DETECTION OF BURIED OBJECTS: THE MUD PROJECT

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Abstract: *The aim of the Mine Underwater Detection (MUD) project at TNO is to experimentally investigate the acoustic and magnetic detection of explosives underwater, buried in a soft sediment layer. This problem is relevant for the protection of harbors and littoral assets against terrorist attacks and for the detection of underwater unexploded ordnance (UXO). The present article focuses on the acoustic part of the project. An experimental system, referred to as 'MUD system', has been developed for the purpose. The design and development of this vessel-deployed system focuses on modularity in order to be able to test different system configurations (tilt angle, depth, bandwidth etc.). The system has been tested in a trial conducted in close collaboration with the Royal Netherlands Navy (RNLN). The trial was situated in the Haringvliet, an estuary in the Netherlands with water depth up to 20 m. The trial results include comparison of sidescan and Synthetic Aperture Sonar (SAS) images for different configurations of the MUD system, a study of the detection performance and a comparison of the MUD system with detections done by a REMUS Autonomous Underwater Vehicle (AUV), equipped with a high frequency sonar. The results show that all the trial test objects have been detected by both systems, suggesting that the objects were not completely buried. A firm conclusion on the possibility to detect explosives buried in a mud layer can therefore not be drawn at this stage, although several features in the examined data indicate that this is the case. A new trial incorporating the knowledge acquired in the MUD project will be performed in 2011 using an upgraded version of the MUD system.*

Keywords: *buried target, unexploded ordnance, detection*

1. INTRODUCTION

For practical and economical reasons, harbours around the world are for a large majority located at the delta of rivers. The harbour of Rotterdam (The Netherlands) for instance is located at the delta of the Rhine. Rivers carry sediment along their course and for the Rhine “About half of the sediment from the Rhine that reaches Rotterdam settles in the port. The remainder flows directly with the river into the North Sea.” [1]. In this soft sediment layer, located in the vicinity of the delta of the river, objects laying on the seabed can be relatively quickly buried or revealed depending on the sediment streams. In these particular locations with a thin soft sediment layer, it is important to be able to detect buried objects in order to assess a possible hidden threat such as UXOs, Improvised Explosive Devices (IEDs) or other hazardous material.

TNO was tasked by the Netherlands Ministry of Defence (NL MoD) to demonstrate a capability of detecting objects buried in soft sediments. An adapted TNO experimental low frequency side scan sonar system was used for that purpose and deployed in a suitable area together with the SEA SPY magnetic gradiometer system that TNO acquired from Marine Magnetics Inc. For the sake of brevity, this article will further only focus on the acoustical part of the MUD system.

The acoustical part of the TNO MUD system and the trial area are presented in section 2. A selection of results is presented in section 3 before a summary of the work achieved in section 4. Remarks about the MUD 2 trial, planned for April 2011, are also made.

2. MUD TRIAL SETUP

2.1. The MUD system

The acoustical part of the MUD system consists of a low-frequency (LF) sidescan sonar. Low-frequencies are necessary to penetrate into the mud layer, but the use of low-frequencies implies low resolution and poor signal-to-reverberation ratios. This is a delicate balance and to find the optimal frequencies and pulses is one of the aims of the project. To improve the signal-to-reverberation ratio at low frequencies by enhancement of the resolution, SAS processing is added to the LF sidescan sonar. Therefore this part of the MUD system is referred to as the LF-SAS system in the remainder of this document.

The MUD system is an experimental system developed for research purposes. Therefore, the system is designed to be flexible so that different setup parameters can be varied (frequency, tilt angle and operational depth for instance). The wet end of the LF-SAS system is composed of (See Fig.1):

- Two acoustical sources covering (not simultaneously) a frequency bandwidth of 5 kHz (from 4 kHz up to 9 kHz) for the LF source and 15 kHz (from 11 kHz up to 26 kHz) for the HF source.
- Two receiving arrays composed of 16 hydrophones each mounted in front of a sheet of absorbing material.
- A frame supporting these components. The depth and tilt angle of the frame can be adjusted prior to its mounting along the side of a ship.

The dry end of the LF-SAS system is composed of the necessary hardware and software allowing the control of the sources and the acoustical data acquisition. It also includes two navigation sensors: a high resolution Real Time Kinematic (RTK) GPS and a Motion Reference Unit (MRU). The latter is mounted together with a GPS antenna on top of the support frame (see "navigation support" in Fig.1). These two navigation sensors are necessary to obtain an accurate measure of the platform motion and hydrophone positions in time. The data from these sensors are necessary inputs for the SAS processing.

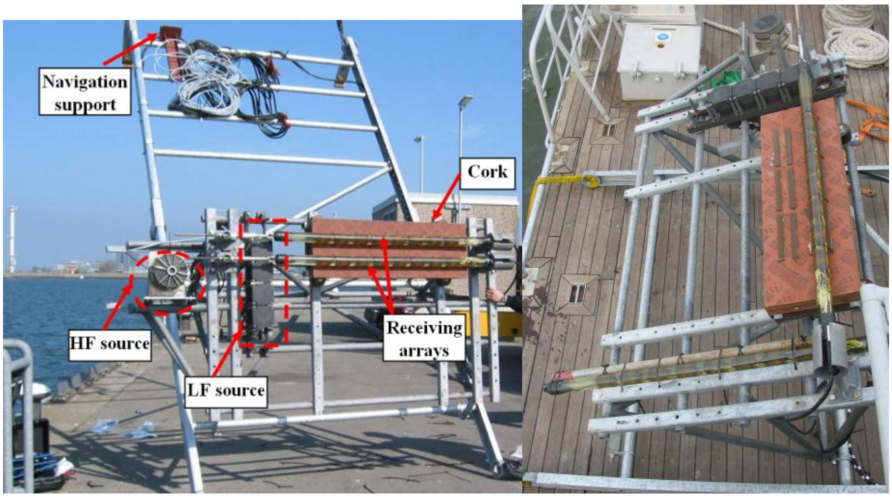

Fig.1: Left hand side: Picture of the MUD LF-SAS system wet end composed of two acoustical sources (LF and HF), two receiving arrays, a sheet of absorbing material (Cork) mounted on a support frame. Right hand side: MUD LF-SAS system on the deck of the support vessel NAUTILUS, the lower receiving array is mounted vertically.

2.2. Trial location and setup

The Haringvliet is an old access to the North Sea, closed in 1970 by the Haringvliet-dam (Fig.2, left hand side). Its water is therefore mostly fresh water and the location independent of tide and sea streams. This location was chosen for the presence of a mud layer on the bottom. The mud layer thickness was estimated to be about 1 m in the selected area.

The trial took place from Monday 11th to Wednesday 13th May 2009. A selection of test objects was deployed in this area: two sand-filled cylinders and one boulder buried in the mud, two (calibrated) spherical objects and one air-filled barrel were placed with anchors above the mud layer as references. The air-filled barrel unfortunately imploded due to the hydrostatic pressure, most likely during its installation. It could therefore not be further used as a reference in the trial. The buried objects were installed several weeks prior to the trial to make sure they would be well buried and to avoid artefacts from the digging (sediments in suspension, bubbles). At the exception of the barrel, the test objects have been placed on a line with a spacing of about 15 m (see Fig.2 right hand side for the exact setup). Considering the installation time, recovery time and the test of the magnetic sensor, the time constraints on the acquisition of all the different LF-SAS system setup parameters was challenging.

A selection of four parameters has been varied during the one week trial: the tilt angle of the LF-SAS system, the closest point of approach to the test objects, the objects aspect angle and the frequency band. A ‘run’ is defined for this trial as a track along or across the test objects line, a selection of four GPS tracks corresponding to four runs, two along and two across the test objects line, is given as illustration in Fig.2 on the right hand side.

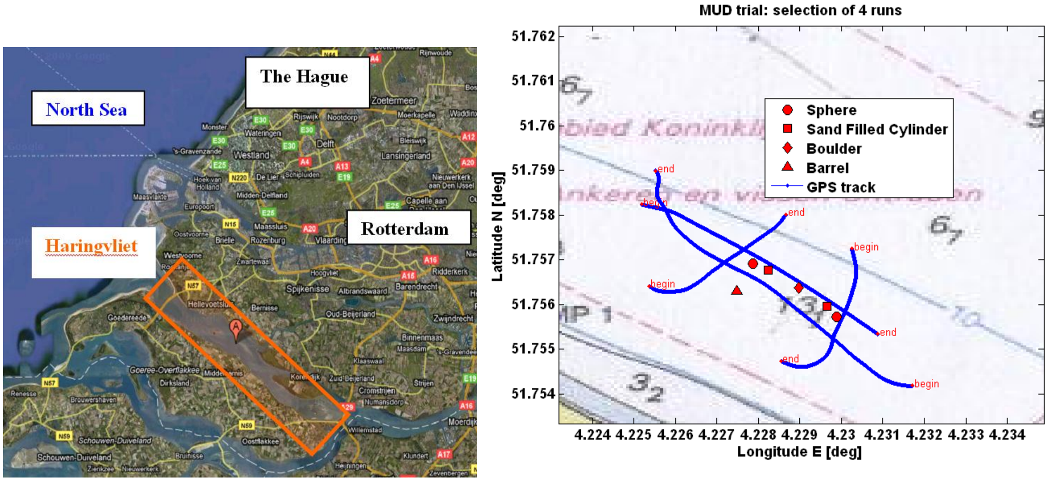

Fig.2: Left hand side: MUD trial location: the haringvliet (orange box) is located close to Rotterdam and The Hague in the Netherlands. Right hand side: latitude/longitude position of the MUD trial test objects in the test area (red circles for the two calibrated spheres, red squares for the two sand-filled cylinders, red diamond for the boulder and red triangle for the air-filled barrel). The GPS track corresponding to four runs of the MUD trial are plotted in blue.

3. PROCESSING AND RESULTS

3.1. Processing

The acoustical data processing was entirely developed at TNO. Two main processing packages are to be distinguished: The so-called “online processing suite”, designed as to be used for monitoring the data acquisition in real time during the trial and the so-called “offline processing suite”, designed for the post trial data analysis.

The primary role of the online processing suite is to ensure that both the quality of the acquired acoustical and non acoustical data meets the trial specifications (the GPS quality should always be RTK for instance). Its secondary role is to help monitor the different trial runs in real time and to provide feedback for possible modifications of the trial run plan (reschedule a run if the data quality is not sufficient for instance). The online processing suite consists of a graphical user interface showing the acquired acoustical and non acoustical data (composed of time series, sidescan and frequency spectrum) and a real time geographic information system displaying the positions of both the platform and the test objects.

The offline processing suite is then used to precondition all the acquired data and to analyze these with more advanced signal processing and imaging techniques such as SAS for instance. The preconditioning of the data involves equalisation, match filtering of the acoustical data, a decoding and synchronisation of the navigation systems on the acoustical data timing. This synchronisation is made possible with an analogue recording of the navigation frames. The RTK-GPS and the MRU are used as inputs for the motion compensation necessary for the SAS imaging. An example of processing outputs is provided in Fig.3: sidescan output on the left hand side and corresponding SAS output on the right hand side.

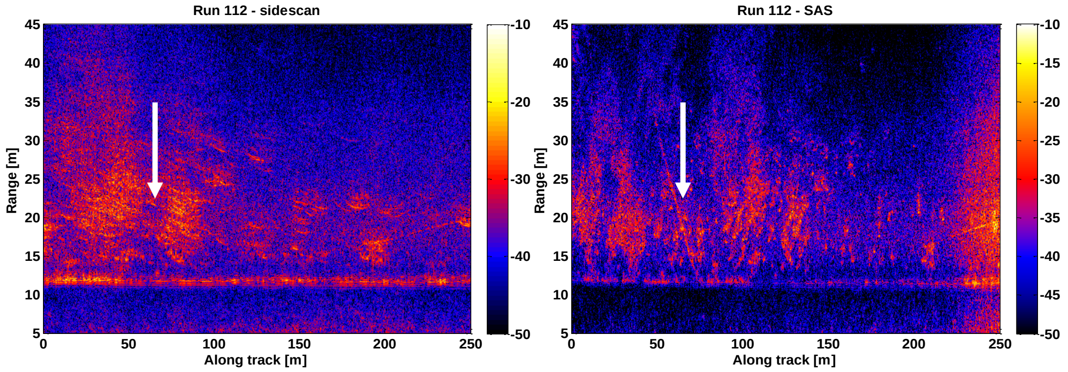

Fig.3: Example of a sidescan (left hand side) and a SAS (right hand side) output for one MUD run (limited to a 250 m length along track). The horizontal axis represents the along track in meters the vertical axis the slant range in meters. Energy in dB normalized to the maximum in the image. At the white arrow location a line structure appears on the SAS image.

The sidescan and SAS pictures examples provided in Fig.3 are representative of the MUD runs. The first few meters in slant range are dominated by the direct path from the source (LF source in this example) to the receivers and direct scattering from the water surface (the LF-SAS frame is mounted just two meters below the water surface). The bottom is visible at a range of about 12 meters, and starting from this range, bottom structures and echoes are visible. The displayed energy is normalised to the maximum found in the run after discarding the first 5 meters to avoid any direct path contribution from the sources. Note in Fig.3 that the run has been cropped to its first 250 meters and that the maximum is not present in this part of the run. As expected, the scatterers in the sidescan images have the shape of hyperbolae corresponding to the range of the contact to the LF-SAS system passing along them. In the SAS images, enhancing the along-track resolution, these hyperbolae are focused to points. In fig.3, for instance, a line structure is clearly visible at the location of the white arrow after SAS processing.

3.2. Results

A qualitative comparison of the runs acquired with different parameter settings during the MUD trial has been performed during the post trial data analysis. The variations of the LF-SAS system tilt angle and the frequency bands used or the aspect angle to the contact objects have carefully been compared. Furthermore, a REMUS 100 AUV equipped with a 900 kHz sidescan sonar from the RNLN has surveyed the test area during the trial. A comparison of the contacts from the REMUS with the contacts from the LF-SAS system has been performed. A summary of the main results is given in this section.

Results of comparable runs with a tilt angle of 45 degrees and 60 degrees, defined as the angle between the horizontal and the LF-SAS system, have been analyzed. Contacts were observed for each tested tilt angle. The signal to reverberation ratio and detection ranges of the different contacts were dependent on the tilt angle. This was expected since the tilt angle directly influences the sonar footprint and grazing angles. It is difficult to further evaluate the gain of the one compared with the other, since more runs and hence more statistics would be necessary in order to achieve this.

Results of comparable runs with the LF and the HF sources of the LF-SAS system have been analyzed. It appears that approximately twice as many contacts are found with the LF source compared to the HF source. Since the penetration in the sediment is frequency dependent and lower frequencies are bound to be less attenuated than higher ones, this suggests that these extra contacts are buried deeper.

Results of comparable runs with different aspect angles on the test objects have been analyzed. It was in particular noticed that a small slope is present in the test area, the measures from up- or down- slope looking runs give different performances linked with the associated footprints and grazing angles.

On the last day of the trial, the lowest receiving array, originally placed horizontally (see Fig.1), was mounted vertically on the side of the LF-SAS system frame. This configuration is useful for identifying multipaths and for identifying the vertical angle of the received echoes. It is then possible to filter the vertical contributions in the processing and to select only those coming from specific angles [2-4]. As an illustration, Fig.4 presents a comparison of two sidescans produced using the horizontal array (left hand side) and the vertical array (right hand side). In the very shallow environment of the MUD trial, the gain in signal to reverberation is clearly visible. A cable-like contact, for instance, is visible throughout the entire track in the vertical sidescan (white arrows in Fig. 4, right hand side).

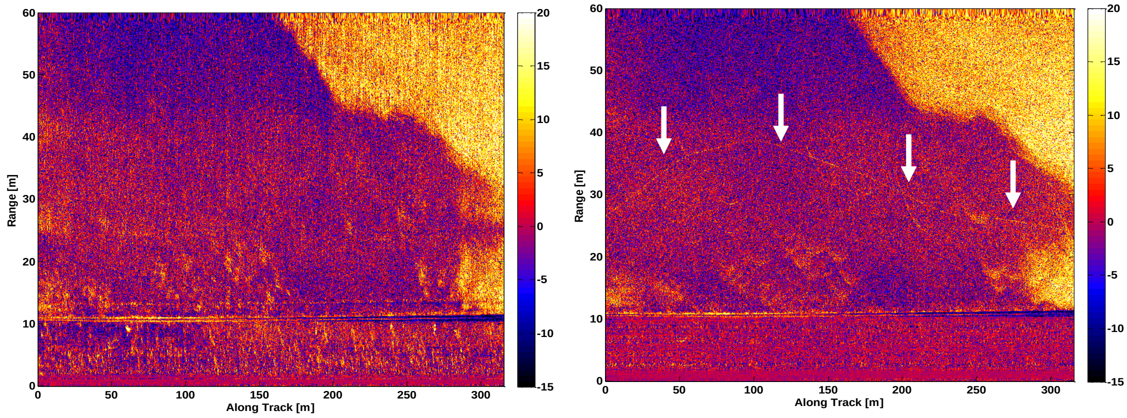

Fig.4: Sidescan produced using the horizontal line array on the left hand side and sidescan produced using the vertical line array on the right hand side. The horizontal axes correspond to the along-track distance in meters and the vertical axes to the slant range in meters. Both images are normalized along slant range by mean of a median filter.

A comparison of the REMUS detections with the LF-SAS detections has been performed. The LF-SAS detections have been identified on sidescan images of every run by two TNO scientists. These contacts have then been clustered and the resulting areas imaged with SAS. A selection of SAS outputs is presented in Fig.5. The REMUS detections are automatically saved as positions and snippets (zoom on the sidescan around the considered detection). Nevertheless, and in order to obtain a comparable procedure, a third person went trough the REMUS data as well. Examples of REMUS contacts for all the MUD bottom test objects are given in Fig.6.

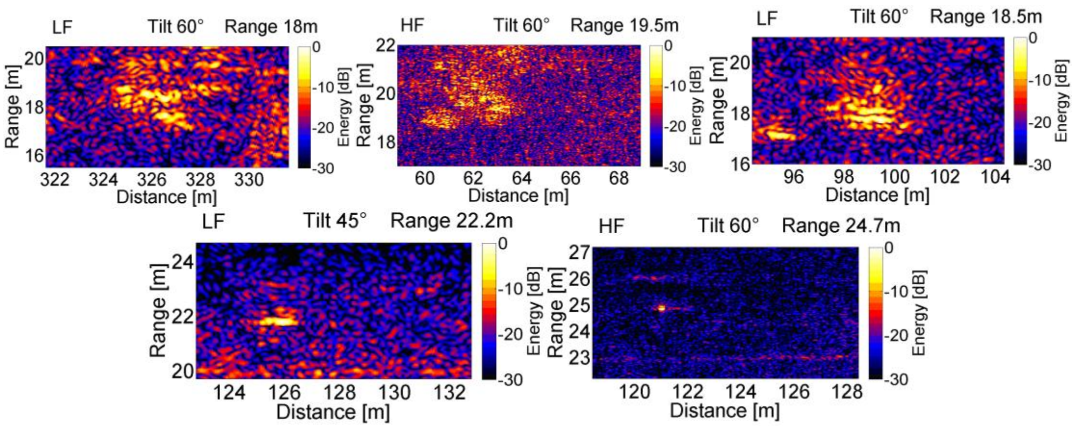

Fig.5: SAS outputs corresponding to the three test objects laid on the bottom. From left to right and top to bottom: first sand-filled cylinder imaged with the LF source, first sand-filled cylinder imaged with the HF source, second sand-filled cylinder imaged with the LF source, boulder imaged with the LF source, boulder imaged with the HF source. The horizontal axes correspond to the along-track distance in meters, the vertical axes to the slant range in meters and the colour represents the acoustical energy in decibels normalized to the maximum of each snippet.

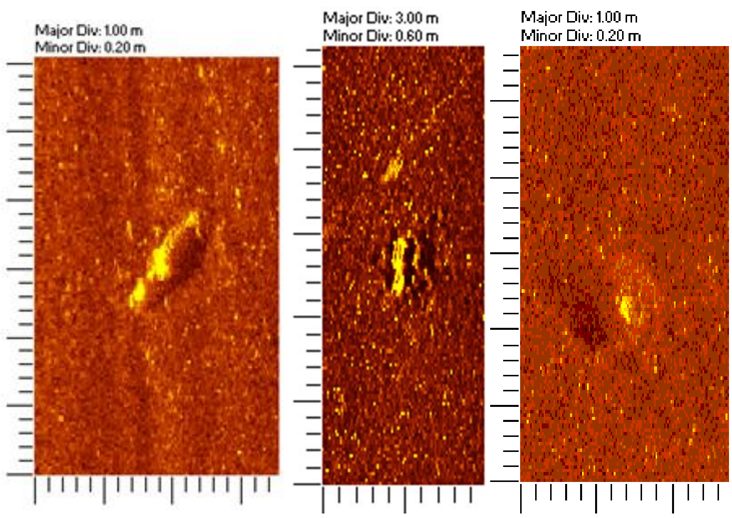

Fig.6: REMUS snippets corresponding to the bottom test objects of the MUD trial. From left to right: Two sand-filled cylinders and a boulder. The horizontal axes correspond to the along-track distance in meters, the vertical axes to the slant range in meters.

It is clear from Fig.6 that all the test objects used for MUD are visible and detected by the REMUS AUV. A theoretical study has further shown that the frequency used by the REMUS AUV would not penetrate the sediment in the MUD trial configuration [5]. This shows that the MUD objects are then most likely not entirely buried.

4. SUMMARY AND WAY AHEAD

The main objective of the MUD trial was to demonstrate detection capabilities of objects in mud by deploying an adapted system in a suitable area. The MUD system was designed and built for this purpose; a trial was planned and successfully conducted in the Haringvliet area. A large collection of data (88 runs) has been collected during this trial and analyzed.

All the test objects placed in the test area have been detected by both the LF and HF sources of the LFSAS system. These objects have also been detected by a REMUS AUV equipped with a high frequency sidescan sonar, which suggests that the detected objects are most probably not entirely buried. Nevertheless, extra unknown contacts have also been detected by the MUD LF-SAS system, and these were not detected by the REMUS AUV. This suggests that these contacts are most probably buried in the mud layer.

A definitive conclusion can not be drawn at this stage. For this reason, the MUD 2 trial is planned in April 2011 in the same area, in order to further assess the detection capabilities of the system in soft sediment.

The MUD 2 trial is a repetition of the MUD trial with several updates based on the knowledge built during the first trial: 20 tests objects are placed in the trial area up to 6 months prior to the trial. This allows for the soft sediment to settle back after having been disturbed by the burial. A special attention is given to their burial in the mud layer. The trial period has been extended from three days to five days. The LF-SAS system has been updated as well. In the wet end, one receiving array is placed permanently vertically, the absorption sheet has been extended, and an extra very low frequency source is available as well. For the dry end, the navigation systems and processing suites have also been updated.

5. ACKNOWLEDGEMENTS

This work has been carried out in a project on behalf of NL MoD. The MUD trial would not have been possible without the acoustical source kindly lent by the Direction Générale de l'Armement (France). The MUD trial would also not have been possible without the skilled technicians of the sonar department of TNO: Wim Groen, Mark van Spellen and Jeroen Janmaat. The crew of the RNLN dive support vessel NAUTILUS is also thanked for their help and collaboration.

REFERENCES

[1] **Port of Rotterdam Authority**, "Sediment management: towards a clean port", *Fact brochure*, 2005.

[2] **A. Tesei, A. Maguer, W.L.J. Fox, R. Lim, H. Schmidt**, "Measurements and modeling of acoustic scatteringfrom partially and completely buried spherical shells," *J. Acoust. Soc. Am.* 112, 1817 – 1830 (2002)

[3] **A. Tesei, M. Zampolli, G. Canepa**, "At-sea measurements of acoustic-elastic scattering by a 1.5m-long cylinder made of composite materials," *Proc. 2nd UAM Conf.*, Heraklion, Greece (2007).

[4] **K.L. Williams, S.G. Kargl, E.I. Thorsos, D.S. Burnett, J.L. Lopes, M. Zampolli, P.L. Marston**, "Acoustic scattering from a solid aluminum cylinder in contact with a sand sediment: Measurements, modeling, and interpretation," *J. Acoust. Soc. Am.* 127, 3356 – 3371 (2010).

[5] **B.A.J. Quesson, S.P. Beerens, M. Zampolli, M.A. Ainslie.**, Detection of buried objects: theoretical and experimental aspects, *TNO report*, TNO-DV 2010 A308, 2010