# Easily deployable underwater sensor nodes – the NILUS MK 2 demonstrator system

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## Abstract

Easily deployable underwater sensor nodes and communication networks provide a promising concept for future naval operations. Experimental systems such as the NILUS (Networked Intelligent Underwater Sensors) demonstrator system have provided useful experience with the concept. The newly developed NILUS MK 2 augments the sensor and processing capabilities of NILUS, and adds a flexible software modem option. We present example results from sea trials which have proven good performance of NILUS MK 2, and its suitability for experimenting with and obtaining higher insight into the concept. The key operational benefit will be to retain presence in a sea area while the supporting ships can go elsewhere and perform other operations.

## 1. Introduction

As modern navies have limited numbers of vessels and large areas to cover, standoff operations provide the potential to more efficiently being present and obtaining situational awareness. Standoff naval operations make use of unmanned sensor platforms. They therefore benefit from versatile and robust networked communications concepts that can accommodate static as well as mobile nodes. Furthermore, such operations utilize smart on-board processing of the data collected by the platform sensors.

The Norwegian Defence Research Establishment (FFI) has been developing the NILUS (Networked Intelligent Underwater Sensors) sensor concept since 2008. NILUS are networked autonomous nodes with acoustic and magnetic sensors, that can be easily dropped from a vessel of any size (rubber boat or bigger) onto the seafloor where they can remain on station for an extended duration. Once deployed, they can run signal processing algorithms and report detections through an acoustic communication link. Based on the experience built up with NILUS, FFI developed the improved NILUS MK 2 system. Within a bilateral cooperation between Norway (FFI) and The Netherlands (Defence Materiel Organisation, DMO, and Organisation for Applied Research, TNO), a robust acoustic communication link in the form of a software-defined modem and associated network layer were developed and integrated with NILUS MK 2. This cooperation is a relevant example of technology partly obtained in previous projects, nationally in Dutch-Norwegian defence research projects and in the EDA (European Defence Agency) project RACUN (Robust Acoustic Communication in Underwater Networks), being applied in high technology readiness level systems for specific operational applications.

This paper presents results of this cooperation and experience obtained so far with NILUS MK 2. It also discusses potential operational applications, such as choke point barriers and standoff operations.

## 2. The NILUS MK 2 system

Starting from 2008, FFI developed the NILUS system to demonstrate and evaluate the concept of easily deployable underwater sensor networks. The system consisted of four seafloor sensor nodes and a gateway buoy, and was employed in numerous national and international sea trials. For underwater communication, NILUS MK 1 mostly used Teledyne Benthos modems with Seaweb [1] firmware. Some of the experiences obtained with the NILUS system up to 2012 are summarized in [2]. The NILUS system was extensively used in international collaborations such as the NGAS JRP (Next Generation Autonomous Systems Joint Research Project) [3] and the EDA project RACUN [4].

Advances in processor technology, and lessons learnt from NILUS MK 1, led to the development of NILUS MK 2 from 2014. There was also a desire to use NILUS as a platform for developing and testing new underwater communication technology in-house, and hence the Dutch-Norwegian software-defined modem was developed as an optional replacement for the Teledyne Benthos modems.

### 2.1. Sensor node

The NILUS MK 2 sensor node is a man-portable tripod platform, shown in Figure 1. Its mechanical design is not much changed since NILUS MK 1. The two white containers house batteries and electronics for data acquisition, processing, timekeeping, and communication. Four low-noise hydrophones are forming a tetrahedral array; three alongside the legs and one on the top of the tripod inside a protective cage. A tri-axial fluxgate magnetometer provides for magnetic target detection. The on-board processing unit processes the acoustic and magnetic sensor data to automatically detect passing targets, and report information extracted from the data to the operator through the acoustic modem.

Figure 1 NILUS MK 2 sensor node (left), with transmit unit for software-defined modem (right). From [5].

The sensor node is easily deployed, by simply throwing it over board from a vessel of any size (from rubber boats to large ships). It always lands on its feet due to the weight distribution: A heavy battery container underneath, and a modem float pulling upwards at the top. When an operation is ended, the node is brought back to the surface by instructing it through the acoustic link to open a valve. This causes an inflatable lift bag to be filled with compressed air from a diving bottle.

## 2.2. Software-defined modem

### *2.2.1. Software*

The modem software consists of a physical layer and a network layer [5] (next to an application layer and medium-access control). The physical layer consists of a state-of-the-art spread spectrum modulation-demodulation scheme developed jointly by TNO and FFI. This modulation [6] (Frequency-Repetition Spread Spectrum, FRSS) makes use of redundant frequency bands to achieve low bit error rates even in adverse conditions.

The network layer is programmed in the MIRACLE/DESERT Underwater framework under NS2. This makes it possible to use exactly the same software for the network protocol stack in network simulations and at sea. We use the flooding-based network protocol “Dflood” developed at FFI in the RACUN project [7], [8]. Both the network layer and the physical layer are implemented in C++.

### *2.2.2. Hardware*

The software-defined modem hardware is designed to take advantage of the latest developments in portable consumer electronics in terms of power consumption, computer power and flexibility. It was therefore implemented on an ARM-processor-based System on Module (SOM) [5]. Such technology is commonly found in tablets and smartphones. A dedicated transmitter unit for the 4–8 kHz band was designed and built at TNO. The receiving chain of the modem makes use of the NILUS hydrophones.

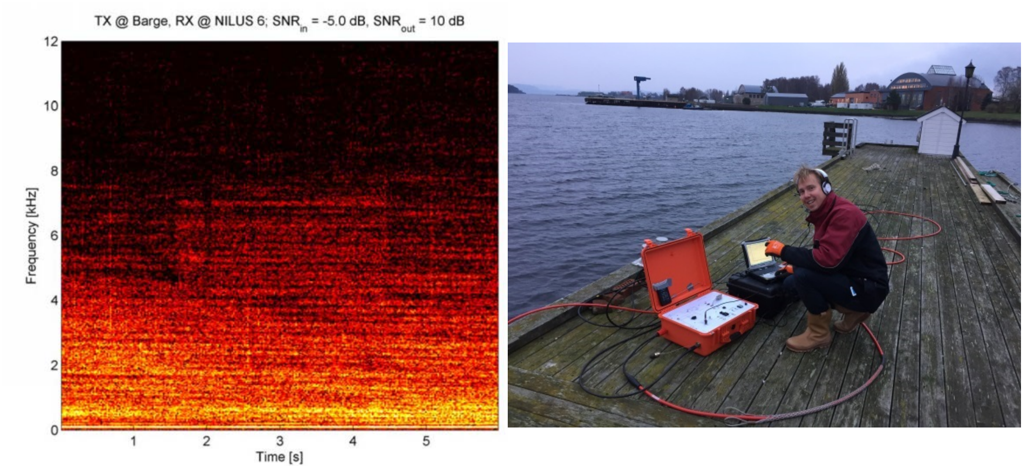



**Figure 2 Left: Spectrogram of a successfully (error-free) demodulated modem transmission received during a ship passage. Right: Deck unit of the NILUS software-defined modem.**

A deck unit was also developed. It is connected to its own modem transmitter and allows communication with the underwater nodes.

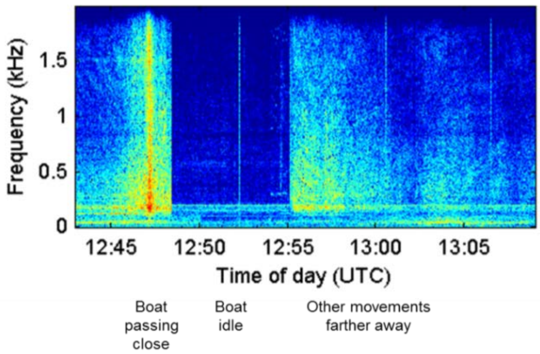
# 3. NILUS MK 2 experiences

The NILUS MK 2 system has been tested in two joint Dutch-Norwegian sea trials in November 2014 and April 2015, and also in national sea trials in the two countries. In this section, we summarize experiences obtained this far with NILUS MK 2.

## 3.1. Sensor performance

The recorded acoustic sensor data has proved to be of high quality, much better than with NILUS MK 1. The improvements are due to better hydrophones with built-in preamplifiers, being mounted farther away from other electronics and air-filled containers. Also, the maximum sampling rate and the distance between hydrophones have been increased.

The on-board signal processing of sensor data is implemented in the GStreamer framework, as described in [9]. Algorithms for automatic target detection and bearing estimation from NILUS MK 1 were ported into this framework. Figure 3 illustrates acoustic sensor data and signal processing performance during the very first sea trial with NILUS MK 2.



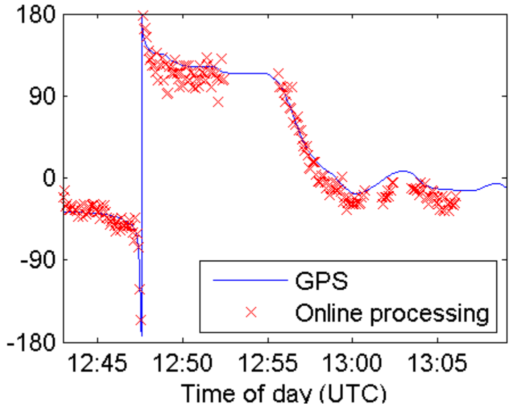




**Figure 3 Illustrations of acoustic sensor data and signal processing in November 2014 sea trials, from [9]. Left: Spectrogram of top hydrophone. Right: Bearing estimates computed inside the node while it was deployed.**

We have experienced that the modularity of the GStreamer framework, and the increased processing capacity compared to NILUS MK 1, make it easy to reconfigure and augment the signal processing capabilities of the node. For example, bearing estimation performance is already better than what Figure 3 suggests.

Figure 4 shows an example of magnetic sensor data collected with NILUS MK 2. Previously developed algorithms for automatic magnetic detection [10] were also implemented in the GStreamer framework, and are working as expected in NILUS MK 2. The resulting automatic detection of a passing ship is marked by a purple cross in Figure 4.

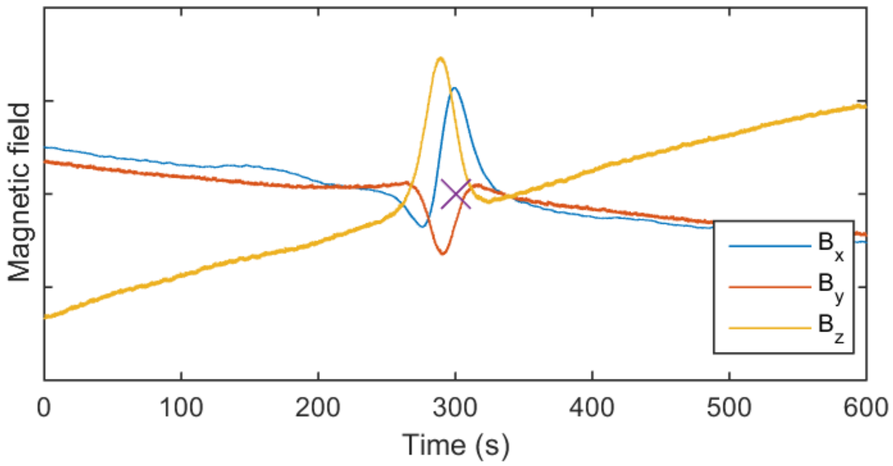



**Figure 4 Example of magnetic data collected during April 2015 sea trials, while a ship passed the NILUS MK 2 sensor node. The purple cross indicates the time at which the passing tug was automatically detected by the node.**

The sensor node records acoustic and magnetic sensor data to SD card or USB memory stick, so they can be used for detailed evaluation of algorithm performance and development of new algorithms. The signal processing framework running inside the node can also be run on a PC platform to test implementations of new algorithms.

### 3.2. Communication performance

Already in the first experiment with NILUS MK 2 in November 2014, the communication system performance was found to be satisfactory [5]. This was confirmed by a national Dutch trial in March 2015 in the shallow Haringvliet river, where a packet delivery ratio of about 0.95 was achieved in a 4-node network with an average internode distance of about 3 km. Both experiments featured direct line of sight between all nodes.

After these initial trials, the system was again tested in the Horten area in April 2015. One of the scenarios tested was a relay connection between the inner harbor of Horten and the Oslo Fjord, see Figure 5. The network featured long-range point-to-point connections in deep water with direct line of sight (e.g., F–G), whereas hopping was needed for large ranges in shallow water without direct line of sight (e.g., C–F, up to 3 hops). Without relay nodes C and D, the nodes in the harbor would have been disconnected from the nodes in the fjord. On the network-layer level, the PDR was 1.0 between all NILUS nodes and the base station, achieved through the retransmission scheme of the applied NET protocol. The modem source level was more than sufficient for the longest link in the network (F–G, 2.4 km) and the point-to-point communication range was mainly limited by acoustic shadowing and delay-Doppler spreading, especially in the very shallow sections of the network area. This nicely illustrates the usefulness of multihop networks with alternative routes to the destination.

Another experiment showed that the unique hardware and software design of the modem allowed error-free communications at ranges in excess of 5 nmi.

National Norwegian experiments with NILUS MK 2 have successfully used the Teledyne Benthos modems as in NILUS MK 1, instead of the software modem. Thanks to a modular system design, replacing one communication option with another is straightforward. These experiments are not described further here.

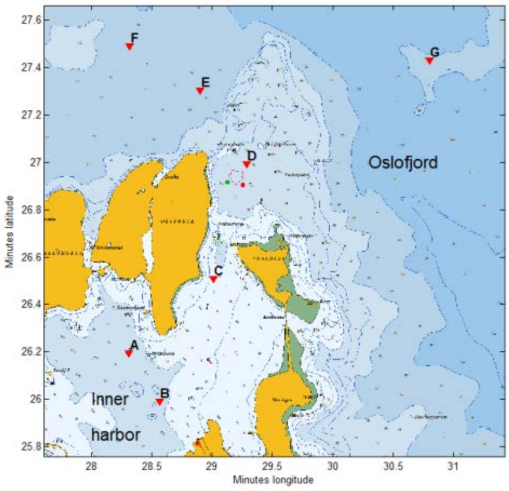



**Figure 5 Map of Horten harbor and Oslofjord (mosaic of TELchart/C-Map screenshots) with NILUS modem positions indicated (A-G).**

## 4. Potential operational applications

The NILUS MK 2 system allows for experimentation with the future concept of easily deployable underwater sensor and communication networks. The key operational benefit of this concept will be to retain presence in a sea area while the naval ships can go elsewhere and perform other operations. Communication with the nodes can happen through a surface buoy, or directly from a supporting ship if it stays within acoustic communication range.

As an example, a barrier of NILUS nodes can be deployed across a natural choke point, and report back to the operator information on what passes through the choke points in either direction. The NILUS nodes can be deployed as the operation starts, but can also be deployed days or weeks before in preparation of operations, and kept on standby in a low-power mode.

Additionally, thanks to their long-range communication capabilities, the NILUS nodes can extend the communication range of mobile nodes with more limited communication means, such as Autonomous Underwater Vehicles. This might facilitate longer range standoff operations for mine counter measures and other applications, as illustrated in Figure 6.

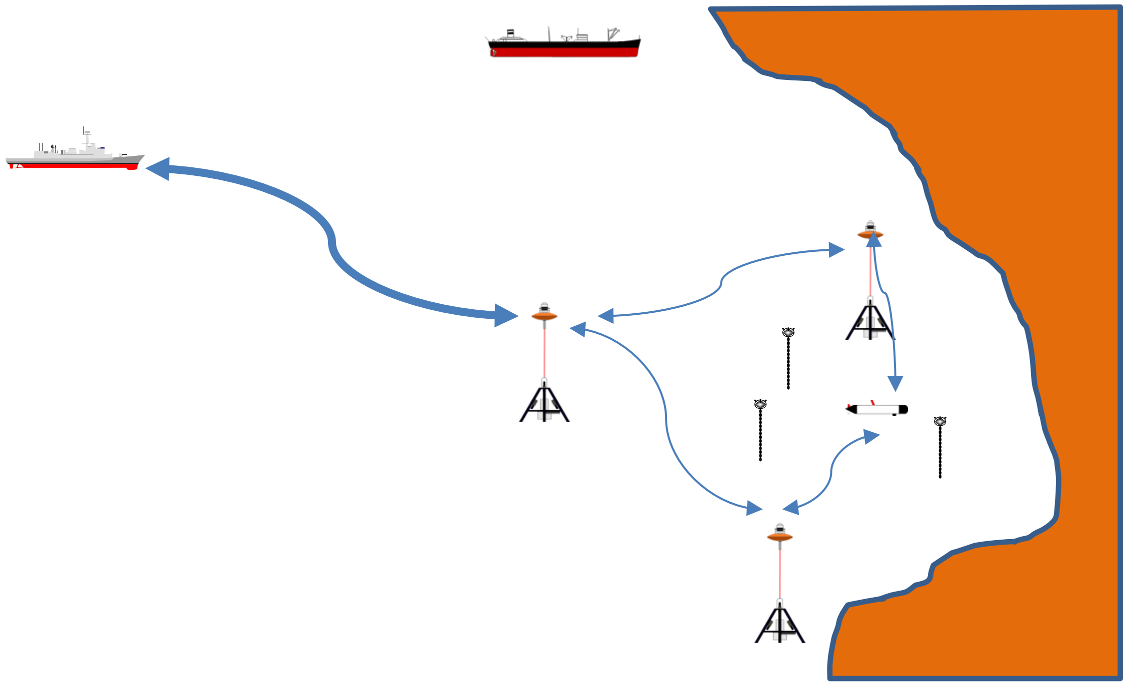


Figure 6 Example of a standoff mine countermeasure scenario in which NILUS support long-range communication.

## 5. Conclusions

The successful sea trials with the NILUS MK 2 bottom nodes, including the software-defined modems, show that this new version of NILUS provides high-quality acoustic and magnetic sensor data and has sufficient computational resources to perform advanced on-board signal processing. Also, it shows that generic (open) architectures can be applied to underwater acoustic modems, while still meeting (semi) operational requirements in terms of processing power, size and endurance.

It is found that the NILUS MK 2 system is suitable to experiment with and obtain higher insight into deployable underwater sensor and communication networks. The key operational benefit of this concept will be to retain presence in a sea area, relieving naval ships to go elsewhere and perform other operations.

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