UXO and Landmine Detection using 3-dimensional Ground Penetrating Radar System in a Network Centric Environment

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1. Introduction

This paper addresses the need for improved sensors for mine clearance operations and humanitarian demining efforts. These operations require an information system that is capable of supporting activities such as planning, training, simulation, execution, documentation and assessment. To achieve this goal the system is best implemented using a service-based architecture, with sensors and other sources feeding into a common database that is capable of fusing the diverse information and users being able to request tailored and specific information in various formats and through a multitude of communication channels and operator interfaces.

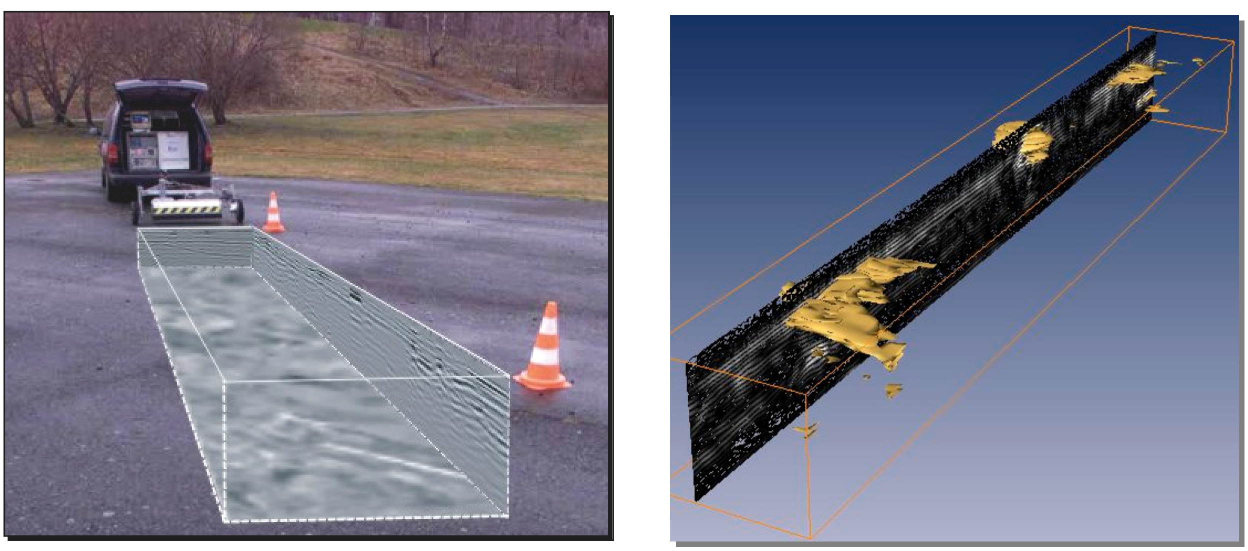

Figure 1. The 3d-Radar system has been developed for research purposes at the Norwegian University of Science and Technology. Currently the system is being exploited for applications in the commercial and military/public market.

In a Network Centric Concept the sensor systems need to be able to comply with the specific requirements of precision, flexibility and mobility. The first of these issues may directly be associated with image resolution and accurate geo-referencing of radar data. It also implicit that precision requires a high degree of accuracy in object identification through automatic means and/or machine-assisted operator functionality.

2. The 3-Dimensional Radar System

The sensor being described is a novel step-frequency GPR system that uses an advanced antenna array for high-resolution 3-dimensional subsurface imaging. The system was originally developed at the Norwegian University of Science and Technology during the period 1998 – 2001 to demonstrate high-resolution radar imaging [1]. The system has been further developed and industrialized into a field-proven GPR system that has already been applied for underground utility mapping and railroad inspection. Unlike most existing GPR systems that uses bistatic ground-coupled antennas, the 3d-Radar GPR system was designed to operate with a standoff antenna array to obtain maximum resolution at shallow depths. This makes the system suitable for detecting landmines and UXO closely below the ground surface.

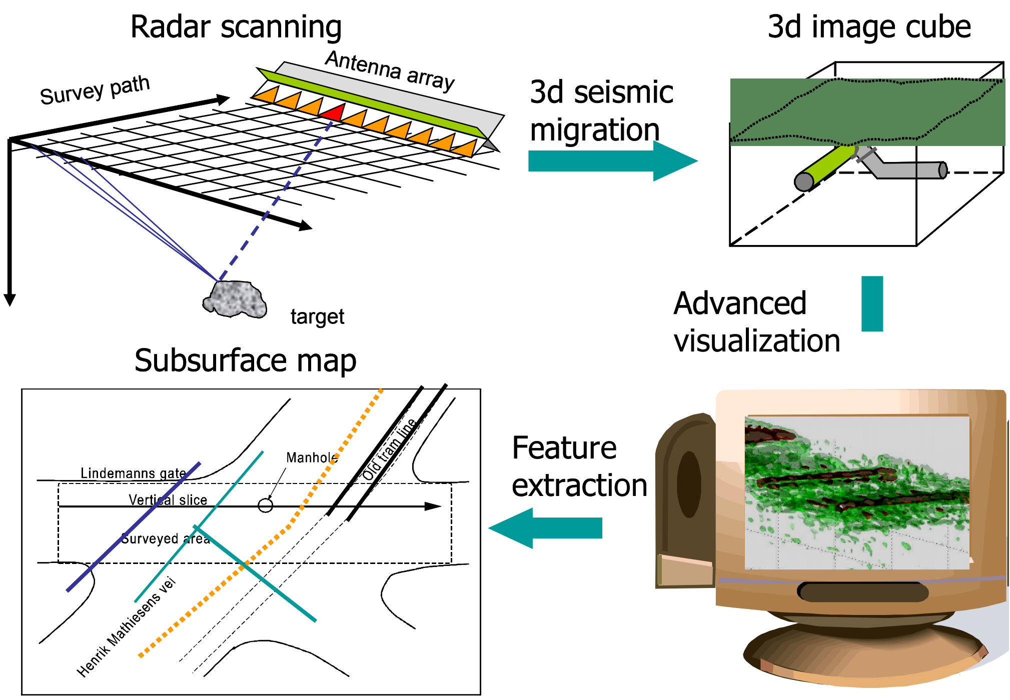

Figure 2 Conceptual overview of the 3d-Radar system.

The radar system can be programmed to operate in the frequency range from 10 MHz to 3.4 GHz using digitally generated step-frequency waveforms. The high bandwidth gives image resolution in the order of 5 centimeters depending on the soil conditions. In practice the frequency range is limited by the frequency coverage of the antenna array. The current version of the antenna array can operate from 100 MHz to 2.4 GHz, but future versions of the antenna array will be designed to support higher frequencies. In general the modular design of the radar system allows a wide range of antennas to be configured and used for the different operational requirements. Data from the radar can be tagged with position information from high precision GPS surveying systems or other navigation aids. The radar electronics module weights approximately 30 kg and runs directly off 12/24V DC with a power consumption of less than 200 Watts.

Unique concept and product features are:

- The frequency-domain system gives very high down-range resolution, and susceptibility to interference can be greatly reduced.
- The use of transversal arrays facilitates 3d-data acquisition and focussing.
- The use of all-digital signal sources gives a fast and flexible system.
- Dedicated microwave circuits gives high dynamic range which translates into high penetration and non-smear images.
- Fast data acquisition facilitates efficient field operation.
- The antenna array is compact and lightweight for easy logistics.
- The system is prepared for dual polarization operation for better detection capabilities.
- Modular design makes it easy to adapt to customer needs and to meet specific application requirements.
- Modern signal processing and data interfaces allow integration into sensor networks.
- Adaptable Human Interface using COTS and MOTS solutions.
- Embedded 3d-imaging and visualization and target discrimination.

3. Ultra-Wideband Antenna Array

3-dimensional GPR data is collected using a linear array of antenna elements in the cross-line direction in combination with physical motion in the so-called in-line direction. The 3d-Radar antenna array consists of 63 electronically switched transmit/receive bow-tie antenna pairs with a distance interval of 3.75 centimeters between each pair. The bow-tie monopole transmit/receive configuration gives a geometry that resembles a monostatic antenna but still with 20 – 30 dB isolation between the transmitter and receiver [2]. The bow-tie monopole elements are arranged in a fractal-like interleaved pattern where the high frequency elements with smallest size are located between the larger low-frequency antenna elements [3]. In this way it is possible to both fulfill the spatial sampling requirements at the high frequencies while at the same time ensure sufficient low-frequency radiation through the more sparsely distributed large elements. A dual-polarized version of the antenna array is also under development.

For practical reasons, the GPR antenna array should be as small and lightweight as possible to ensure easy field operation and high mobility. The current version of the antenna array has a size of 29 × 39 × 240 centimeters and a weight of 40 kg. This allows the antenna to be mounted on a large range of platforms ranging from small remote controlled vehicles to larger military vehicles. The vehicle-mounted configuration is especially well suited for scanning of roads and road shoulders for landmines. Each survey lane is approximately 2.4 meter wide. The survey velocity is mainly determined by the required integration time for each antenna pair. With integration time in the range 0.3 – 0.5 seconds per antenna it is possible to run the system at velocities up to 5 km/h.

4. Signal Processing

The embedded computer system of the radar is capable of performing the necessary signal processing tasks that is required to form a 3-dimensional image. These tasks include system and antenna deconvolution, filtering, suppression of surface reflections, trace balancing, and 3-dimensional image formation based on seismic wavenumber migration technique [4]. To obtain good image quality it is very important to equalize and align the traces from each antenna pair properly, and different techniques for this has been tested and evaluated.

The resulting images can be viewed through the radar's graphical user interface. Most of the low-level signal processing is done near real-time today, and we expect to implement near-real-time algorithms for the wavenumber migration in the future. This will give radar imaging capabilities with very low latency. More advanced clutter reduction techniques and target detection algorithms are also under development.

5. Application areas

The current system has been realised in a set of operational prototypes that have been tested on a range of applications. Through interactions with users, experiments and tests have been set up to facilitate concept development and operational evaluation. Focus has initially been on civilian applications, with introductory testing at military facilities for de-mining and environmental cleanup purposes. This section gives a short review of application areas covered and main results achieved.

5.1 Utility Mapping

Utility mapping includes scanning for and mapping of underground features that are critical to construction and utility management. The utility mapping cycle (Figure 3) of successive planning, surveying, verification clearly makes the case for actual means of deep surveillance beyond the reach of visual inspection.

Figure 3. The utility mapping cycle.

Over the past 5 years, the system has been demonstrated and tested for a variety of targets and applications, from pipe detection, cable detection, object detection, interface detection and profiling, and in a range of environments from being sandy soils to realistic clay and moist environments.

This range of activities has lead to an understanding of critical technical and operational issues, and has been addressed in the later realizations of the system. The concept of 3d-imaging facilitates a different way of GPR operation, and much like a TV set is a much better way of looking at a TV-transmission than an oscilloscope. A 3D-image or interactive visualization makes it possible for operators to achieve much greater operational flexibility and cognitive understanding of the area under investigation.

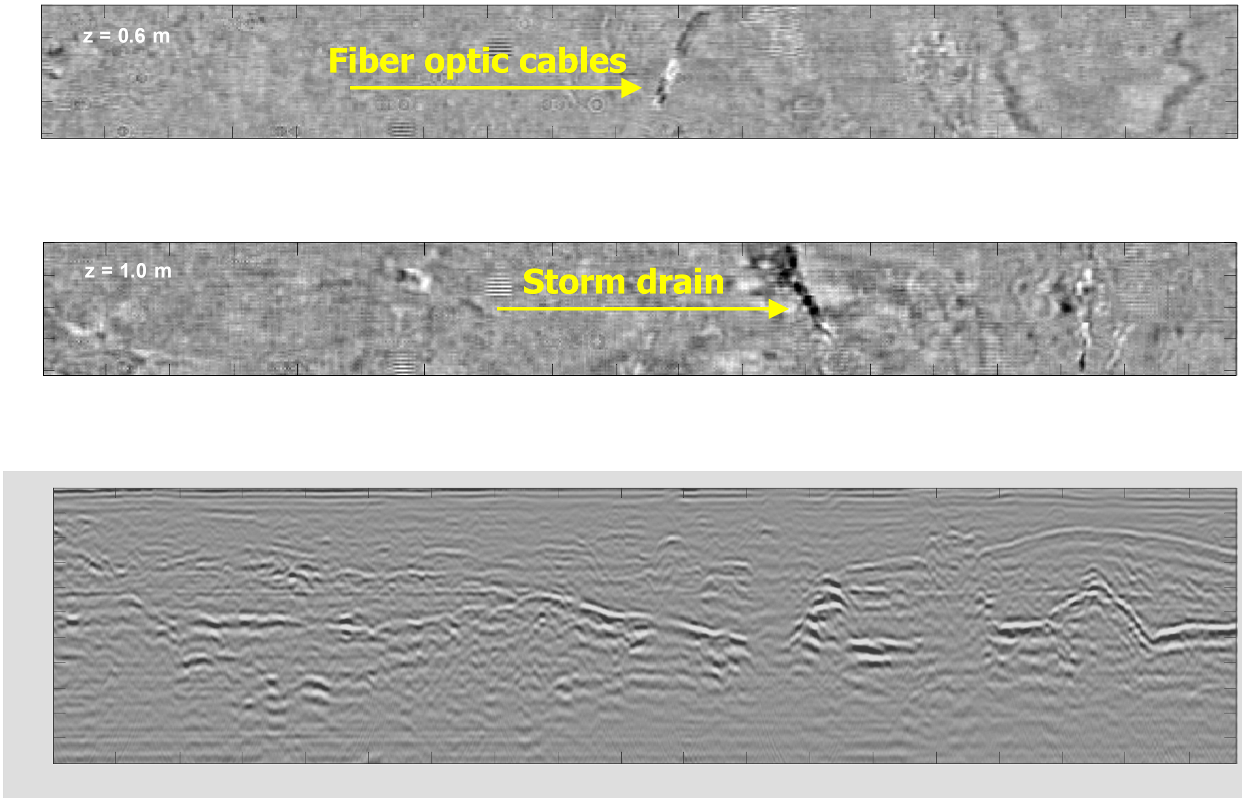

Figure 4. 3D-imaging allows slicing in all planes - sample data from survey at NTNU University Campus.

5.3 Road inspection

Road inspection typically involves measurements of asphalt thickness, base layers, instabilities, deformations and damages. In USA, $ 40 billion is spent each year on road maintenance, and some estimates suggest a 10% saving potential employing imaging methods on a large scale. There are a number of existing systems, and it has been a thrust of the current efforts to determine the value-added impact of 3d-systems for road maintenance.

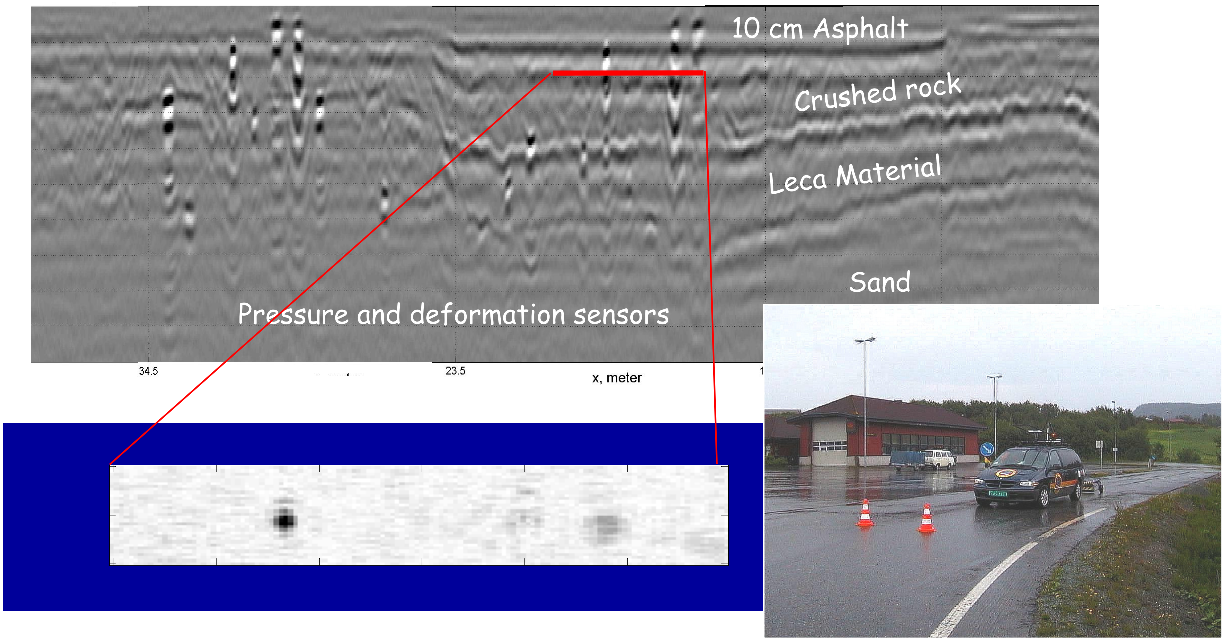

Figure 5 . Road Survey with vertical and horizontal data slices.

Initial testing on roads in Scandinavia to determine the value of routine measurements has been performed. Figure 5 shows a sample set of data where resolution corresponding to the diffraction limit (2 inches) is demonstrated.

Given the high resolution and clarity of the 3d-images this technique also holds premise for the detection of buried objects or to be used as a road-side scanner to scan for objects or malice objects intentionally put to cause harm.

5.4 Railway ballast survey

Railway ballast surveys give measurements of ballast thickness and quality and an identification of the base layers. In the US alone, $5 billion is spent each year on railway maintenance. A significant saving in maintenance cost is anticipated through the use of diagnostic techniques.

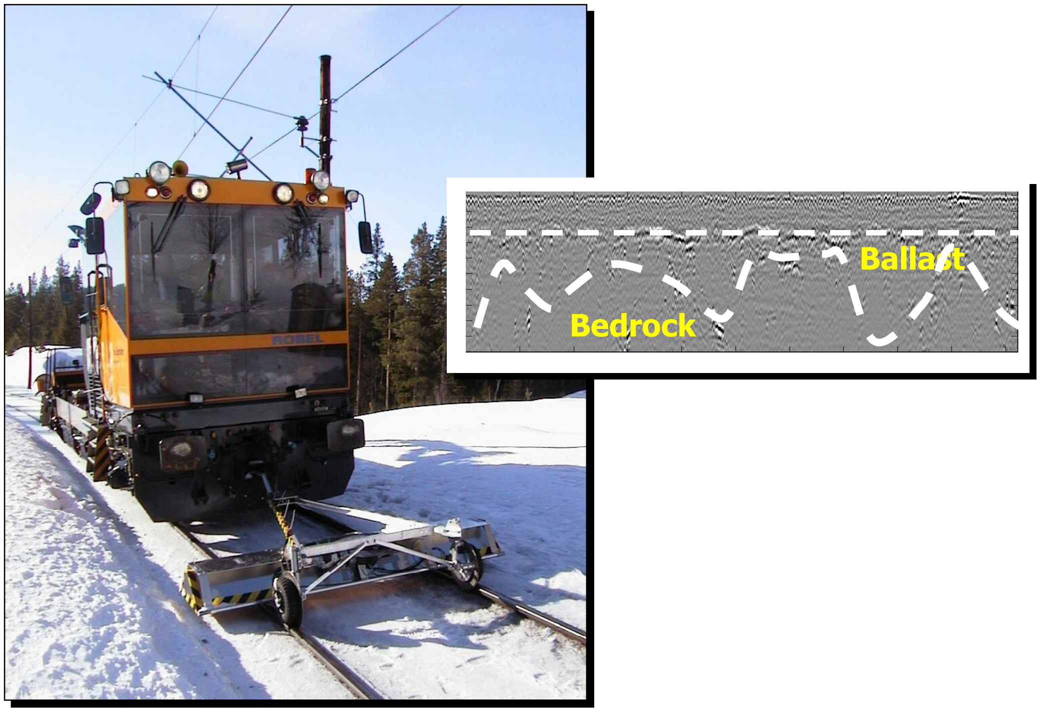

Figure 6. Railway ballast surveys gives accurate indication of ballast layers, bedrock and also allows the detection of concealed objects.

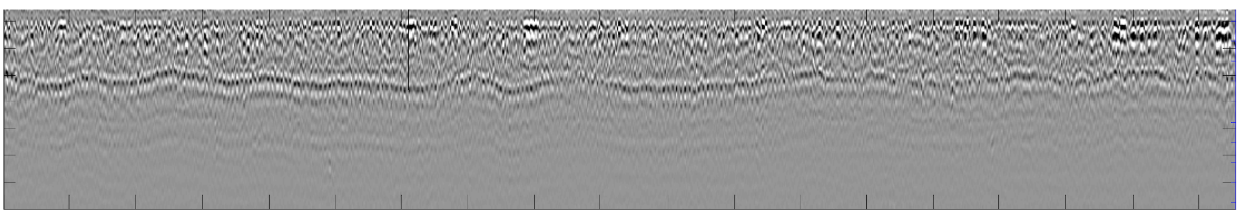

Figure 7. Vertical slice of railway data. Sleepers and ballast layers are clearly visible and unwanted object may clearly be identified.

A challenging application is scanning of railways for the detection of concealed objects, such as objects designed to derail the train or to explode. This is achieved with the current system, with certain challenges to be met for very high speed scanning.

5.5 Scanning for buried objects

3d-Radar has an inherent advantage in scanning for deep targets as compared to 2-dimensional systems. The added dimension gives an advantage in terms of equivalent antenna gain and ability to correct for phasefront distortion on the surface, and the extra dimensionality of the data sets makes it possible to make use of human data interpretation or artificial intelligence for target detection.

Figure 8 depicts a scene from a Norwegian airport where the system has been successfully used to detect buried aircraft abandoned after the Second World War. The resulting detection and analysis reveals buried structures that may be characterized in terms of dimensions and internal structure.

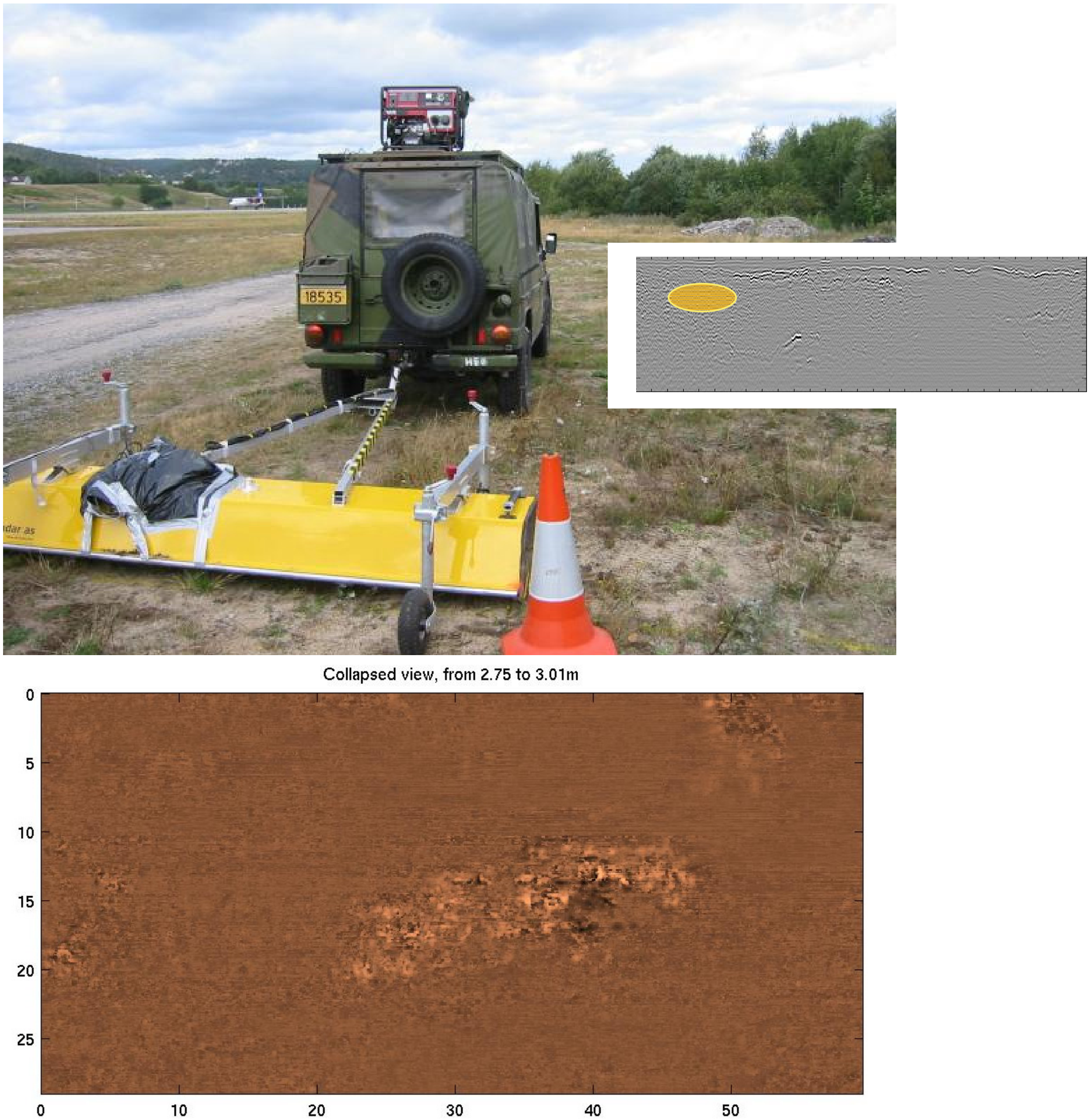

Figure 8. Successful scanning for buried aircraft at Norwegian airport. Inset shows target detection while large picture depicts horizontal slice at 3m depth with target (wrecked aircraft parts) present.

5.6 Military applications

The radar system has been tested at demining training facilities operated by the Norwegian Army with promising results. AT mines with low metal content give strong reflections and appear as bright features in the radar images while AP plastic mines are more difficult to detect. Metallic targets such as shells and other UXO give strong reflections, and the high resolution of the radar images makes it possible to recognize the shape and orientation of these targets. Even if the signal-to-clutter ratio of the radar images still is low, we expect to improve this number significantly by introducing the dual-polarization array together with advanced clutter reduction techniques.

There are a large number of military applications to be pursued, and it is the belief of the authors that radar 3D-imaging may contribute to existing solutions and that we also will see novel applications when combined with other sensor systems and integrated into data fusion networks.

6. References

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[4] Jørgen Binningsbø, Egil S. Eide, and Jens F. Hjelmstad, "3D migration of GPR array-antenna data", GPR 2000: Eighth International Conference on Ground Penetrating Radar. Gold Coast, Australia, 22 – 26 May, 2000.