field is measured in a receiver coil mounted on the second sledge behind the ATV. From the decay rate, the specific electric resistivity in the ground layers can be calculated, since the decay of the secondary magnetic field depends on the resistivity, which again depends on the geological layers below the surface. For instance, clay deposits are characterized by a low resistivity and the response will be long. In sand or gravel in which the resistivity is high, the response will be short, as the magnetic field will decay quickly. All geophysical measurements will be georeferenced with the help of a GPS fixed on the transmitter coil. In appendix A, you will find the technical specifications for the tTEM system as a whole, including the placing of the various units, transmitter wave form, and configuration of the low and the high moment.

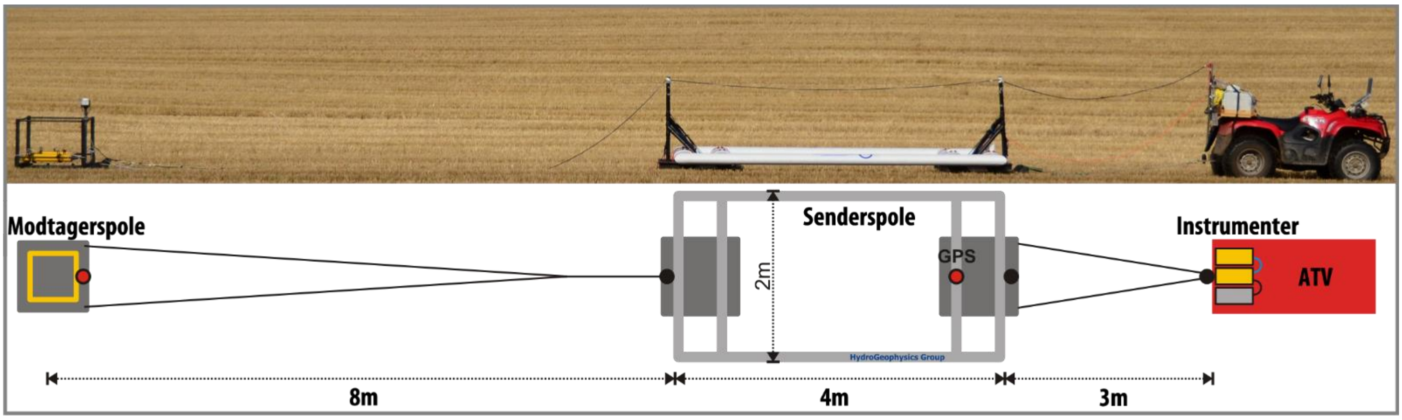


Figure 4. The tTEM system n the first production setup from September 2017. The dimensions are unchanged in the present setup.

Mapping is carried out at a speed of 3-5 m per second, and with this setup, it is typically possible to measure 100 – 240 ha per day with a line density of 10-25 m. The method has a very small sensitivity volume or footprint, which provides a lateral solubility down to 3-10 m. Thus, three-dimensional structures can be measured on field scale. The small footprint further offers the advantage that you can go much closer to noise sources like power cables and other manmade installations that normally disturb electromagnetic surveys.

Data processing

tTEM data processing is carried out in Aarhus Workbench with a designated tTEM module. During the development of this module we have worked on optimizing the data flow, and as many processes as possible have been automated. The data is imported directly in the formats delivered by the instrument, they are filtered for vibration and 50 Hz noise, and uncertainties are calculated for each data point. After processing, data is inverted to earth models using the well-known techniques like Laterally Constrained Inversion or Spatial Constrained Inversion.

The method has been published in several international and Danish journals. At present 8 articles/conference contributions have been published and further 3 articles that have been written and submitted are being reviewed scientifically. Articles and conference contributions can be found under References.

Examples of mapping in Denmark performed by AU.

In September 2017, the first tTEM-system was used to map N-retention in the Innovation Fund Denmark project, rOpen. Mapping took place near Javngyde where 1000 ha were mapped with a 10-25 m line distance. Since then 27 mappings have been carried out, focusing on mapping point source pollution, natural resources, rising groundwater table, water resources, soil surveys, and N-retention.

During this same period further 3 mappings have been carried out in Sweden, 1 in Greenland, and 24 mappings in 8 states in the USA. Figure 5 provides an overview of the locations and purposes of the Danish mappings. In the following, 5 mappings will be presented as examples. For the remaining mappings, partners, purposes, size, as well as time spent will be listed.

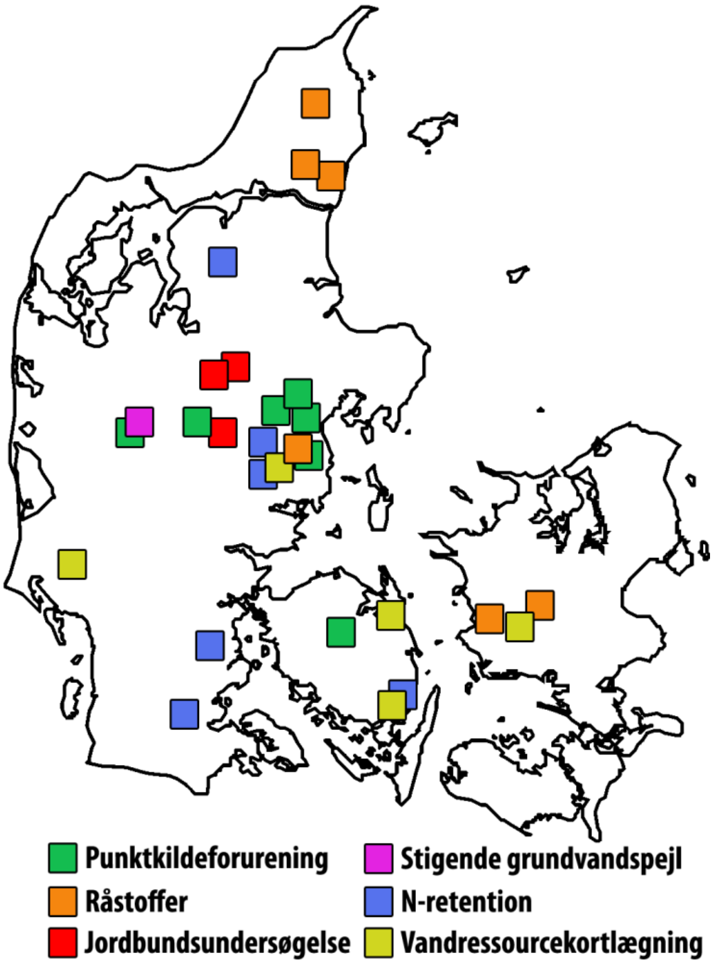
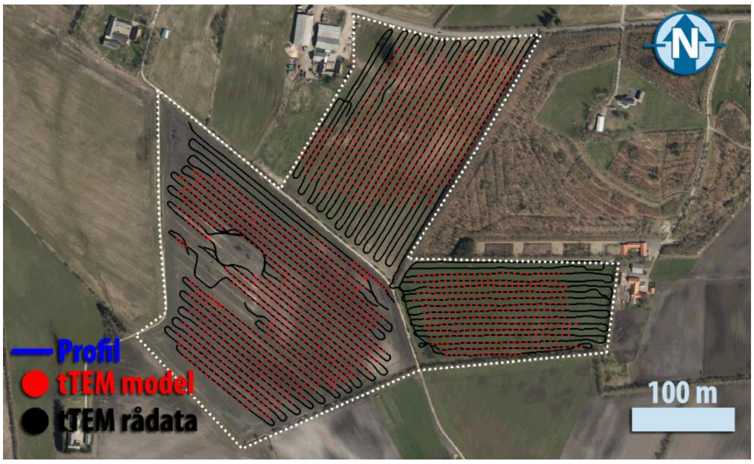


Figure 5. Overview of the Danish tTEM-mappings 2017-2019.

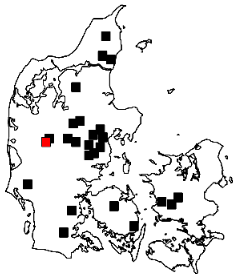
1. Optimized risk assessment of ground pollution

EU-Interreg Topsoil project med Central Denmark Region



AREA	VILDBJERG
GEOLOGY	Moraine clay, mycqua quartz sand, and mica clay.
SIZE/TIME	29 ha/<1 day
LINE-KM	29
LINE-DISTANCE	10 m

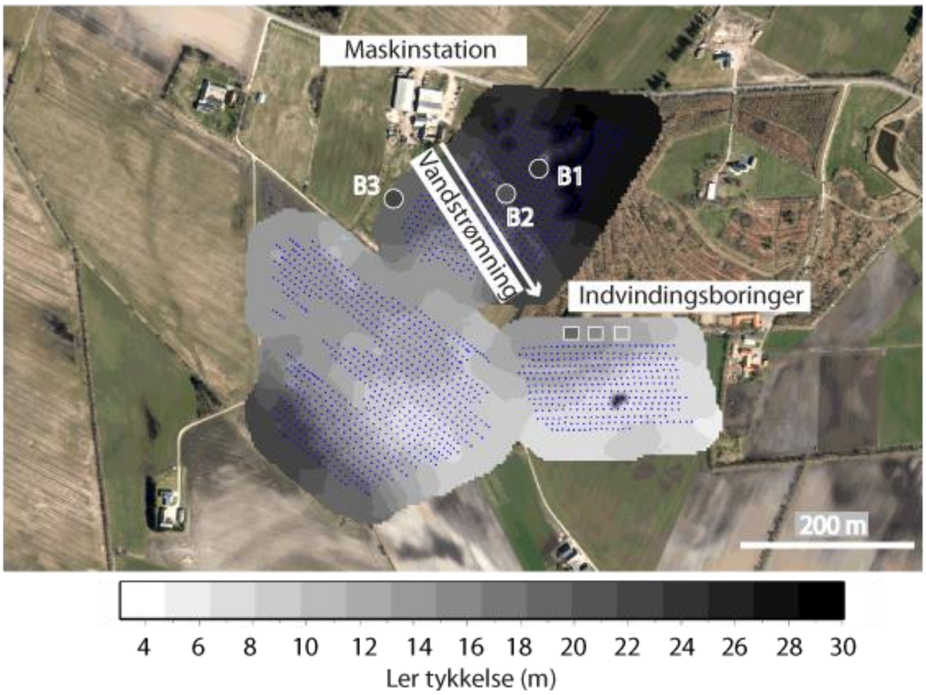
Purpuse:
Mapping of clay cover around a pesticide pollution 200 m upstream from water abstraction



Results

Pollution with pesticides was found near a contractor pool outside Vildbjerg. The water runs southeast and directly towards the abstraction wells of Vildbjerg waterworks. From existing wells (B1, B2, B3) there is a known mica layer of a certain thickness, but it is not possible to ascertain whether the layer is constant and without windows to the aquifer below. The area between the contractor pool and the abstraction wells was mapped with tTEM. tTEM provides a detailed image of the local geology enabling an assessment of the risk of percolate spreading, by mapping the special variation of clay and sand layers.

The figure below shows the thickness of the clay layer as found by tTEM and drilings. As shown, the thickness of the mica layer is more than 15 m all over and there are no windows. This makes for a small risk of the pollution spreading towards southeast. Acquiring this knowledge would have been difficult and costly depending on borehole information alone.

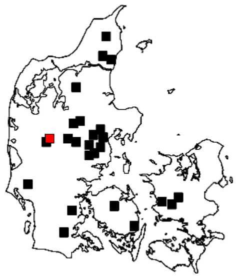


2. Geological mapping on land and at sea

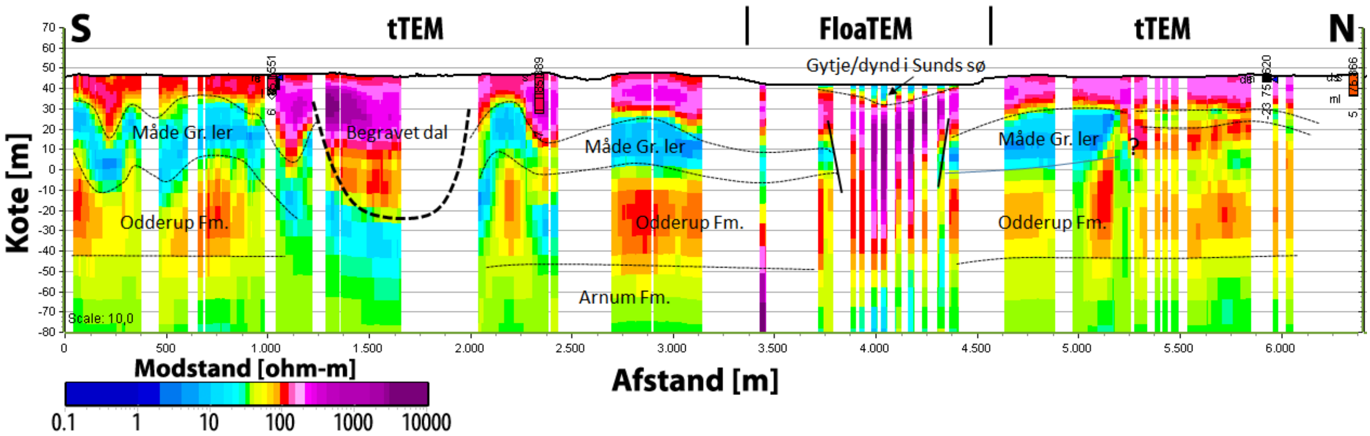
EU-Interreg Topsoil project with GEUS, Central Denmark Region, Herning municipality and Herning Water

AREA	SUNDS
GEOLOGY	Hedeslette over Miocænt kvartssand og ler fra Måde fm.
SIZE/TIME	816 ha/8 days
LINE-KM	326,4
LINE-DISTANCE	25 m

Purpose:
Geological mapping on land and lake to understand the hydrological system, understand and avoid a rising ground water table in and around the town of Sunds.

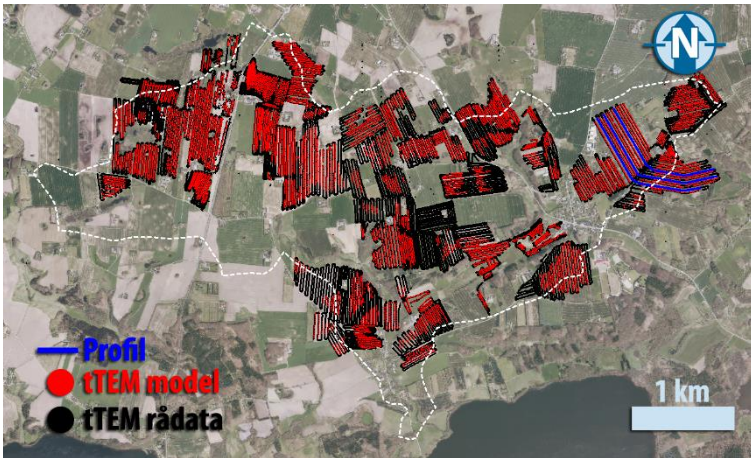


Results
The town of Sunds surrounds Sunds lake in the middle of the heath plain, characterized by flat topography and sandy deposits. The groundwater table in the town and the surrounding farmland is close to the surface and reacts quickly to precipitation events, which has often led to flooded basements and fields. This is expected to get worse in connection with the renovation of the city's sewer system and the future precipitation expected due to climate change.A geological mapping with tTEM and FloaTEM was initiated in order to understand the hydrological system around and under the town and lake of Sunds. Before the start of the project, the general understanding of the area's geology was that it was a giant sand box down to a depth of more than 20 m. The geophysical mapping has shown that this is far from the truth. Below the first 20 m of glacial sand, glacially deformed clay layers from the Mådegruppen appear interchanging with Miocene sand. The layers are greatly disturbed. Likewise, you find a thick gytje deposit (10-20 m) under parts of Sunds Lake. The spatial extent of the clay and gytje deposits is important to the hydrological circuit, and it is expected that with this new knowledge, climate proofing of the town and surrounding farmland will be possible.



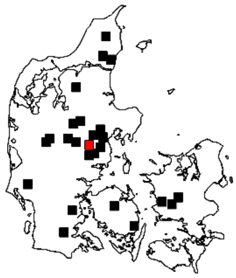
3. Field scale nitrate retention mapping

Innovation Fund Denmark project, rOPEN



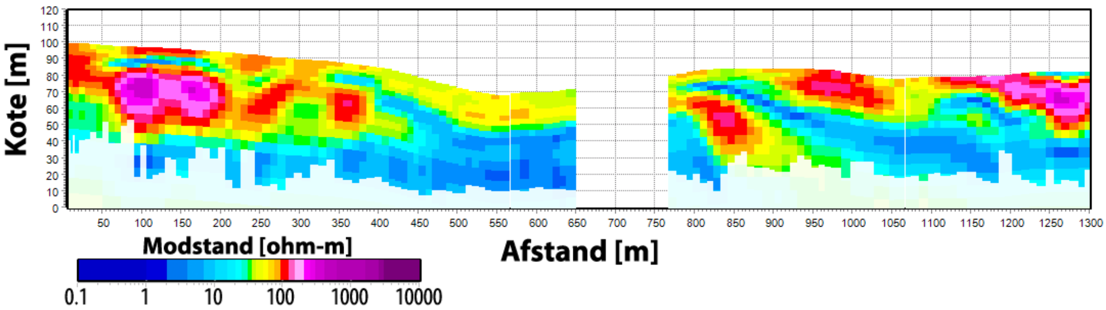
AREA	**JAVNGYDE**
GEOLOGY	Smeltevandssand og ler fra Måde-formationen
SIZE/TIME	1001 ha/11 days
LINE-KM	400,4
LINE-DISTANCE	10-25 m

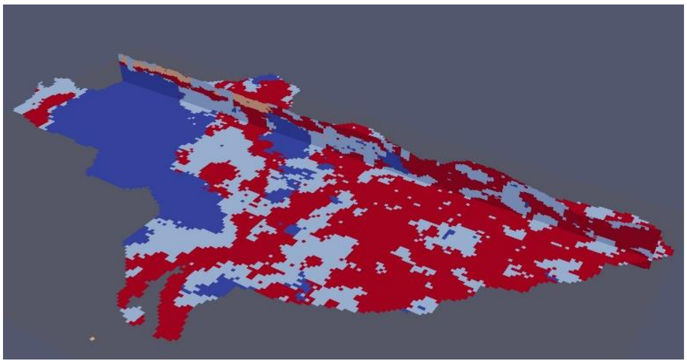
Purpose:
Geological mapping at field scale for developing automated N-retention maps in ID15 catchments

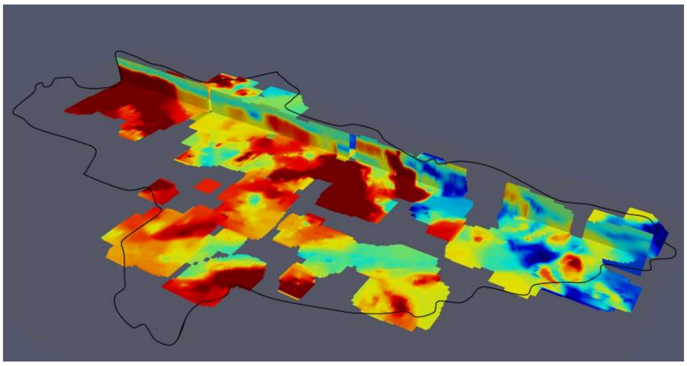


Results
The objective of rOpen is to develop a tool for assessing N-retention at field scale. Two ID15 catchments (Javngyde and Sillerup) have been chosen as pilot areas, and geophysical, geochemical, and hydrological surveys have been performed in the catchments. tTEM has been used to map the farmland and the results are turned into a hydrostratigraphical model, that will be connected to the agricultural practices and redox mapping in order to produce N-retention maps in a transparent and data driven workflow.

The figures below first show the complex geology that is being mapped with tTEM along a profile in the north eastern part of the area. Below is shown a single realization of the auto generated hydrostratigraphic model compared to the corresponding image of the resistivity. In the translation from resistivity to hydrostratigraphy, the ACT concept is used, which includes all relevant borehole information. One strength of this concept is that all uncertainties are being handled in a way that together with the final retention map can produce uncertainty maps for the use of administrating the area use.

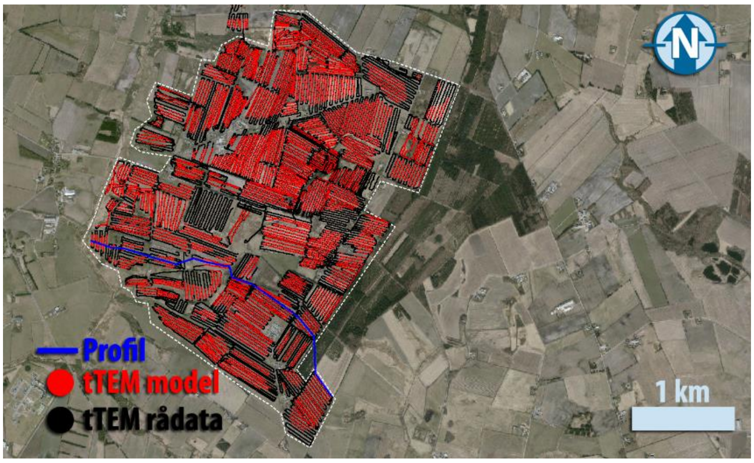






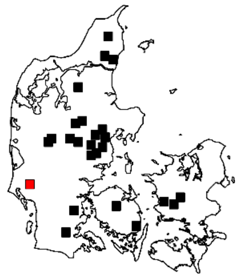
4. Vulnerability mapping and establishing a new source field

EU-Interreg Topsoil project with GEUS and DIN Forsyning (Your Supply)



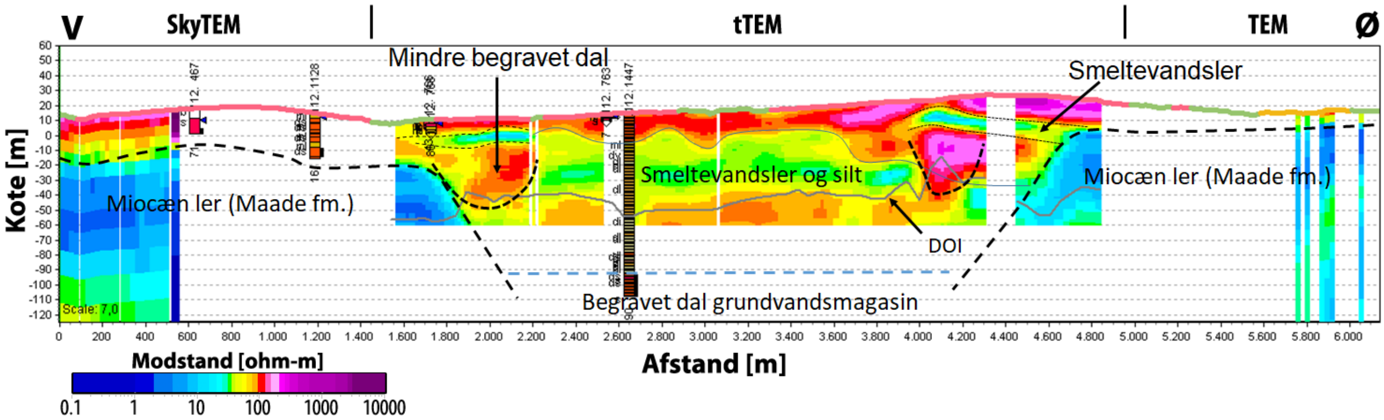
AREA	VARDE
GEOLOGY	Smeltevandssand og ler fra måde formationen
SIZE/TIME	906 ha/10 days
LINE-KM	326,4
LINE-DISTANCE	25 m

Purpose:
Detailed mapping to localize a buried valley and assess the vulnerability of the potential source field.



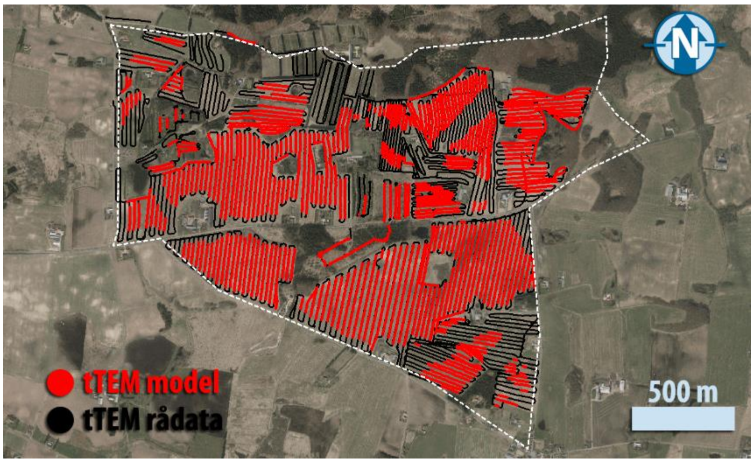
Results

Din Forsyning is in charge of the water supply to the citizens of Varde. During later years, BAM has been found in the potable water in the town of Varde and newer surveys have shown problems with the substances DMC and DPC in the water works outside the town. Existing wells are threatened by environmentally unsound substances, and as a consequence of this, the supply company is searching for a new well field. During this process, tTEM was used to map the spatial boundaries of a buried valley near Varde. Another high priority was to assess the vulnerability of the groundwater aquifer. The tTEM method is extremely useful for this purpose, as the system possesses a unique vertical resolution in the upper 20 m. The thickness of the clay layers in the upper 30 m will typically be what decides the vulnerability of an aquifer. The thicker the clay the more robust the aquifer will be towards for instance nitrate. The tTEM results show a 2,4 km wide buried valley with a more that 20 m thick clay cover. Early water analyses in the valley have shown that the quality of the water is good and based on the geophysical surveys and boreholes it is expected that a new well field can be established in the erea.



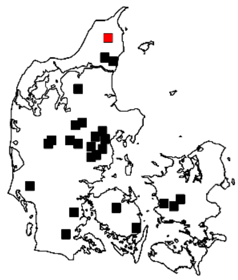
5. Mapping of potential mineral resources

Development project with Orbicon and the North Denmark Region



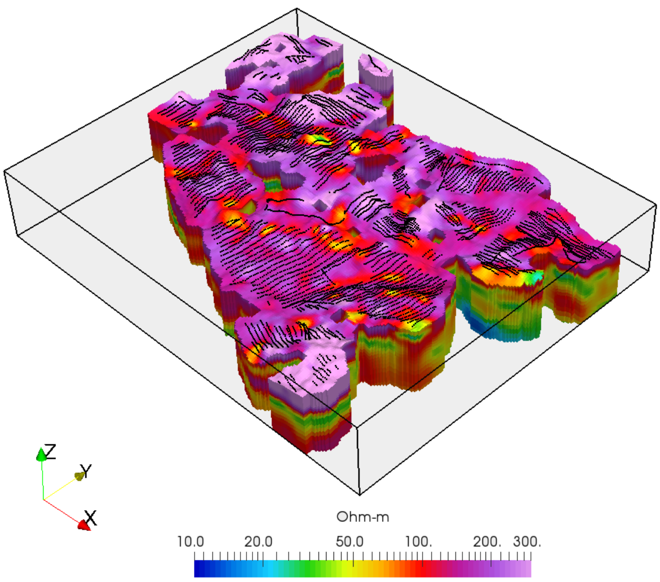
AREA	STENDALMARK
GEOLOGY	Smeltevands-sand og ler-aflejringer. Marine aflejeringer.
SIZE/TIME	365 ha/3 days
LINE-KM	146
LINE-DISTANCE	25 m

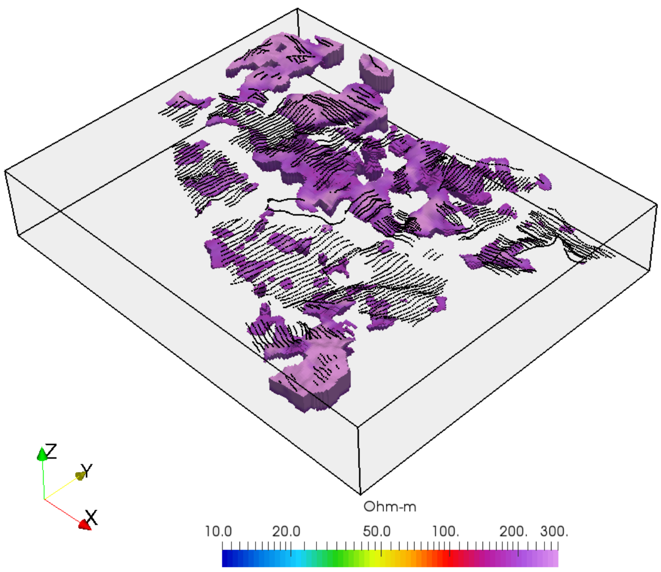
Purpose:
Mapping of sand/gravel resources to support development of the infrastructure



Results

Stable supplies of gravel are crucial for extending and maintaining the country’s infrastructure such as roads and railways, as well as for the construction industry. There is a need for finding new gravel pits using a cost-effective method, since drilling alone would be too costly a procedure. In a development project with Orbicon and North Denmark Region, 365 ha were mapped with tTEM in order to assess the method’s ability to locate mineral resources. The mapping was carried out as part of the Region’s mineral resources planning that aims to ensure that sufficient areas are laid out to secure the gravel supply for the next 12 years. The area was mapped in just three days and extensive areas with high resistivities were located. By means of the tTEM mapping the Region now has a very precise spatial delimitation of potential gravel deposits and a sound basis for follow up surveys. The figure below shows a 3D image of the mapping results. To the left the whole volume is shown with conductive layers and high resistivity layers. To the right is an iso-resistivity map with a cut-off value of 200 ohm-m showing only the high resistivity layers.



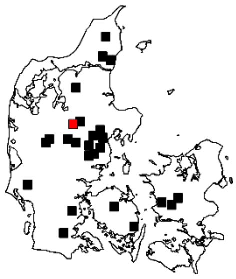


Soil survey before land development

Development project with Agro, AU

AREA	VEJRUMBRO
SIZE/TIME	10 ha/<1 day
LINE-KM	20
LINE-DISTANCE	5 m

Purpose:
Soil mapping in order to pinpoint possible wet areas ahead of land development.

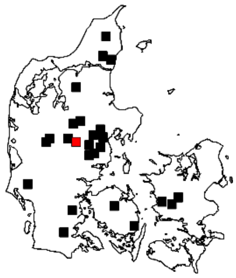


Improved drainage of fields

Development project with SEGES

AREA	SALTEN
SIZE/TIME	31 ha/<1 day
LINE-KM	31
LINE-DISTANCE	10 m

Purpose:
Soil mapping for investigating why wet areas occur and how to mitigate

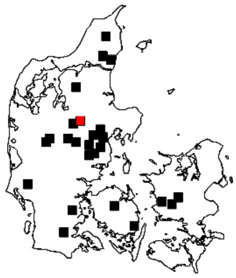


Soil survey for understanding the hydrological circuit

Development projekt with Agro, AU

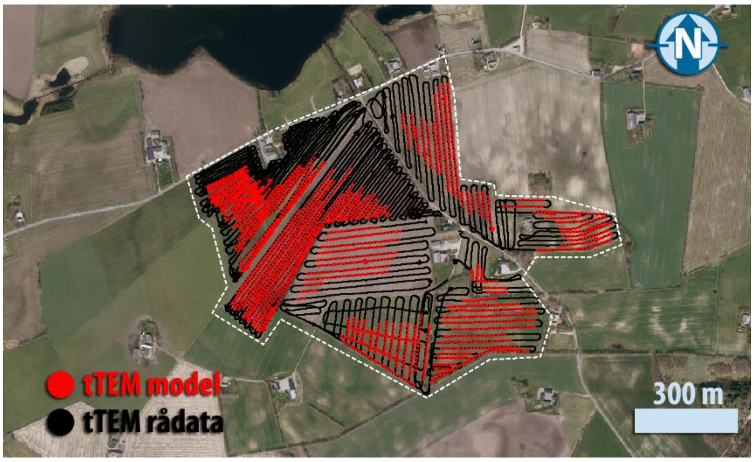
AREA	JUELSGÅRD
SIZE/TIME	28 ha/<1 day
LINE-KM	11,2
LINE-DISTANCE	25 m

Purpose:
Soil mapping for understanding the hydrological circuit in near surface geology



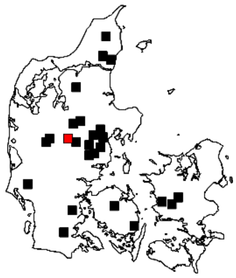
Optimized risk evaluation of soil pollution

EU-Interreg Topsoil-project with Central Denmark Region



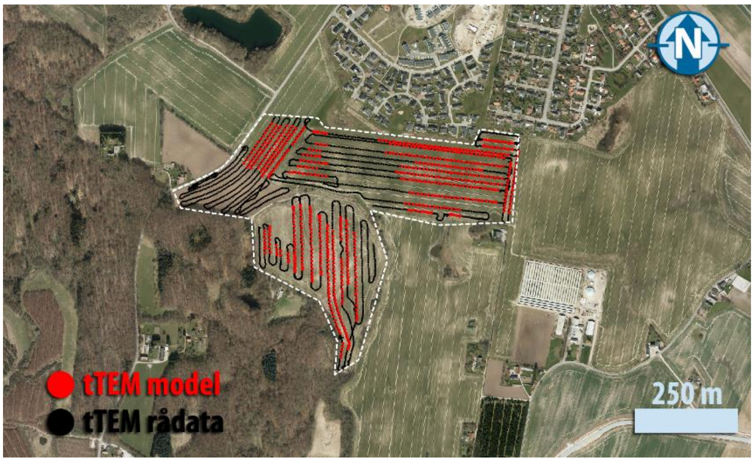
AREA	KJELLERUP
SIZE/TIME	67 ha/<1 day
LINE-KM	67
LINE-DISTANCE	10 m

Purpose:
Mapping the geology around a point source pollution for assessing the risk of percolate spreading to the groundwater



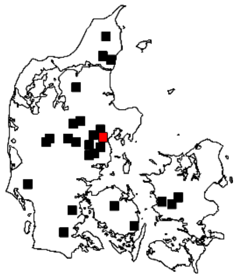
Optimized risk evaluation of soil pollution

Development project with Central Denmark Region



AREA	ELEV
SIZE/TIME	31 ha/<1 day
LINE-KM	31
LINE-DISTANCE	10 m

Purpose:
Mapping the geology around a landfill in order to assess the risk of percolate spreading to the ground water

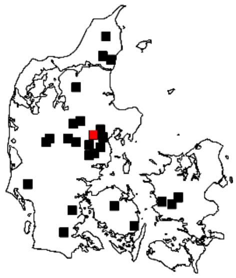


Optimized risk evaluation of soil pollution

Development project with Central Denmark Region

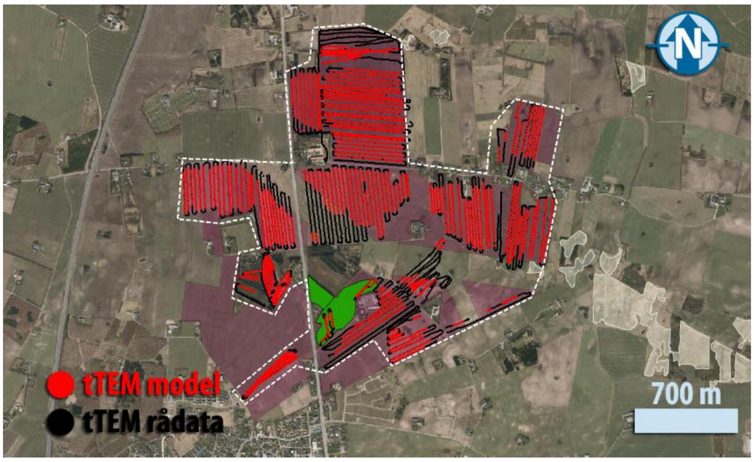
AREA	HARLEV
SIZE/TIME	50 ha/<1 day
LINE-KM	20
LINE-DISTANCE	25 m

Purpose:
Mapping the geology around a landfill in order to assess the risk of percolate spreading to the ground water



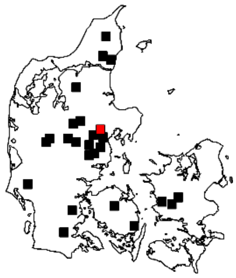
Optimized risk evaluation of soil pollution

Development project with Central Denmark Region



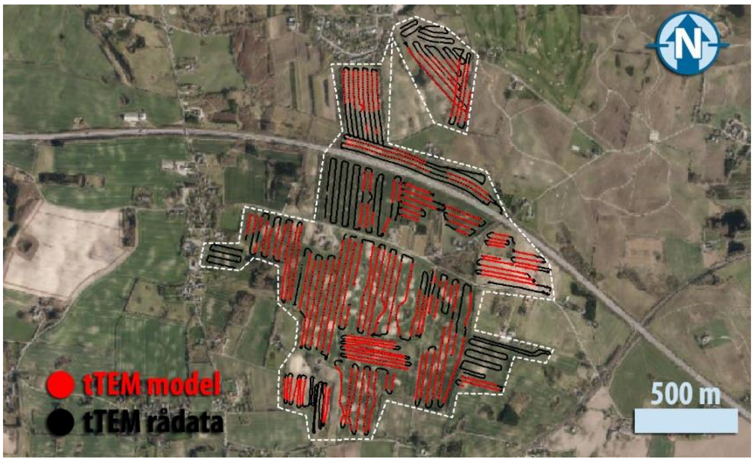
AREA	TRIGE
SIZE/TIME	280 ha/4 days
LINE-KM	112
LINE-DISTANCE	25 m

Purpose:
Mapping the geology around a landfill in order to assess the risk of percolate spreading to the ground water



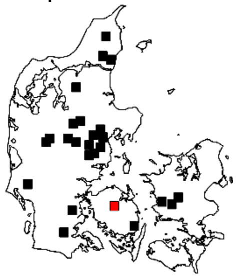
Optimized risk evaluation of soil pollution

Development project with South Denmark Region



AREA	ODENSE V.
SIZE/TIME	174 ha/3 days
LINE-KM	69,6
LINE-DISTANCE	25 m

Purpose:
Mapping the geology around a point source pollution for assessing the risk of percolate spreading to the groundwater

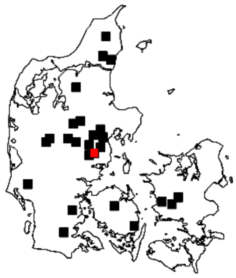


Mapping of the vulnerability of ground water resources

EU-Interreg Topsoil-projekt med Region Midtjylland, Horsens Kommune, og Go-gris

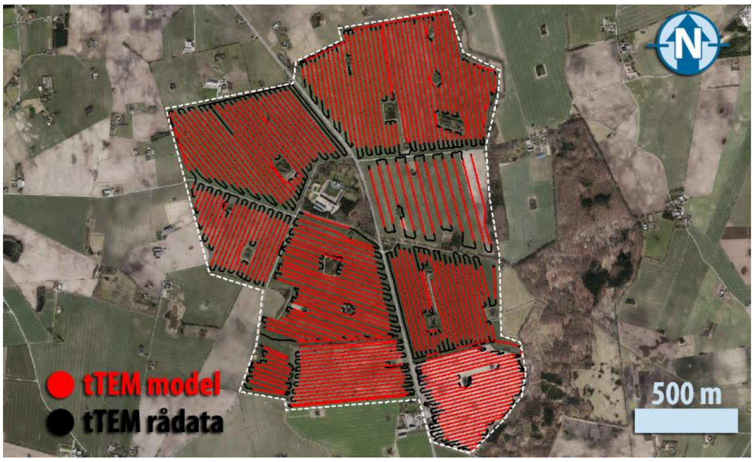
AREA	GEDVED
SIZE/TIME	160 ha/2 days
LINE-KM	64
LINE-DISTANCE	25 m

Purpose:
Mapping the geology of a farm (Go-gris) for understanding the hydrological system. The results are used to assess how to reduce leaching of nitrate til Horsens Fjord.



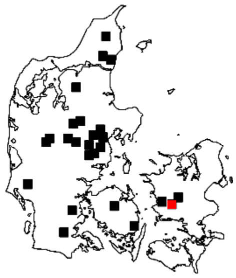
Mapping at field level in order to understand differences in N-transportation

Development project with Department of Agroecology, AU



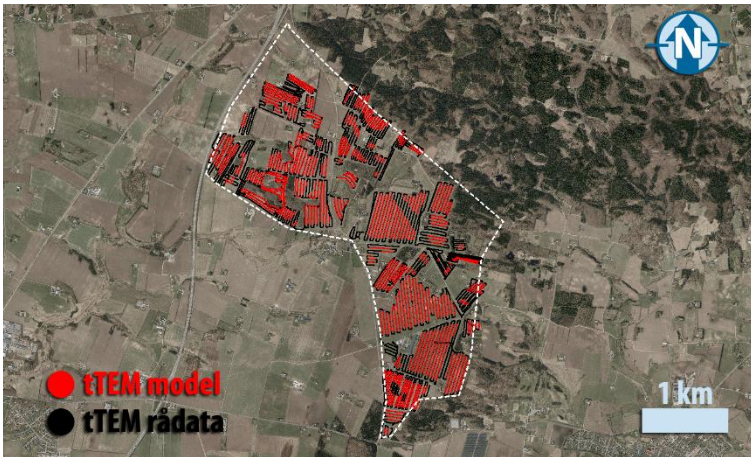
AREA	GYLDENHOLM
SIZE/TIME	435 ha/3 days
LINE-KM	174
LINE-DISTANCE	25 m

Purpose:
Mapping the geology at Gyldenholm manor to achieve a better understanding of the differences in drain response from apparently alike fields



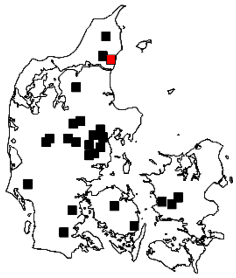
Mapping of mineral resources

Development project with Orbicon and North Denmark Region



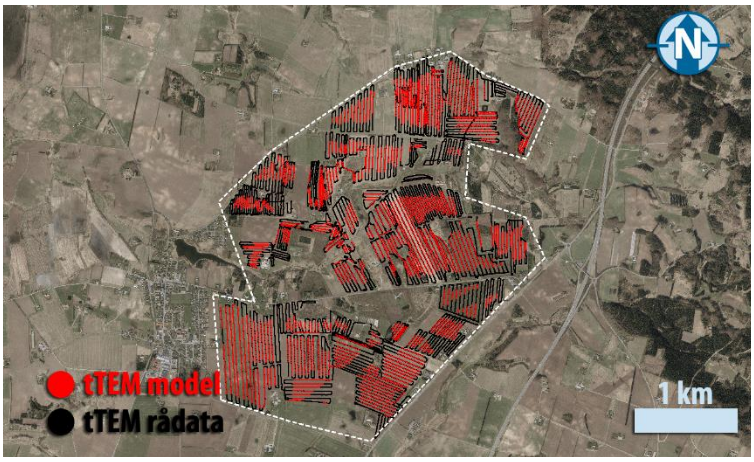
AREA	DRONNINGLUND
SIZE/TIME	470 ha/4 days
LINE-KM	188
LINE-DISTANCE	25 m

Purpose:
Mapping of sand/gravel resources to support infrastructure development



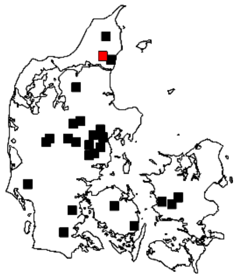
Mapping of mineral resources

Development project with Orbicon and North Denmark Region



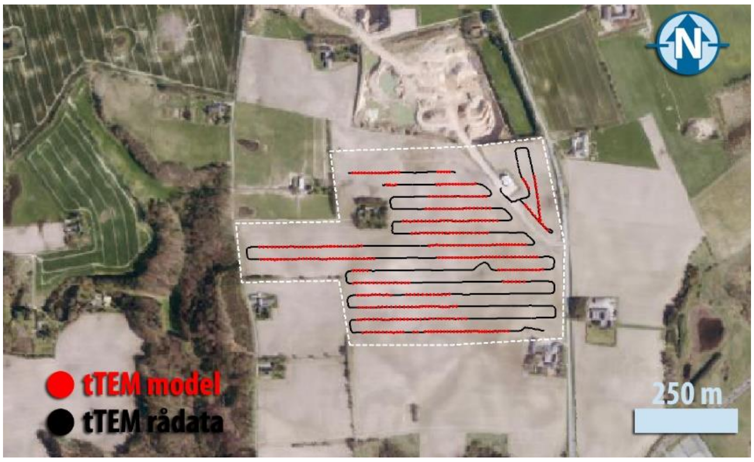
AREA	KLOKKERHOLM
SIZE/TIME	486 ha/5 days
LINE-KM	194,4
LINE-DISTANCE	25 m

Purpose:
Mapping of sand/gravel resources to support infrastructure development



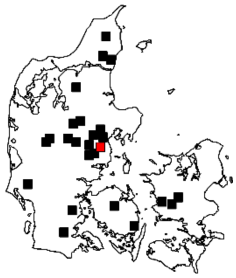
Mapping of mineral resources

Development project with Central Denmark Region



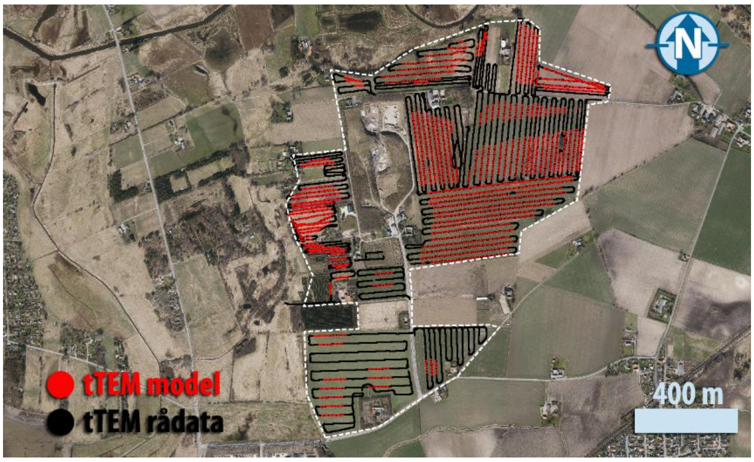
AREA	JEKSEN
SIZE/TIME	25 ha/<1 day
LINE-KM	10
LINE-DISTANCE	25 m

Purpose:
Mapping of sand/gravel resources to support infrastructure development



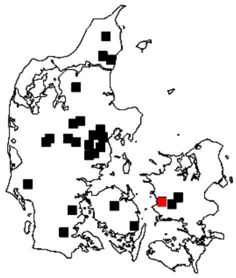
Mapping of mineral resources

Development project with Orbicon og Region Zealand



AREA	FORLEV
SIZE/TIME	120 ha/<1 day
LINE-KM	48
LINE-DISTANCE	25 m

Purpose:
Mapping of sand/gravel resources to support infrastructure development

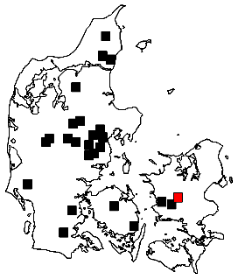


Mapping of mineral resources

Development project with Rambøll og Region Zealand

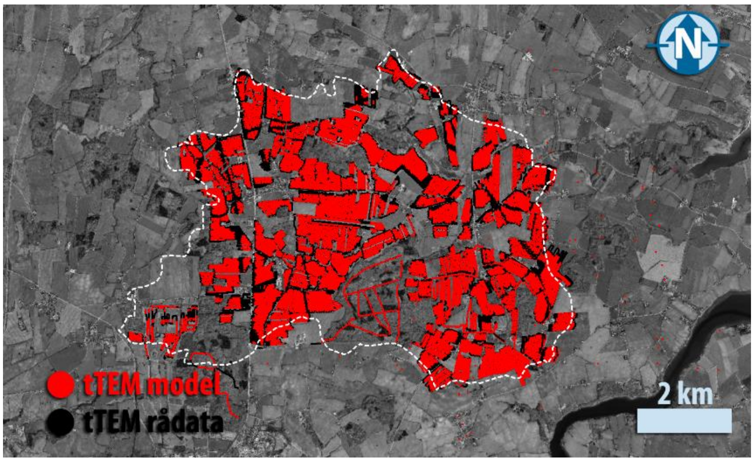
AREA	SORØ
SIZE/TIME	51 ha/<1 day
LINE-KM	20,4
LINE-DISTANCE	25 m

Purpose:
Mapping of sand/gravel resources to support infrastructure development



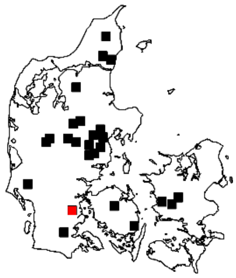
Field scale nitrate retention mapping

Innovationsfund Denmark project, rOPEN



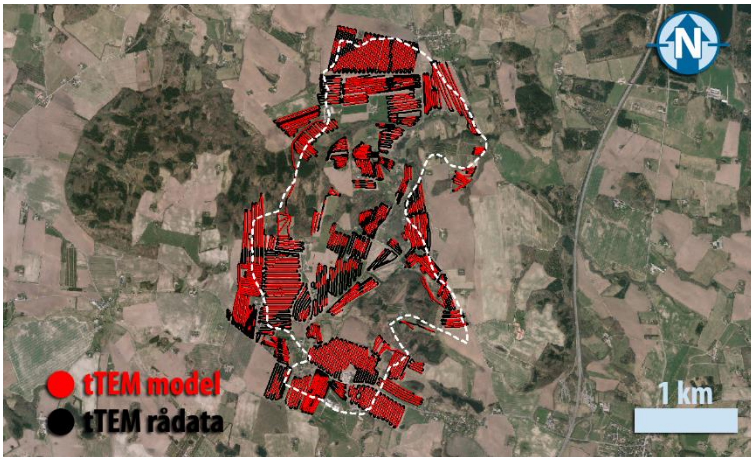
AREA	SILLERUP
SIZE/TIME	2144 ha/24 days
LINE-KM	857,6
LINE-DISTANCE	25 m

Purpose:
Geological mapping at field scale for developing automated N retention maps in ID15 catchments



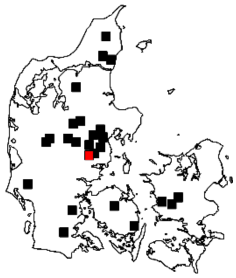
Field scale nitrate retention mapping

Innovationsfund Denmark project MapField



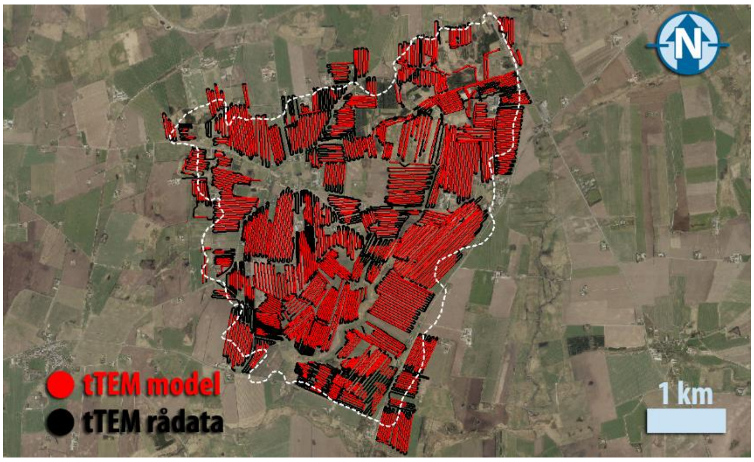
AREA	EJER BAUNEHØJ
SIZE/TIME	545 ha/6 days
LINE-KM	218
LINE-DISTANCE	25 m

Purpose:
Geological mapping at field scale for developing automated N retention maps in ID15 catchments.



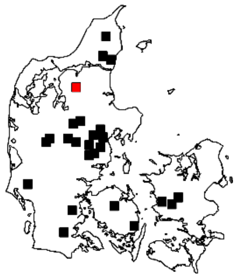
Field scale nitrate retention mapping

Innovationsfund Denmark project MapField



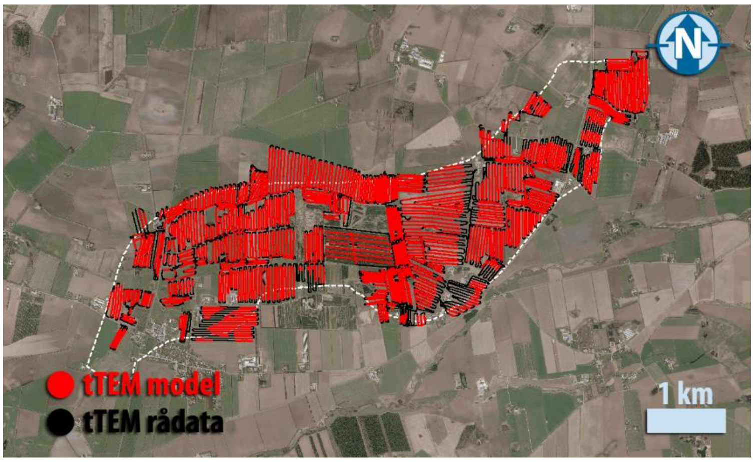
AREA	AARS
SIZE/TIME	1140 ha/8 days
LINE-KM	456
LINE-DISTANCE	25 m

Purpose:
Geological mapping at field scale for developing automated N retention maps in ID15 catchments



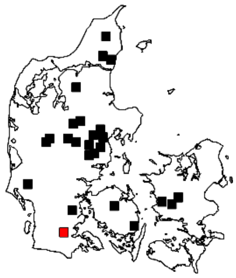
Field scale nitrate retention mapping

Innovationsfund Denmark project MapField



AREA	BOLBRO
SIZE/TIME	761 ha/5 days
LINE-KM	304,4
LINE-DISTANCE	25 m

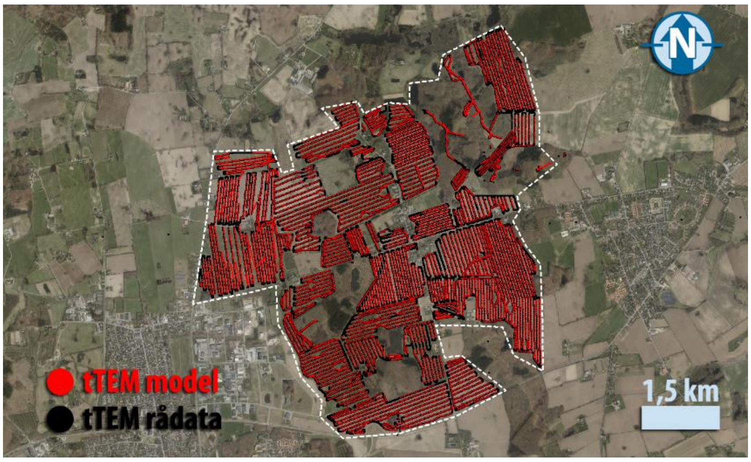
Purpose:
Geological mapping at field scale for developing automated N retention maps in ID15 catchments



Examples of mapping in Denmark performed by advisory companies

Mapping of groundwater resources

Mapping performed by NIRAS for Svendborg water and waste



AREA	SVENDBORG
SIZE/TIME	500 ha/4 days
LINE-KM	200
LINE-DISTANCE	25 m

Purpose:
Detaljeret Mapping for at undersøge udbredelsen af grundvandsressourcen og overliggende lerlag.

Optimized risk assessment of soil pollution

Mapping performed by NIRAS for Central Denmark Region

AREA	MALLING
SIZE/TIME	16 ha/<1 day
LINE-KM	6,4
LINE-DISTANCE	25 m

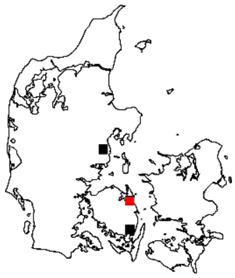
Purpose:
Mapping of the geology surrounding a point source pollution for assessing the risk of pesticides spreading to the primary groundwater aquifer

Identification of water resources

Mapping performed by Orbicon for the Lindø shipyard

AREA	LINDØ
SIZE/TIME	102 ha/<1 day
LINE-KM	24
LINE-DISTANCE	25-200 m

Purpose:
Mapping of the geology around the Lindø shipyard in order to identify new water resources for the industry.



Examples of mapping from abroad

The following shows an overview of tTEM/FloaTEM/SnowTEM mappings performed abroad since 2018. tTEM has been used in Sweden and in the USA, and SnowTEM in Greenland Grønland. FloaTEM has been used for mapping large areas in the USA.

Sweden - Infiltration of water in the Gråbo delta

Development project with the Geological Survey of Sweden (SGU)

AREA	GRÅBO
SIZE/TIME	52 ha/<1 day
LINE-KM	16
LINE-DISTANCE	10-100 m
METHOD	tTEM

Purpose:
In some areas of southern Sweden, clean drinking water is in short supply. Thus, the SGU has initiated a 3D geological mapping of particularly interesting areas to assess whether water can be infiltrated into sand/gravel deposits to establish a sustainable supply of drinking water. In this project, a former gravel pit was mapped to examine the dimensions of the potential groundwater reservoir and the depth of the underlying clay/bedrock.

Sweden - Geological mapping

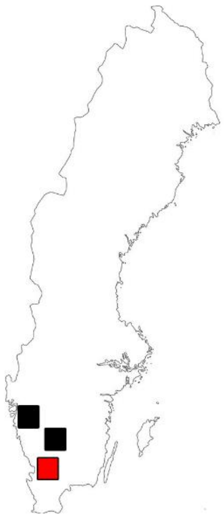
Development project with Geological Survey of Sweden (SGU)

AREA	GISLAVED
SIZE/TIME	2000 ha/<1 day
LINE-KM	13,6
LINE-DISTANCE	Rekognoscerings linjer
METHOD	tTEM

Purpose:
The Nissan River, a meandering river, runs southwest of the town of Gislaved. The course of the river has formed the landscape in the area, which is characterized by a complex geology of fine-grained sand/gravel deposits and sporadic clay deposits. In parts of the area, bedrock is found at surface level. A series of reconnaissance lines were performed in the 600 ha large fluvial sediment area to achieve an idea of the geological complexity. This knowledge would be difficult to achieve with drilling alone, due to the variation in the geology.

Sweden - 3D Geological mapping

Development project with Geological Survey of Sweden (SGU)



AREA	YLLEVALD
SIZE/TIME	64 ha/<1 day
LINE-KM	25,6
LINE-DISTANCE	25 m
METHOD	tTEM

Purpose:
The mapping area in Yllavald is characterized by significant topographis and geological differences. In some areas bedrock is found at surface level, whereas sand or clay is found in other areas.
The areas was recently mapped with SkyTEM, but in the upper 30 m the resolution was not sufficiently adequate to map the complex geological structures. With tTEM the area was mapped in a 3D resolution (25x10m grid). Several thin layers of sand and clay were identified in the upper 30 m and the bedrock could be mapped accurately.

Greenland – locating lost engine parts

Development project with the Danish and the French Accident Investigation Board

AREA	THE ICE CAP
SIZE/TIME	20000 ha/1 måned
LINE-KM	4000
LINE-DISTANCE	5 m
METHOD	SnowTEM

Purpose:
In 2017 an Airbus scheduled flight suffered an engine failure. The engine parts landed in southwestern Greenland. Not all parts have been found and thus it has not been possible to determine what exactly caused the accident. The Accident Investigation Board has designated a 10x20 km large impact area that will be mapped in part with two SnowTEM systems in the hope of locating the lost engine parts. The ice cap is characterized by a high electrical resistivity and any engine parts will appear as coupling in the SnowTEM equipment.

USA - Hydrogeological mapping on the rivers and storm protection in the Mississippi delta

Development project with the US Geological Survey (USGS)

AREA	MISSISSIPPI DELTA
STATE	Mississippi
SIZE/TIME	352 km/7 days
LINE-KM	352
LINE-DISTANCE	Not relevant
METHOD	FloaTEM

Purpose:
The Mississippi delta is characterized by rich fauna, fertile land, and agriculture. Along the banks of the river are large fields and farm buildings. The population and the industry in the area depend on the water in the river and the subsoil, and at present, the USGS is setting up a hydrological model for the whole area to ensure clean water for agriculture and fauna and to ensure infrastructure like dikes for flood protection. The USGS has used FloaTEM at several locations in the delta to map the subsoil below the rivers for understanding the inflow and outflow in the complex hydrogeological environment. Additionally they use the resistivity of the river water to assess the water quality.

USA - Hydrogeological mapping and infiltration of water in the Mississippi delta

Development project with the US Geological Survey (USGS)

AREA	MISSISSIPPI DELTA
STATE	Mississippi
SIZE/TIME	260 ha/3 days
LINE-KM	130
LINE-DISTANCE	20
METHOD	tTEM

Purpose:
The USGS has used tTEM at several locations to map the subsoil and infiltrate water to support agriculture in the area. In another area, the dikes were mapped to ensure that they were intact and able to withstand flooding.

USA - Hydrogeological mapping on rivers in Connecticut

Development project with the US Geological Survey (USGS)

AREA	FARMINGTON & RAINBOW RIVERS
STATE	Connecticut
SIZE/TIME	32 km/2 days
LINE-KM	32
LINE-DISTANCE	Not relevant
METHOD	FloaTEM

Purpose:
The USGS has used FloaTEM in 2 locations in Connecticut to map the hydrogeological system of the Rainbow and Farmingtion rivers.

USA - Hydrogeological mapping of rivers, bays and lakes in Massachusetts

Development project with the US Geological Survey (USGS)

AREA	EEL RIVER, WAQUIET BAY & ASHUMOT LAKE
STATE	Massachusetts
SIZE/TIME	28 km/2 days
LINE-KM	28
LINE-DISTANCE	Not relevant
METHOD	FloaTEM

Purpose:
The USGS has used FloaTEM at 3 locations in Massachusetts to map the hydrogeolocial system of Eel River, the Waquiet Bay and lake Ashumot.

USA – Hydrogeological mapping of rivers in Pennsylvania

Development project med US Geological Survey (USGS)

AREA	DELAWARE FLODEN
STATE	Pennsylvania
SIZE/TIME	82 km/2 days
LINE-KM	82
LINE-DISTANCE	Not relevant
METHOD	FloaTEM

Purpose:
The USGS has used FloaTEM in Pennsylvania to map the hydrogeolocial system of the Delaware river.

USA – Salt water infiltration and geological mapping in Cape

Development project with the US Geological Survey (USGS)

AREA	CAPE COD
STATE	Massachusetts
SIZE/TIME	28 km/4 days
LINE-KM	28
LINE-DISTANCE	Reconnaissance lines
METHOD	tTEM

Purpose:
The USGS has used tTEM at 4 locations in Cape Cod, Massachusetts, to map the salt-water infiltration in the coastal area and to map the upper 30 m of the subsurface.

USA - Mapping of fractures in bedrock

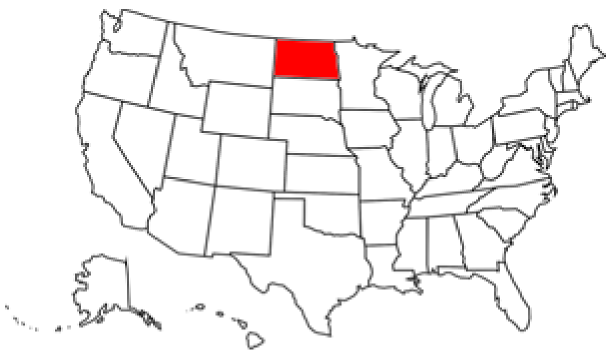
Development project with the US Geological Survey (USGS)

AREA	HADDAM
STATE	Connecticut
SIZE/TIME	10 ha/<1 day
LINE-KM	10
LINE-DISTANCE	10
METHOD	tTEM

Purpose:
The USGS has used tTEM at 1 location in Haddam, Connecticut, to map fractures in the bedrock.

USA - Mapping of geological structures

Development project with the US Geological Survey (USGS)

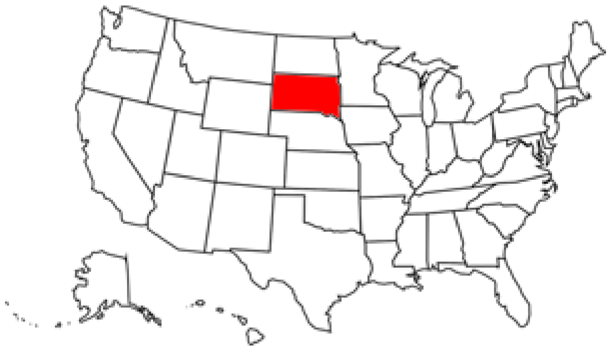


AREA	JAMESTOWN
STATE	North Dakota
SIZE/TIME	160 ha/<1 day
LINE-KM	21
LINE-DISTANCE	Reconnaissance lines
METHOD	tTEM

Purpose:
The USGS has used tTEM at 1 location in Jamestown, North Dakota to map sand and clay layers.

USA - Mapping of geological structures

Development project with the US Geological Survey (USGS)



AREA	RAPID CITY
STATE	South Dakota
SIZE/TIME	19 ha/2 days
LINE-KM	10
LINE-DISTANCE	19
METHOD	tTEM

Purpose:
The USGS has used tTEM at 3 locations in Rapid city, South Dakota to map the distribution of sand and clay layers.

USA - Mapping af saltholdigt grundvand omkring kulmine

Development project with the US Geological Survey (USGS)

AREA	TULLY
STATE	New York
SIZE/TIME	3 km/<1 day
LINE-KM	3
LINE-DISTANCE	Reconnaissance lines
METHOD	tTEM

Purpose:
The USGS has used tTEM at 1 location in Tully, New York, to map the distribution of salty ground water at a coalmine.

USA - Infiltration of water in the central valley

Development project with Stanford University

AREA	TULARE
STATE	Californien
SIZE/TIME	30 ha/<1 day
LINE-KM	10
LINE-DISTANCE	25 m
METHOD	tTEM

Purpose:
Stanford University has used tTEM to map the ground water resources in Central Valley, California. Specifically, they were surveying the distribution of sand, gravel, og clay layers at field scale to find the optimal place for infiltrating and pumping water.

References

Scientific articles and conference contributions on the tTEM method.

/1/ Auken, E., N. Foged, J. Larsen, K. Lassen, P. Maurya, S. Dath, and T. Eiskjær, 2018, tTEM — A towed transient electromagnetic system for detailed 3D imaging of the top 70 m of the subsurface, Geophysics,E13-E22., https://doi.org/10.1190/geo2018-0355.1

/2/ Behroozmand, AA, Auken, E., Knight, R., 2018, Assessment of managed aquifer recharge sites using a new geophysical imaging method, Vadose Zone J., https://doi.org/10.2136/vzj2018.10.0184

/3/ Auken, E, Pedersen, JB & Maurya, PK, 2018, A new towed geophysical transient electromagnetic system for near-surface mapping, *Preview*, vol. 194, pp. 33-35. https://doi.org/10.1071/PVv2018n194p33

/4/ Auken, E, Christiansen, AV, Pedersen, JB, Foged, N & Eiskjær, T, 2019, Creating 3D images of the subsurface from high resolution towed transient electromagnetic data' Paper presented at 88th Society of Exploration Geophysicists International Exposition and Annual Meeting, SEG 2018, Anaheim, United States, 14/10/2018 - 19/10/2018, pp. 4924-4927. https://doi.org/10.1190/segam2018-2998489.1

/5/ Vilhelmsen, TN, Auken, E, Christiansen, AV, Barfod, A, Foged, N, Pedersen, JB & Maurya, PK, 2018, 'Quantification of subsurface structural uncertainty in groundwater models using 3D geophysical data', CMWR, Saint Malo, France, 03/06/2018 - 07/06/2018.

/6/ Maurya, PK, Auken, E, Christiansen, AV, Foged, N & Eiskjær, TT, 2019, A new towed ground-based TEM-system for 3D mapping of the top 50 meters of the subsurface. in 24th European Meeting of Environmental and Engineering Geophysics. European Association of Geoscientists and Engineers, EAGE, 24th European Meeting of Environmental and Engineering Geophysics, Porto, Portugal, 09/09/2018. https://doi.org/10.3997/2214-4609.201802504

/7/ Kallesøe, AJ, Pedersen, JB, Sandersen, P, Høyer, AS, Jørgensen, F, Christiansen, AV, Auken, E & Hansen, BG, 2018, Ny geofysisk metode inviterer til detaljeret geologisk Mapping, Vand og jord II, 2018.

Appendix A – technical specifications

tTEM-udstyret
tTEM-systemet er et tidsdomæne elektromagnetisk system, som er udviklet med henblik på hydrogeofysiske og miljømæssige undersøgelser. tTEM-systemet måler kontinuert, imens udstyret trækkes på terræn. Systemet er designet til overfladenær Mapping med unik detaljerigdom i de øverste 30 m af jorden grundet tidlige gates og en hurtig repetitionsfrekvens. I det følgende gennemgås de tekniske specifikationer på instrumentet.

Instrument
tTEM-systemet er opsat i en offset konfiguration med modtagerspolen cirka 8 meter bag ved senderspolen. Modtagerspolen er placeret horisontalt, og måler dermed z-komponenten af det magnetiske felt. En ATV anvendes til at trække systemet, og distancen mellem ATV og senderspole er cirka 3 meter. Senderspolen er 2x4 meter stor og fastmonteret på arme, som er boltet fast i de 2 senderspoleslæder. Dermed kan senderspolen nemt udskiftes i felten, hvis der er et behov. GPS til positionering er fastmonteret på fronten af senderrammen for præcis positionering af de elektromagnetiske målinger. Modtagerspolen er fastmonteret på en lille slæde og er suspenderet for at undgå støj introduceret pga. vibrationer. Effekten af vibrationsstøj må dog vurderes som minimal grundet den meget høje repetitionsfrekvens. Senderelektronikken, modtagerelektronik, batteri etc. er lokaliseret bag på ATV'en. Under dataindsamling kan føreren monitorere vigtige dataparametre så som sendt strøm, sendertemperatur og GPS forbindelse og se de målte kurver og indmålte datapunkter i realtid på en tablet monteret i fronten af ATV'en.

Måleprocedure
De transiente elektromagnetiske målinger udføres med to momenter – en lav- og højt-moment efter hinanden. En lav- og høj-momentsekvens tager typisk et halvt sekund at måle og består af adskillige hundrede individuelle målinger.

Mappingshastigheden tilpasses Mappingsområdet og Purposeet med Mappingen, men ligger typisk på 3-5 meter per sekund, hvilket svarer til 10-20 kilometer i timen. Udover GPS og de transiente elektromagnetiske målinger, måles og monitoreres en række væsentlige instrumentparametre for at kvalitetssikre data. Det drejer sig bl.a. om strømniveauer, spænding og sendertemperatur.

Mappingsdybde
Mappingsdybden for tTEM-systemet afhænger af sendermoment, geologien i Mappingsområdet, baggrundsstøjen, vibrationsstøjen og antallet af måle-repetitioner. Typisk opnår man en Mappingsdybde på omkring 70 meter i områder, hvor jordlagene har en gennemsnitsmodstand på 40 ohm-m. Mappingsdybden vil være større i områder med højere modstande og lavere i områder med jordlag med meget lave modstande (0.1-10 ohm-m). I tolkningen af de indsamlede data, estimeres Mappingsdybden for hver modstandsmodel.

Konfiguration
I dette afsnit listes de tekniske detaljer for et typisk tTEM systemsetup. tTEM-systemet er konfigureret i en standard to-moment opsætning. Instrumentopsætningen fremgår af figur 4. Positioneringen af de enkelte instrumenter og hjørnerne af senderspolen fremgår af tabel 1. Begyndelsespunktet er defineret som centrum af senderspolen.

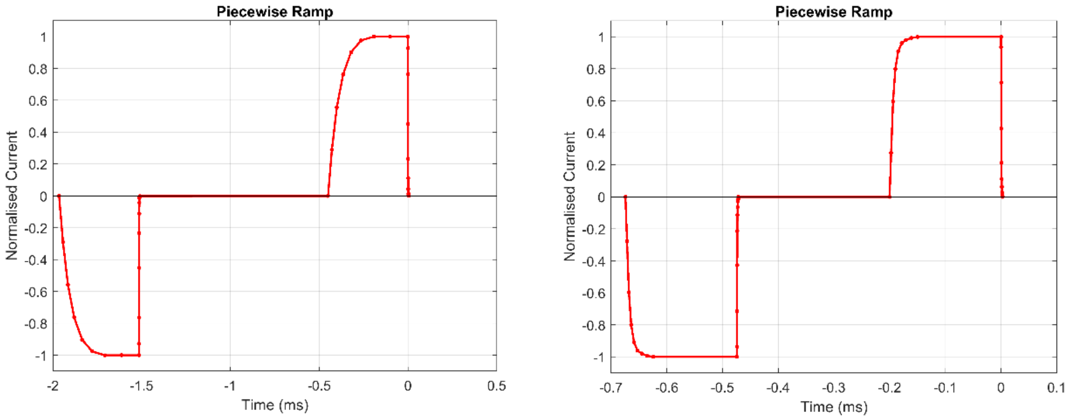
Specifikationerne for lav-moment (LM) og højt-moment fremgår af tabel 2. Senderbølgeformen for begge momenter fremgår af figur 6 med detaljer for slukketiden for LM i figur 7.

Instrument	X (m)	Y (m)	Z(m)
GPS_Senderspole	1.40	0.00	-0.40
RxZ (Z-modtagerspole)	-10.17	0.00	-0.43
Tx-Coil, centrum	0.00	0.00	-0.30
Tx-Coil hjørne 1	-02.00	-01.00	-0.30
Tx-Coil hjørne 2	02.00	-01.00	-0.30
Tx-Coil hjørne 3	02.00	01.00	-0.30
Tx-Coil hjørne 4	-02.00	01.00	-0.30

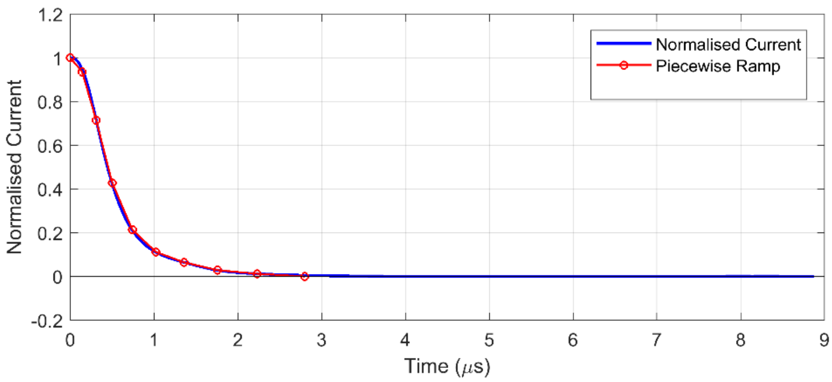
Tabel 1. Instrumentpositioner. Modtager- og senderspoleposition. Begyndelsespunktet er centrum af senderspolen. Z er positiv nedad.

Parameter	LM	HM
Vindinger	1	1
Senderareal (m^2)	8 m^2	8 m^2
Senderstrøm	~ 2.8 A	~ 30 A
Sendermoment	~ 22.4 Am^2	~ 240 Am^2
Repetitionsfrekvens	1055 Hz	330 Hz
Stakstørrelse, rådata	422	264
Moment cyklustid	0.22 s	0.40 s
Sender on-tid	0.2 ms	0.45 ms
Duty cycle	42 %	30 %
Slukketid, sender	2.5 µs	4.0 µs
Antal gates	4	23
Gate tidsinterval	4 µs –10 µs	10 µs – 900 µs
Front-gate tid	4 µs	7 µs

Tabel 2. Specifikationer for lav-moment (LM) og høj-moment (HM).



Figur 6. Bølgeform for lav-moment (venstre) og høj-moment (højre). Den røde linje indikerer den stykvist lineære modellering af bølgeformen.



Figur 7. Slukketid for lavt moment. Den røde linje indikerer stykvist lineære modellering af bølgeformen.