SLDV III – The next generation of acousto-optical landmine detection

Volker Klein* [a], Marcus Hebel [b], Manfred Resch [c]

[a] Kayser-Threde GmbH, Wolfratshauser Straße 48, D-81379 München, Germany
Volker.Klein@kayser-threde.de

[b] FGAN-FOM Research Institute for Optronics and Pattern Recognition, Gutleuthausstraße 1, D-76275 Ettlingen, Germany
hebel@fom.fgan.de

[c] MRglobal, Birkenweg 14, D-82110 Germering, Germany
info@mrglobal.de

ABSTRACT

A new generation of **S**canning **L**aser **D**oppler **V**ibrometer (SLDV) has been realized; based on experience and results of a former proof-of-concept design and a number of field tests. This new device SLDV III comprises a number of technical improvements in the transmitter and receiver section as well as in the evaluation of the recorded vibration signals. The subsequent paper summarizes the main features of this instrument.

Keywords: Acoustic landmine detection, laser vibrometry, SLDV, phase analysis

1. SLDV BASICS

SLDV is an acousto-optical measurement technique for stand-off investigation of buried objects, such as landmines. In the past it could be shown that the SLDV technique is basically capable to detect buried objects due to their influence on a sound field, emitted and recorded by the SLDV sensor. A Scanning Laser Doppler Vibrometer is the combination of a strong acoustic transmitter and a sensitive laser based optical receiver.

The acoustic transmitter (e.g. a loudspeaker or sound transducer) emits its acoustic energy towards the ground and as these sound waves hit the ground, a small portion of this acoustic energy is coupled into the soil and propagates into the ground. The physical mechanisms describing sound propagation through soil have been studied extensively and have been published in numerous scientific articles, e.g. [2] and [5].

During SLDV investigations, the acoustical transmitter emits a powerful sound spectrum towards the area to be investigated. The composition of this sound spectrum is determined by the spectral data that will be used during the sounding. Typical values cover the spectrum from about 50 Hz through 500 Hz. Future developments may compress this spectral range. The SLDV instrument investigates the surface of the ground from a typical distance of some 100 cm (may vary due to operational constrains). Like done by a camera the soil surface is investigated in a 2-dimensional pattern. The SLDV sensor is equipped with an eye safe HeNe laser, operating at 633 nm which probes the vibration of the soil surface and a bore sight CCD camera for visual referencing.

* Volker.Klein@kayser-threde.de

The SLDV system is based on an optical technique; similar to the well known *Heterodyning*, used in nearly all RF-receivers. The original laser beam is split into two sections, a sounding beam that is directed onto the soil and an internal reference beam. Fig. 1 illustrates this optical detection scheme.

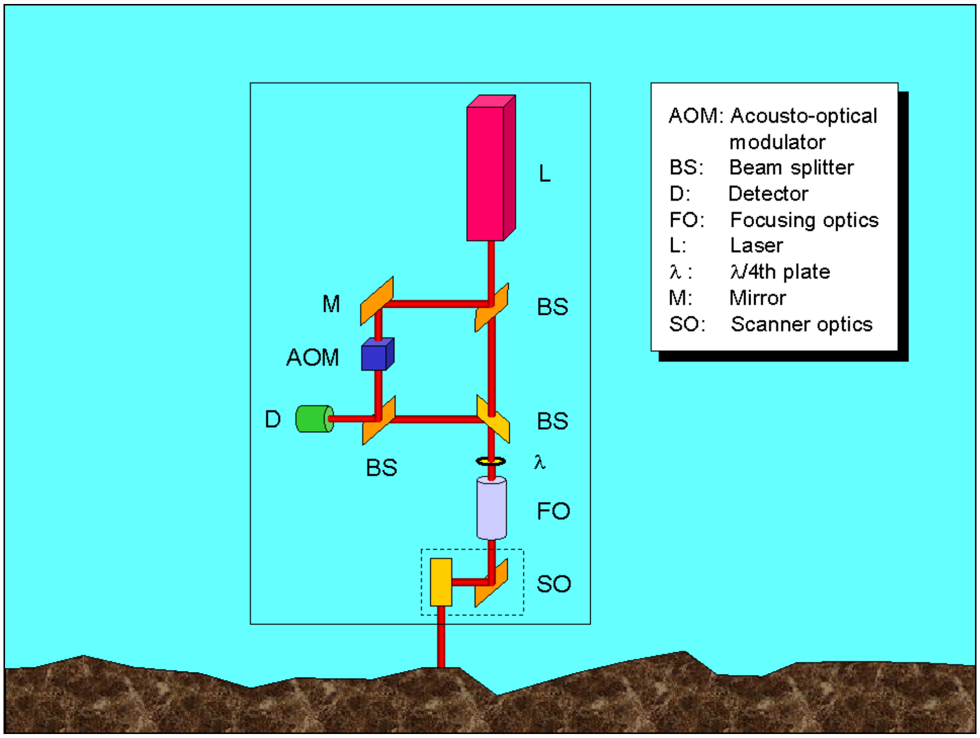


Figure 1: Optical schematics of the SLDV system

The emitted sound is coupled into the soil (acoustic-to-seismic – or A/S coupling) and propagates through its upper layers by means of its internal porosity. These propagating sound waves are called Biot type II waves in contrast to type I waves that are dominantly propagating due to the porosity of the soil. A thorough presentation of the theoretical background for A/S coupling is given in [2].

Biot type II waves are subject to enhanced attenuation, compared to type I waves. Solid objects within their way will scatter these waves. If a buried object (e.g. a mine) is present, part of the propagating wave is scattered back to the surface, generating an object shaped area of increased vibration intensity. It is this enhanced vibration intensity that is picked up and analyzed by the sensor to determine the location of a buried mine. Further spectral analysis of this enhanced vibration pattern provides additional valuable information to distinguish harmless clutter objects from potentially lethal ones.

A fraction of the emitted laser beam is scattered back by the vibrating soil surface and is superimposed on the detector with the internal reference beam, generating an electric beat (or heterodyne) signal (see Fig. 1). This electric signal comprises an additive and a subtractive component, however only the latter one is used for the subsequent data processing. A low pass filter extracts this transformed vibration signal. Subsequent filtering and amplification prepares this signal for the frequency analysis which is carried out by means of a FFT (Fast Fourier Transformation) operation. The result is a survey of signal contributions as a function of frequency within the emitted acoustical sound spectrum.

2. SLDV III HARDWARE

SLDV III is based on a strict modular design concept, comprising only two units - connected by a single umbilical cable for power supply, system control and data transfer. The sensor head includes the transmitter stage with the three sound transducers and the optical receiver with the laser vibrometer, a two-axes scanner unit as well as a CCD bore sight camera (Fig. 2). The control unit includes a ruggedised industrial PC for system control and data handling. A custom made S/P-DIF data acquisition board with a high-speed bus to the PC is directly connected to the output of the vibrometer. System control and visualization of results is performed via a TFT display. SLDV III operates from a standard DC power line, accepting 16 Volts through 36 Volts.

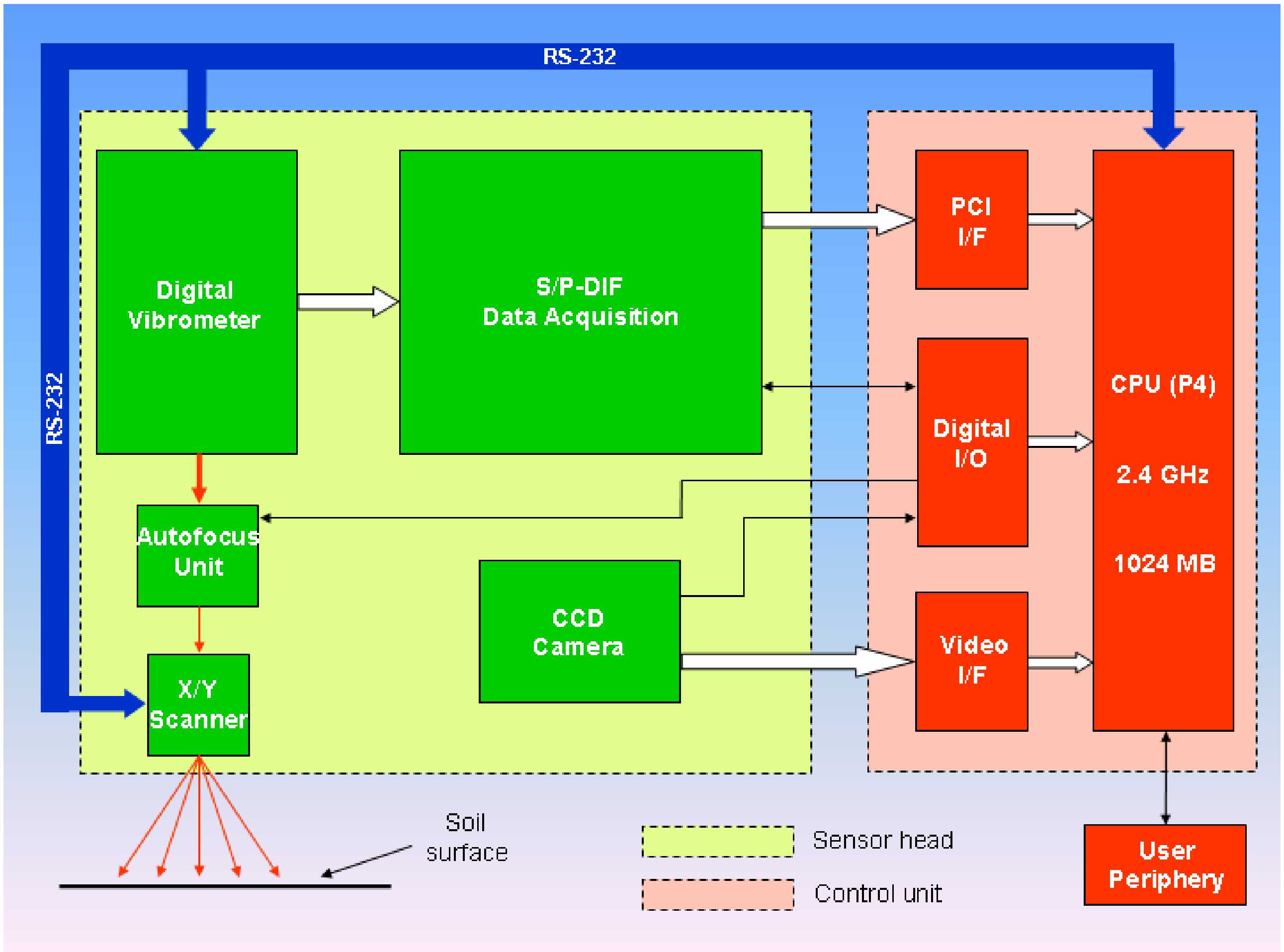


Figure 2: SLDV III block diagram

2.1. Mechanical Structure

A solid mechanical interface is used to mount the instrument on stationary test rigs or vehicles for mobile outdoor evaluation. This base plate is mechanically decoupled from external structures via spring loaded guide tubes and two hydraulic shock absorbers.

The vibrometer and all optical subsystems, like CCD camera, scanner and autofocus unit are mounted in a solid housing, milled out of a solid block of aluminum (Fig. 3). This housing is mounted via shock absorbers into an outer shell, also made from solid aluminum. Finally this outer shell is mounted via another set of shock absorbers to the above mentioned base plate. All shock absorbers are specifically selected for their spectral transfer functions and resonance frequencies.

This approach ensures undisturbed operation of the sensitive vibrometer head in its direct vicinity of the powerful sound transducers. The laser beam and the CCD camera share a double AR-coated window, which is mechanically decoupled from the outer housing by a multilayer foam structure (Fig. 4).

Figure 3: SLDV III sensor head during field trials, depicting the central housing and the three sound transducers.

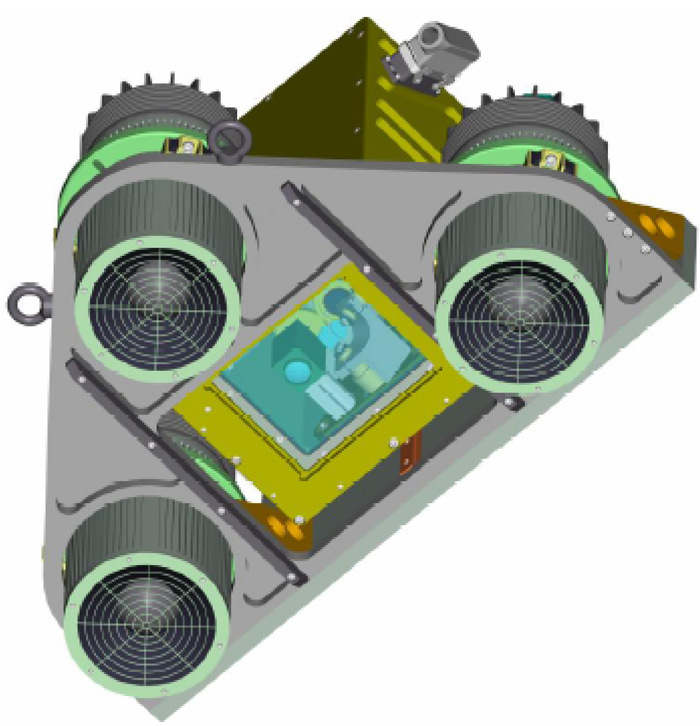


Figure 4: Window for the CCD camera and the laser

2.2. Digital Vibrometer

SLDV III is equipped with a new generation of digital vibrometers. The main difference to the previously operated instrument is that the new unit is free of calibration errors. This advantage has been achieved by the so-called *Early Digitizing* method. Conventional vibrometers convert the optical information (heterodyne signal) with their signal and reference detectors and amplify and filter the resulting RF signal prior to digitization. This approach is based on hardware filter banks and other analogue electronic modules. Since even high quality analogue electronics may show temperature induced sensitivity shifts or signs of aging, periodic recalibration of these vibrometers is a must.

In comparison, *Early Digitizing* is free of signal deviations, since the detector signal is directly converted into numerical data by means of high speed ADC modules, excluding any analogue filters or mixers. This approach is a solid improvement towards field applicability of laser vibrometry. SLDV III operates in real time mode, achieving the extreme high speed resolution of only 50 nm/s. Full speed range is 0.5 m/s, offering a dynamic range of 7 decades. The vibrometer electronics converts the detector signals in different formats. Output data are available in analogue form (for control purposes) and in digital form for the S/P-DIF interface (see section 2.6).

Besides the regular data output line the new vibrometer is equipped with an RS-232 interface for bi-directional information exchange, including numerical data about soil albedo and inside temperature. The front optics of the vibrometer comprises a photo lens with variable focal length in order to focus the laser beam onto the soil surface.

2.3. Laser Beam Autofocus Unit

As briefly explained before, SLDV III performs a 2D surface scan of the soil surface beneath the sensor head. This means that the laser beam has to be deflected from its central orientation normal to the soil surface towards angles up to 30°. As a result of this sounding geometry the distance between the laser to the soil surface varies according to the deflection angles. In order to compensate for this disturbing effect the bore sight CCD camera feeds its distance information to the system control unit, which calculates the actual distance between the laser and the soil surface as a function of the deflection angles. As a result the laser beam is kept focused onto the soil surface for all measurement points across the investigated area.

2.4. Two-Axes Scanner

The above sections already indicated the need to steer the laser beam of the vibrometer across two perpendicular axes in order to cover a two-dimensional area on the ground. This optical scanning has to be performed in short time and in rapid sequences in order to increase overall system performance.

The laser beam, exiting the autofocus optics of the vibrometer is directed on a set of two mirrors; each driven by a high speed coil actuator. An internal closed-loop sensing system optimizes acceleration and deceleration, hence increasing overall rotational speed and suppressing disturbing post oscillations after reaching a new mirror orientation. The drive system results in a step response time of <400 µs and a bandwidth of >2000 Hz. Active thermal control ensures constant accuracy, independent from ambient conditions. The scanners are operated through a dedicated interface card which is initially loaded with macro commands via its RS-232 interface. This has to be done only once prior to any series of measurements. All subsequent scanner motions are exclusively initiated by trigger pulses through a separate channel.

2.5. Acoustic transmitter

The acoustic transmitter of SLDV III comprises 3 identical sound transducers, creating the intense acoustic signal on the soil surface. Each of these units is equipped with its own DC/DC converter and digital amplifier, feeding a custom made loudspeaker with a Kevlar/ aluminum membrane. These exotic materials had to be selected in order to cope with the enormous forces that are acting at the membrane surface.

The transducers are directly fed by the auxiliary power source, which may range from 16VDC through 36 VDC. The stabilized output of these units directly feeds the digital amplifiers. Besides their small size, the main advantage of these circuits compared to conventional analogue amplifiers is their high efficiency (>90%) and therefore low thermal power dissipation. Each of these amplifiers operates at 180 W output power. The acoustic signal is finally generated by three sound transducers, with the above mentioned Kevlar/Aluminum hybrid membrane of 190 mm diameter. Special Rare-Earth magnets provide the necessary magnetic flux for the coils. The surface of the membrane is covered by a laser cut stainless steel grid; acting as a reliable mechanical protection without disturbing the emitted sound waves. The acoustic transmitters are fed by an internal signal generator, generating a pre-set pseudo random signal, covering 50 Hz through 500 Hz with a selectable spectral resolution. This signal offers the advantage that all frequencies are emitted simultaneously. This set of three transducers generates a sound level, exceeding 108 dB at the soil surface (1 m distance). The spectral enhancements within the received signals are the main parameters to be analyzed during data evaluation. The cylinder shaped housing is a vibration free aluminum construction, covered by a top section with radial cooling ribs in order to dissipate the excess heat from the internal DC/DC converters and digital amplifiers.

2.6. Signal processing unit

Transfer of the vibrometer data to the signal processing unit is realized by a novel interface (S/P-DIF) – specifically designed for acoustic devices and instrumentation. This interface transfers the data in already digitized format with 48 kSamples/sec with a resolution of up to 24 Bits. S/P-DIF has the advantage that signal pre-processing is already performed within the vibrometer itself, where optimized hardware and software routines are implemented to increase overall data transfer speed. The S/P-DIF interface card performs a continuous frequency analysis of the incoming digital vibrometer signal; currently based on the well established FFT algorithm. Complete FFT data sets are transferred to the system control computer at a continuous rate of up 100 Hz; depending on the selected frequency range and resolution. Other signal analyzing algorithms, such as digital filters are also under investigation.

SLDV III uses two parallel digital channels (for signal acquisition and for reference purposes). In addition the interface card is equipped with a number of digital and analogue I/O channels used for system control, triggering and monitoring of housekeeping data, such as vibrometer temperature, soil albedo, level of auxiliary voltage supply, etc. These data are analyzed at individual rates.

2.7. Software for System Control, Data Acquisition and Evaluation

SLDV III is controlled by a ruggedized industrial PC. System software is based on National Instruments *LabView*®, a well recognized graphical programming environment. Dedicated monitor screens are used for system start-up (input of control parameters), soil investigations (search for mines) and graphical data output (location of potentially hazardous objects).

2.8. Summary of instrument data

The below Table 1 summarizes major SLDV III instrument data for reference.

System	
Mass:	130 kg
Height:	800 mm
Depth:	650 mm
Width:	950 mm
Laser autofocus	
Boresight CCD camera	
Power consumption:	<1 kW (16 Volts to36 Volts DC)
Vibrometer	
Laser:	HeNe laser, <1 mW @632.8 nm
Maximum sensitivity:	50 nm / sec
FFT data refresh rate:	50 Hz to 100 Hz (dependent on spectral resolution)
Acoustic transmitter	
Amplifier output power:	3 x 180 W
Sound level at soil surface:	>108 dB (1 m distance)
Signal:	User selectable; standard: pseudo random spectrum
Frequency range:	User selectable, standard: 50 Hz…500 Hz
Frequency resolution:	User selectable, standard: 5 Hz
Electric efficiency:	>90% (DC/DC converter and amplifier)

Table 1: SLDV III technical data

3. ANALYSIS OF SLDV DATA SETS

The approach to automatic SLDV data processing described in [3] has been tested with several new data sets in the last year and has been extended in various ways. In addition to the analysis of the spatially and spectrally resolved magnitude of soil vibration now the phase is investigated as a secondary information channel. By this we expect a verification of alarms received previously and an improvement of classification performance.

This section summarizes each step of the proposed method and shows the possibilities of automatic information collection by evaluation of an exemplary data set. The collected information will be available for classification purposes later on.

3.1. Vibration signatures

The SLDV instrument provides data sets describing the measured vibration of the soil surface as a function of position and frequency. Besides Doppler based sensing of the magnitude of the vibrational velocity of the ground surface, it is also possible to estimate the phase in relation to a reference signal which in our case is the loud speaker signal. Therefore the measured vibration $z(x,y,f)$ can be best represented by complex numbers within a three-dimensional data set. The first step in our data processing scheme is the calculation of absolute values. This generates maps of the spatially resolved vibration magnitude for each frequency band. It is also possible to represent the vibration phase at a fixed frequency f this way. In both cases we get a two-dimensional distribution of values which can be interpreted as a gray value image so that adapted methods for image processing and pattern recognition can be applied. Usually only the vibration magnitude is investigated; in this case objects buried in the ground are assumed to be found by looking for locally amplified surface vibration. The visualization of the vibration magnitude $|z(x,y,f)|$ at a fixed frequency f as a color-coded image may yield very good mine signatures if f is near the resonance frequency of the mine/soil system (Fig. 5a). Unfortunately other frequencies do not show this high contrast even if a landmine is present (Fig. 5b). Another severe problem is the possibility of false alarms: Frequently occurring inhomogenities of the soil consistency can cause vibration signatures which are very similar to those of landmines (Fig. 5c).

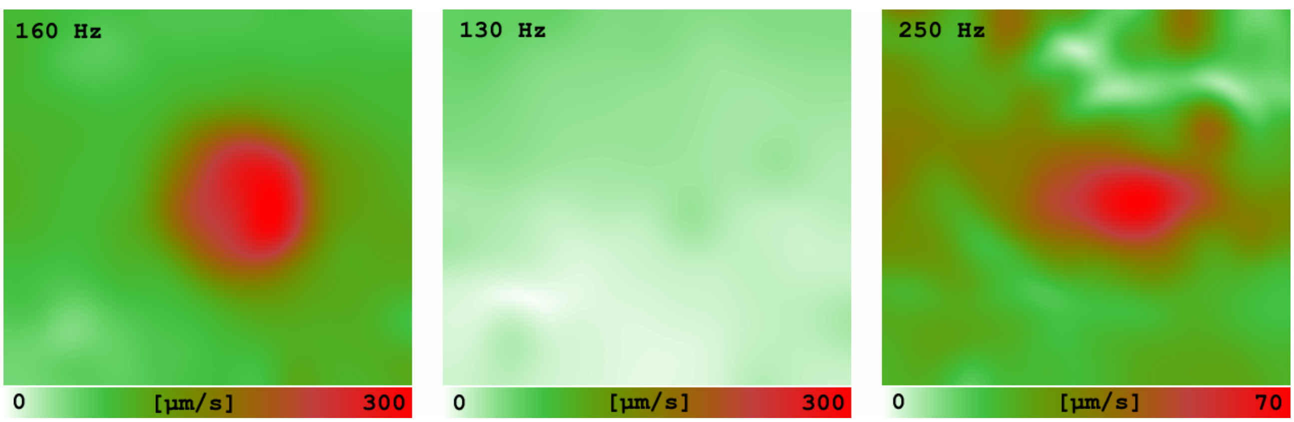


Figure 5: (a) Color map of the vibrational velocity in the frequency band between 160 Hz and 170 Hz with an APM buried 15 mm deep in sand, (b) same conditions, but in the frequency range 130-140 Hz. (c) Scanning result for sand with no buried object, 250-260 Hz. The color scales are given below each image.

The examples in Figure 5 show color maps which were achieved during measurements with a grid of 600 measuring points which cover a scanned area of 0.25 m² resulting in a resolution of 2 cm. Sound waves were generated in a pseudo-random way for the acoustic excitation of the soil in the frequency range between 40 Hz and 600 Hz in steps of 10 Hz. A discrete Fourier transform of the measured velocity of the ground surface at each grid point yielded complex data set entries $z(x,y,f)$. Basic preprocessing of the raw data was done by analyzing the change of vibration in the local neighborhood of each measuring point (Gaussian low-pass filter, median filter). Additional spatial smoothness of the data and a correction of geometrical distortions were achieved by bicubic interpolation.

A lot of examinations of this kind have been done in the past by J. M. Sabatier and N. Xiang. A detailed description of all the possible phenomena and typical acoustic signatures, measured on both anti-tank and anti-personnel landmines, can be found in [6] and [9]. A. Zagrai, D. Donskoy and A. Ekimov have analyzed the multi-modal resonance behavior of landmines experimentally and theoretically [10]. Their studies considered various factors influencing the resonance response, e.g. burial depth and soil moisture.

The examples depicted in Figure 5 show that some frequencies are suitable to detect a buried object while others are not. It is even possible that an alarm is given if absolutely no landmine or other object is present. To overcome this problem, it is necessary to develop a more automated data evaluation method. Sabatier and Xiang found landmine signatures to be broadband in nature [6]. If a buried object is present, there is a consistent amplification of the magnitude velocity over a relatively broad frequency range. The area of enhanced surface vibration remains regular and almost unchanged in its shape when stepping through adjacent frequency bands. Clutter does not show this kind of stability. So the automatic data evaluation should find such consistent areas of increased vibration magnitude in the spectrum. J. M. Keller, P. D. Gader, A. K. Hocaoglu et al. have suggested different aspects of an automatic data processing and classification method in [4], [7] and [8] which is quite similar to the FGAN-FOM approach: First the specification of local regions of interest for each frequency band, then the connection of these regions in the frequency domain resulting in three-dimensional structures and finally the extraction of characteristic features in order to distinguish between landmines and false alarms. Even though this is a straightforward approach, there still are various possibilities to realize the individual steps.

Besides evaluation of the vibration magnitude $|z(x,y,f)|$, we also use the phase information $\varphi(x,y,f)$ in our approach. A buried landmine or some other object often causes phase discontinuities of the surface vibration at the boundary of that object. Therefore the spatial distribution of the vibration phase in relation to the loud speaker signal can be useful as a additional information channel. This analysis may lead to a verification of previously detected mine clues. The inclusion of phase information into the algorithms has already been proposed in [3] and also by other authors [7], [8]. Given the complex number $z(x,y,f)$ that represents the soil vibration at frequency f and location (x,y), the phase angle $\varphi(x,y,f)$ can be computed by means of trigonometric calculations. The distribution of the phase at a fixed frequency f can be represented by a color coded 2D image in which the interval $[0, 2\pi]$ is mapped onto a suitable periodic color table. Some examples are depicted in Figure 6.

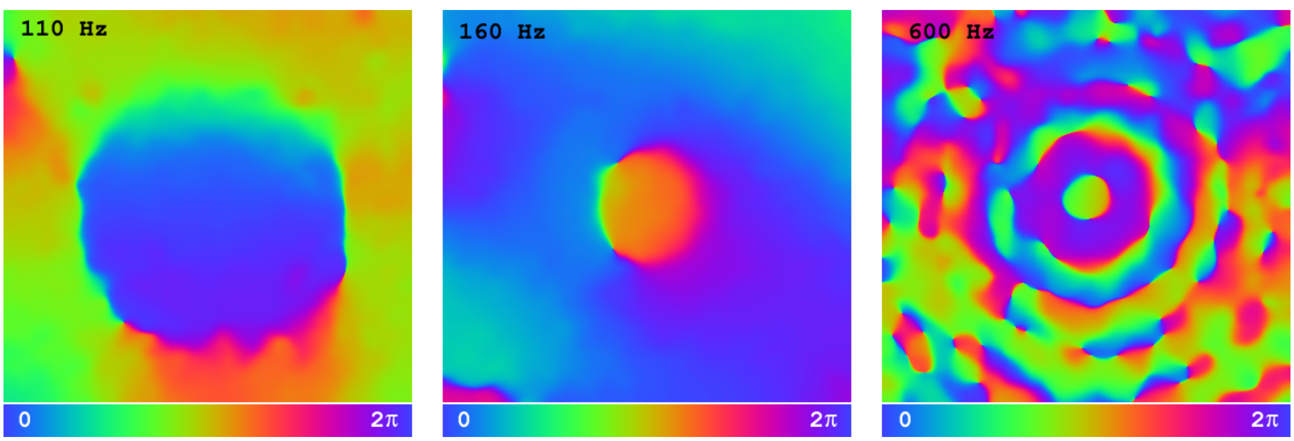


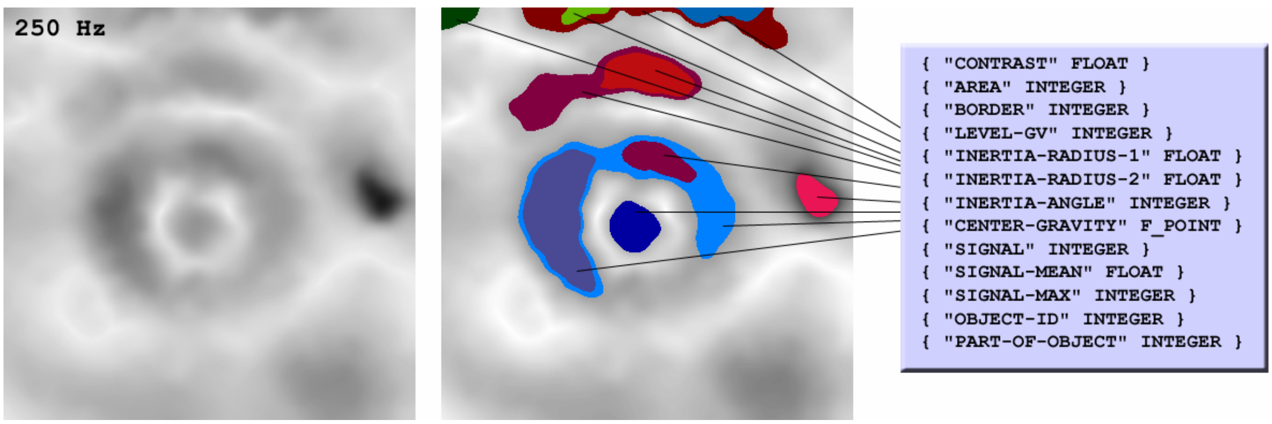
Figure 6: Phase signatures of an ATM (buried 3.5 cm deep in sand) at different frequencies (a) 110 Hz, (b) 160 Hz, (c) 600 Hz.

Regions with a homogeneous distribution of phase angles are clearly visible when the data is visualized with an appropriate color coding. It should be taken into account that phase angles $\varphi(x,y,f)$ are modulo 2π which means they don't have minimum or maximum values. Therefore simple threshold methods are not suitable for this kind of data. Instead we found the analysis of phase gradients to be a more promising approach to detect abrupt phase changes. Subsection 3.3 provides an overview of the algorithms used for the detection of phase edges and segmentation of line structures. A detailed description is given in [3].

3.2. Analysis of the magnitude information

The measured magnitude of surface vibration at a fixed frequency f can be represented by a gray value image as described before. Each pixel in this representation provides information about the vibration at a single measuring point. Sophisticated image processing methods can be applied to find regions of interest in each 2D-map of the vibrational velocity. We assume buried objects to cause an area with amplified surface vibration. Therefore a segmentation procedure can be used to subdivide each map into homogeneous regions corresponding to background or potential objects (i.e. mine clues). After this segmentation, the next step is the extraction of suitable features to characterize the objects.

For the SLDV data analysis in our approach the multi-threshold segmentation procedure *ISOL* is used. ISOL is an abbreviation for *"**I**mage **S**egmentation by **O**ptimization of Threshold **L**evels"* [1]. This method has been developed and implemented at FGAN-FOM and was adapted for the use with SLDV data. Multi-threshold gray-level slicing procedures are adequate tools for the segmentation of area-shaped objects. In principle, segmentation procedures of this kind consist of two main processing phases. In the course of the first phase, the gray value images are sliced at several thresholds, resulting in a large number of binary images. In the second phase, a selection process determines the result of the segmentation on the basis of these binary images. This is done by an optimization of the threshold levels with respect to area size and contrast. In the stack of binary images an object is represented not only once but several times as a series of regions with similar shapes and sizes. Within each series of corresponding regions, the region with the highest contrast is selected as a representative of an object. Besides computation of area size and contrast, several other features can be derived from the segmented objects, e.g. minimal and maximal magnitude, boundary length, perimeter, center of gravity, invariant moments and statistical features (Fig. 7).

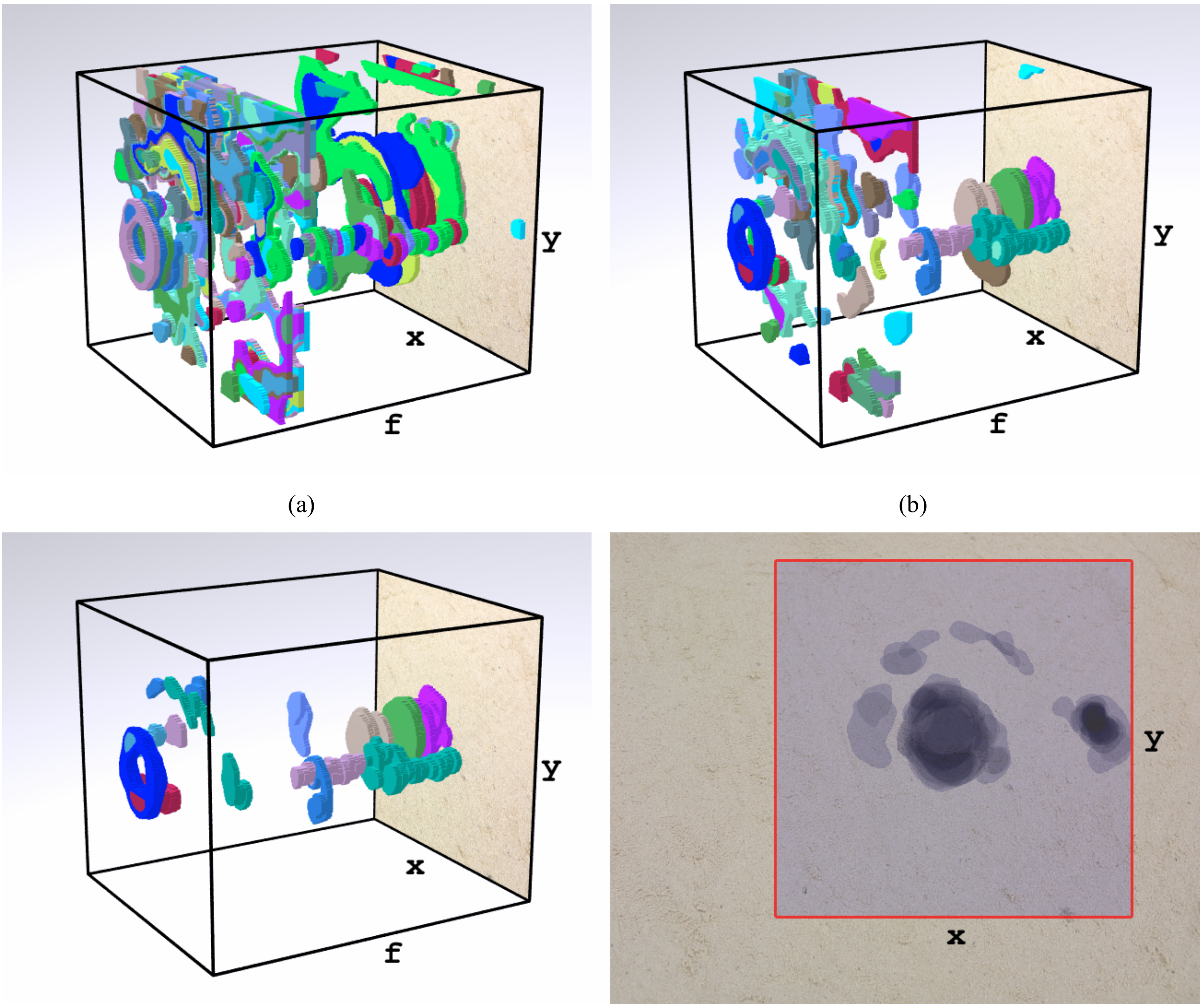


(a) (b) (c)

Figure 7: (a) Gray value representation of the vibrational velocity in the frequency band 250-260 Hz, (b) (Sub)objects detected by the segmentation procedure *ISOL*. (c) Characteristic features that were extracted for each region of increased velocity.

Then the segmented objects derived from different 2D-maps are fused to produce three-dimensional objects in the frequency domain and a symbolic description in terms of a feature vector. This process of connecting objects from frame to frame is an efficient technique for the elimination of false alarms caused by noise and short-term clutter. A buried object (e.g. a landmine) causes regions of increased vibration intensity that are visible over a broad frequency range, whereas clutter and noise don't show this kind of stability. Corresponding objects detected in different frames are connected by means of a *tracking* procedure. A search operation is involved to decide whether objects are to be connected or not. In the implemented tracking approach it is checked if objects in different frames have a meaningful relation to each other. The criteria for the selection of partner objects are the previously extracted features. If a partner object is determined, it is either associated to an existing track or a new track is generated. Based on track analysis, more features can be obtained to describe the resulting three-dimensional objects (e.g. track length or number of gaps).

Figure 8 shows the process described above by investigating an exemplary data set. For this experiment, two different types of landmines were buried under sand within the same grid of 600 measuring points. The first one is an anti-tank mine with a diameter of 30 cm that was buried in 35 mm depth whereas the second one is an anti-personnel mine. APMs are often placed near ATMs to protect these against manual demining. This scenario is also well suited for testing the automatic SLDV data evaluation because of the completely different landmine characteristics. The anti-personnel landmine which was used during the experiments had a diameter of 8 cm and was placed in a distance of 3 cm to the ATM in a depth of 8 mm. Due to their special properties, the vibration signatures of the two landmines occur at different frequencies in the spectrum. The multi-threshold segmentation procedure ISOL is applied independently for each frequency band resulting in a lot of false alarms (Fig. 7, Fig. 8a). However, these can be reduced by the formation of object tracks in the frequency domain (Fig. 8b) and by the analysis of stability-properties like track length (Fig. 8b). In the last step, the 2D maps of the remaining tracks were added up along the spectrum to achieve a two-dimensional histogram representation which then was overlaid with a picture of the scanned ground surface. Note: Figure 8d is an intermediate result of the automated data analysis so there was no need to manually select a special frequency.



(a) (b) (c) (d)

Figure 8: Analysis of the magnitude information: (a) Results of the segmentation procedure ISOL shown in a 3D frequency-space cube, (b) tracking result, (c) reduction of false alarms, (d) scanned ground surface overlaid with a histogram representation of the results.

3.3. Analysis of the phase information

In addition to the data processing described in subsection 3.2, the spatial distribution of the vibration phase in relation to the loud speaker signal can be useful as a secondary information channel. As mentioned earlier, the analysis of this phase information may lead to a verification of previously detected mine clues. The phase angle φ of a given complex number $z(x,y,f)$ representing the soil vibration at frequency f and location (x,y) corresponds to the counterclockwise angle starting from the positive real axis. Since phase angles don't show minimum or maximum values, threshold segmentation is not suitable for this kind of data. Because of this problem, analysis of phase gradients seems to be a more promising approach. Our method uses a discrete convolution to estimate the components of the phase gradient which then are converted to the interval [$-\pi$, π]. After that a simple threshold operation is used in order to find large absolute values of the phase gradient. This operation produces a binary image in which one-valued pixels are potential edge pixels of areas corresponding to objects vibrating out of phase. The edge detection is done by line thinning and edge tracking [3]. During this operations the edge length and edge strength are also determined to get valuable features for subsequent filter operations. Edge detection typically increases the noise level; therefore combining the gradient computation with a Gaussian smoothing can yield better results. The next step is the analysis of these binary edge representations. Obviously, closed contours are of interest and circles in particular. Circles can be detected by an extended Hough transform with a three-dimensional accumulator (radius, location of the center). Figure 9 shows the results of this procedure for a fixed frequency (160 Hz).

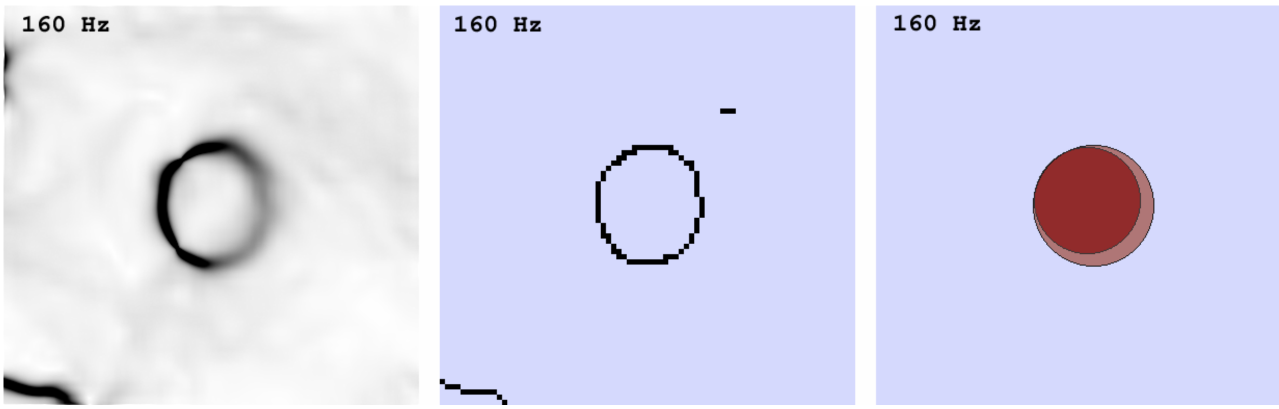


Figure 9: (a) Spatial distribution of the phase gradient at 160 Hz, see also Fig. 6b, (b) detected edges, (c) circles found by an extended Hough transform.

Further steps of our method cover the search for stabilities of these contours in the frequency domain, similar to the analysis of the vibration magnitude. The fusion of the symbolic results of magnitude analysis as well as phase analysis will be part of future investigations. However, a simple combination of the individual results in a single coordinate system is already possible. Figure 10a shows the outcome of both magnitude and phase evaluation in different colors. Moreover, the stack of binary maps can be added up again to a histogram representation as depicted in Fig. 10b.

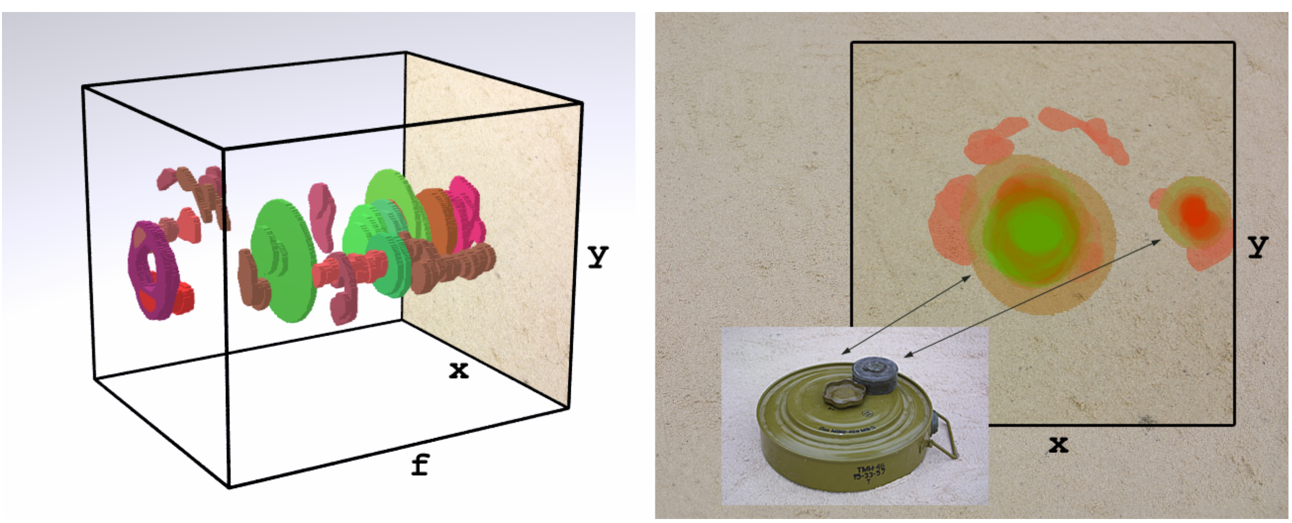


Figure 10: (a) Remaining mine clues after investigation of the magnitude (red) and phase information (green) in a (x,y,f) coordinate system, (b) scanned ground surface overlaid with a histogram representation of all results together with a picture of the buried objects.

4. CONCLUSIONS AND OUTLOOK

With the latest platform SLDV III, acoustic landmine detection has reached a new level of system development. A ruggedized instrument is now available for the development and optimization of improved algorithms for signal evaluation. Recent field trials unveiled clear limitations in sounding speed due to the use of the FFT algorithm. The speed of this algorithm is mainly limited to the resolution and not the absolute values of the frequencies under investigation.

Thus, one of the main tasks for future software development will be devoted to the development and implication of rapid real time frequency analyzers in order to increase the overall instrument sounding speed (investigated area per time interval).

REFERENCES

1. C. Anderer, U. Thönnessen, M. F. Carlsohn, A. Klonz, *Ein Bildsegmentierer für die echtzeitnahe Verarbeitung*, 11. DAGM-Symposium, Proceedings, 380-384 (1989).
2. K. Attenborough, *Acoustical Models and Measurements Treating the Ground as a Rigid Porous Medium*, Detection and Remediation Technologies for Mines and Minelike Targets V, Proceedings of SPIE 4038, 610-620 (2000).
3. M. Hebel, K.-H. Bers, V. Klein, *Model-based Mine Verification with Scanning Laser Doppler Vibrometry Data*, Proceedings of SPIE 5415, 80-90 (2004).
4. J. M. Keller, Z. Cheng, P. D. Gader, A. K. Hocaoglu, *Fourier descriptor features for acoustic landmine detection*, Proceedings of SPIE 4742, 673-684 (2002).
5. J.M. Sabatier, N. Xiang, *Laser-Doppler Based Acoustic-to-Seismic Detection of Buried Mines*, Detection and Remediation Technologies for Mines and Minelike Targets IV, Proceedings of SPIE 3710, 215-222 (1999).
6. J. M. Sabatier, N. Xiang, *An Investigation of a System That Uses Acoustic-to-Seismic Coupling to Detect Buried Anti-Tank Landmines*, IEEE Transactions on Geoscience and Remote Sensing, Vol. 39, No. 6, 1146-1154 (2001).
7. T. Wang, J. M. Keller, P. D. Gader, G. X. Ritter, A. K. Hocaoglu, M. S. Schmalz, *Model-based landmine detection algorithms for acoustic/seismic data*, Proceedings of the SPIE 5089, 558-568 (2003).
8. T. Wang, J. M. Keller, P. D. Gader, A. K. Hocaoglu, *Phase signatures in acoustic-seismic landmine detection*, Proceedings of SPIE 5415, 70-79 (2004).
9. N. Xiang, J. M. Sabatier, *An experimental study on anti-personnel landmine detection using acoustic-to-seismic coupling*, Journal of the Acoustical Society of America, 113(3), 1333-1341 (2003).
10. A. N. Zagrai, D. M. Donskoy, A. E. Ekimov, *Resonance vibrations of buried landmines*, Proceedings of SPIE 5415, 21-29 (2004).

ACKNOWLEDGEMENTS

This work was financed by the Federal Office of Defense Technology and Procurement (BWB), Germany.