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Instruments and Methods

A wideband connection to sperm whales: A fiber-optic, deep-sea hydrophone array

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Abstract

A 10-element, 950 m long, vertical hydrophone array based on fiber-optic data transmission has been developed primarily for studying the beam pattern from deep diving cetaceans emitting sonar pulses. The array elements have a configurable sampling rate and resolution with a maximum signal bandwidth of 90 kHz and a maximum dynamic range of 133 dB. The array has been deployed from a 14 m ketch with a crew of four. In the course of the development a number of mechanical and electrical problems have been solved.

Keywords: Hydrophones; Arrays; Fibre optics; Bioacoustics; Norway; Vesterålen; Andøy; Andenes; Bleik canyon; 69°N/15°E

1. Introduction

Hydrophone arrays were introduced to study cetaceans by Watkins and Schevill (1971a, b, 1977). They recorded various whale and dolphin species as well as sperm whales (Physeter macrocephalus) with a three-dimensional (3-D) four-element hydrophone array with an aperture of 30 m. The small aperture severely limited the possibility for localizing the animals at larger distances than a few hundred meters from the array.

Acoustic localization with arrays of larger aperture was introduced in underwater bioacoustics by Whitney (1968), Dunn (1969), Levenson (1974), Van Parijs et al. (1998), Janik et al. (2000), and Hayes et al. (2000). Møhl et al. (2001, 2003) used a 3-D array with a horizontal variable aperture of up to 2000 m. Their measurements showed that sperm whales emit a highly directional sonar beam, but the directivity could not be accurately determined because the narrow beam rarely hit more than one hydrophone at the same time. Even an on-axis 'hit' on one hydrophone was rare which may be explained by the hydrophones being near the surface while the sperm whales were operating their sonar at depth.

For better measures of the beam pattern of biosonar signals from sperm whales a deep-sea array with many closely spaced hydrophones is needed, which can be lowered to the depths where the whales feed to increase the likelihood that a sonar beam would directly hit a hydrophone. Sperm whales dive to depths exceeding 1000 m and emit

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very narrow-beam sonar signals with source levels up to 236 dB re 1 μPa (Møhl et al., 2003), therefore a wide dynamic range is needed. The spectral composition of the beam varies with the angle from the axis (Møhl et al., 2003), and the bandwidth surpasses 30 kHz (Watkins, 1980), so an array with a bandwidth of at least 45 kHz is needed. To our knowledge no hydrophone system for field work with the desired qualities is available. Initial attempts using copper cables for transmission were abandoned because of the expense and engineering problems.

The existence of fiber-optics suggested that an array could be constructed where the signal was digitized in the array element and transmitted to the surface platform digitally through fiber-optic cable. This would not only provide an appropriate but also a cost-effective technique. The bandwidth and dynamic range would be limited only by the analog-to-digital converter (ADC), and the aperture of the array would be limited only by the optical transceivers (which currently can communicate over 2000 m of fiber-optic cable). As fiber-optic cable is thin and lightweight, a large vessel is not required for array deployment. Fiber-optic arrays have previously been developed for bottom-mounted recorders (Kirkendall et al., 1997), but free-floating applications feasible for recordings of toothed whales are unknown to us. Here, we describe the design principles, mechanical properties, deployment gear, electronics, and software and show an example of a recording made with the array.

2. Overview

The array is configured as a vertical linear array. A linear array is insufficient for 3-D localization of animals, but with sufficient length it can give a 2-D localization with both direction and distance to the animal. Each array element consists of a housing (canister) containing electronics. A hydrophone is connected to the canister via a 1-m cable (Fig. 1). 500 m fiber-optic cable connects the upper canister with the vessel. The distance between two canisters is 50 m, so the bottom canister is 950 m below the vessel. This geometry was chosen to obtain detailed data on the beam pattern of sperm whales, giving a resolution of 2.8° for a whale located 1 km from the array. The optical fibers are brought individually into the canister via pressure-resistant lead-throughs. The fibers are connected to the electronics via two sets of optical transceivers, one for upwards

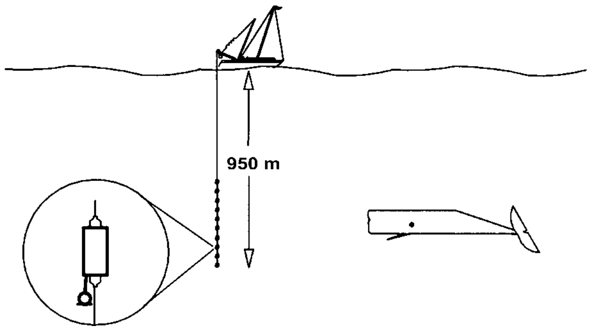

Fig. 1. The concept of the fiber-optic linked deep-sea hydrophone array. The enlarged section shows a canister with a hydrophone attached below it. Not drawn to scale.

and one for downwards data traffic. On the vessel the data are converted to a 16-bit, parallel data stream which is read by a PC and stored on a hard disk.

3. Cable

The cable is a DRAKA Comteq LD00 four-fiber cable reinforced with aramid yarns. One fiber carries the signals from the canisters to the PC on the vessel, and another fiber carries signals and commands from the PC to the canisters; the remaining two fibers are redundant. The nominal tensile strength of this cable is 2000 N, at which level no change in transmission properties occurs. We found experimentally that a tension above 5000 N was required to break the cable provided that there was proper termination of the aramid yarns at each end. A critical factor is the minimum bending radius of the cable of 20 mm. Sharp bends of the cable must be avoided. The mass of 1 km cable is 36 kg. In water the cable has almost neutral buoyancy.

4. Canisters

The pressure-resistant canisters are made from aluminum tubes with O.D. 150 mm, thickness 10 mm, and length 300 mm. Flanges of the same material with O-ring grooves are fastened to the cylinders with stainless steel screws. The cylinders are painted to protect against corrosion.

Waterproof fiber-optic cable connectors with sufficient tensile strength (5000 N) could not be obtained, and a design without connectors was adopted. Consequently, the canisters cannot be detached from the cable at sea, and therefore winching the array up and down is cumbersome.

On each flange a cable termination house is mounted. The main function of this is to transfer the tension from the cable to the canister. This is mediated by fanning out the aramid strands stabilized with an epoxy mould in an aluminum cup. This serves to divide the tension equally between the aramid strands. Such strands are almost inelastic, so if tension is unevenly distributed among the strands, the most stressed strands will break, one at a time, and ultimately the cable will break. The four optical fibers are individually led through the flanges via specially made lead-throughs (the so-called penetrators). The penetrators consist of a centrally drilled hex-nut compressing a cone-shaped Teflon fitting in the flange. MacArtney Subconn connectors were used to connect hydrophones and battery-packs to the canisters.

The canisters with penetrators passed tests in a pressure tank at 100 bar. The weight in water of the complete 10-canister array is about 100 N. To reduce slant a lead ballast of another 15 kg is added at the bottom of the array.

5. Crane and winch

An important consideration is to get the string of canisters and the cable over the rail of the vessel in a rough sea without breaking the glass fibers and tearing the cable. Appreciable dynamic forces because of wave and swell movements of the vessel are added to the static tension of the cable. A simple crane with one pulley is not sufficient. To reduce the dynamic forces in the cable it is necessary to hinge the crane at the base and to suspend it with a spring from the mast. The canisters cannot pass over a single pulley, so it was necessary to add a second pulley to lift the canisters over the first pulley. The crane can be seen in Figs. 2–6. The figures illustrate how a canister passes first one pulley then the next. All joints are flexible, so the crane can adapt if the cable does not go vertically down.

A hydraulically driven capstan pays the cable out or in with a speed of 1–3 m/s. When a canister needs to pass the capstan, the load of the cable is temporarily transferred to an auxiliary rope twined around the tensioned cable.

When on deck, the canisters are stored pair-wise in a set of cassettes with the cable wrapped around, more or less following the principles of a fixed-reel fishing wheel. The entire system is fitted on a 14-m ketch.

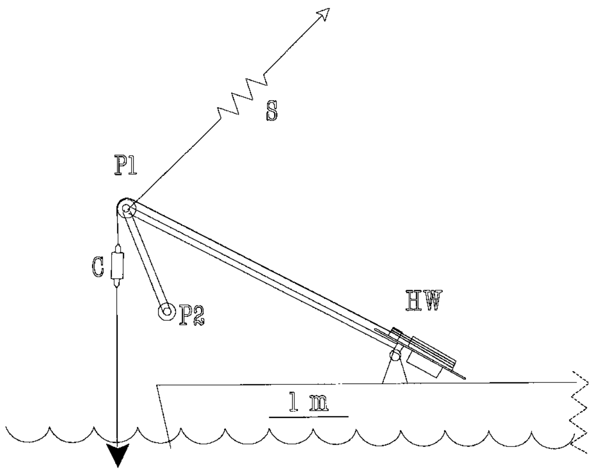

Fig. 2. The crane and the winch. The canister (C) on its way up is approaching the first pulley (P1). S = Spring. HW = hydraulic winch.

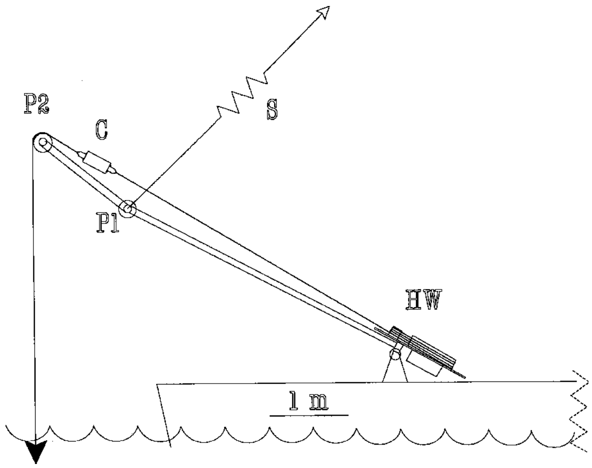

Fig. 3. The crane and the winch. The second pulley (P2) is lifting the canister (C) over the first pulley (P1).

6. Deployment

Deploying the array is a lengthy process. The time history of a deployment is given in Fig. 7 based on data from a Star-Oddi CTD depth and temperature logger fitted to the bottom canister. From the depth profile it is seen that deployment and retrieval each last 1–1.5 h. A staircase pattern is observed during canister deployment, the horizontal part of a step reflecting the time required to move a canister from the cassette, past the capstan, and past the pulleys. The

Fig. 4. The crane. The two pulleys can be seen and part of the suspension from the mast. Photographer: S.F. Hansen.

Fig. 5. A canister on its way up has reached the first pulley. The second pulley on the extension of the crane is being engaged. Photographer: S.F. Hansen.

vertical part of a step reflects the paying out of the cable between two canisters. The drop from 300 to 750 m reflects the paying-out of most of the top 500 m of cable (see Fig. 1).

Fig. 6. The second pulley has lifted the canister over the first pulley. The canister now has to pass the winch. Photographer: S.F. Hansen.

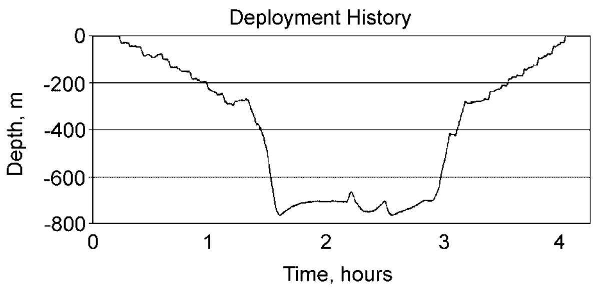

Fig. 7. A graph of the depth of the bottom canister during a deployment.

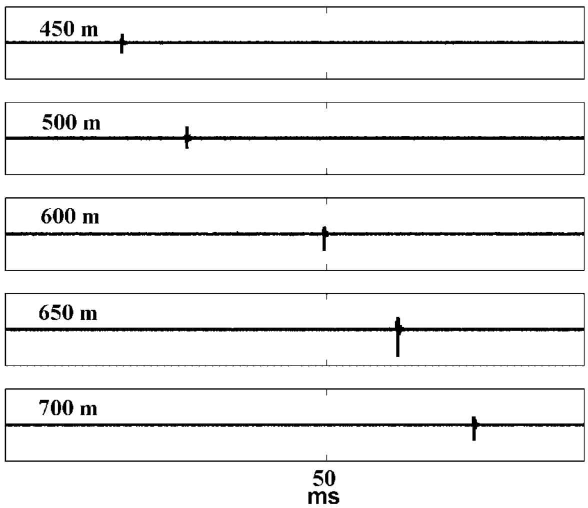

Fig. 8. A recording on five hydrophones of a sperm whale click. The whale is at a horizontal distance of around 2.5 km. Its sonar beam is focused on the 650-m canister with the pinger.

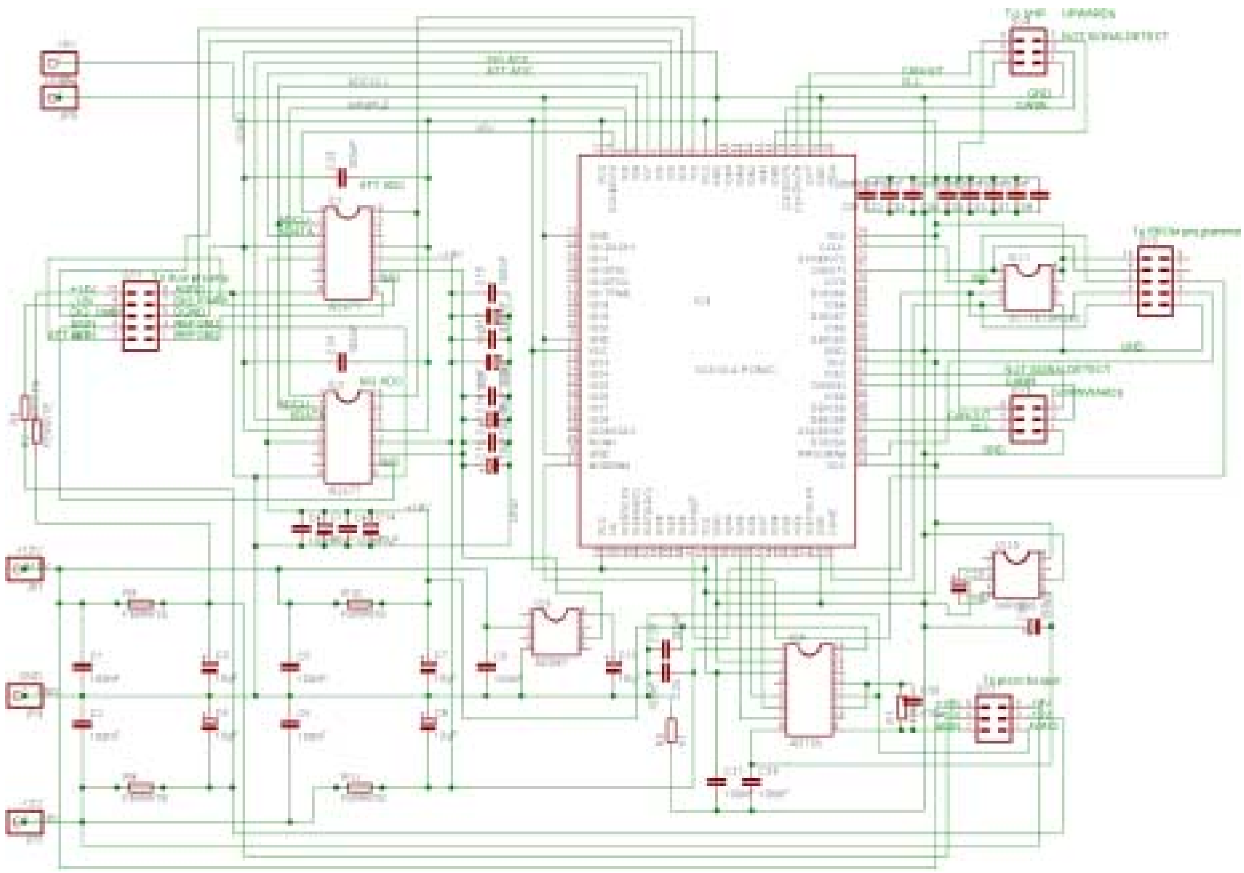

Fig. 9. The two ADCs and the multiplexer.

7. Electronics

To reduce weight, cost, and complexity it was decided that each canister should have its own battery power supply. An external battery container holds 12 disposable alkaline D-cells. The voltage from the battery slowly drops from 18 to 9 V (the lower limit for operation of the switch-mode regulators in the canistes) over a 12-h period at 20 C (6 h at 0 C). Inside the canister the battery voltage is converted by two Traco switch-mode regulators to ± 5 and ± 15 V . The ± 15 V regulator generates a strong AC noise component on top of the DC voltage which needs to be removed, otherwise it will interfere with the recordings. 7 filter stages in series convert the noisy ± 15 V to an extremely lownoise (around 1 μV RMS) ± 12 V for the preamplifier and ADCs.

Reson TC4034 hydrophones were chosen for the array because of their broadband and omni-directional receiving characteristics. These hydrophones have a low sensitivity (−215 dB re 1 V/μPa) (Fig. 8).

The hydrophone signal is conditioned for digitization by two parallel low-noise preamplifiers (Fig. 10), one amplifying the signal 40 dB, the other 0 dB. Each preamplifier includes both an anti-alias filter and a high-pass filter with a −3 dB limit of 500 Hz. The self-noise of the preamplifier is around 9 nV/Hz$^{1/2}$ referred to input. The two signals are digitized by two AD677 16-bit 96-kHz ADCs having an input range from −10 to +10 V (Fig. 9). The full-spectrum RMS noise after digitization is below −93 dB relative to a full-scale sinus. The two ADCs can be configured during the recording either to 192-kHz sampling with 93-dB dynamic range or a 96-kHz sampling with 133-dB dynamic range. The 133-dB dynamic range (clipping the signal at a received level of 232 dB re 1 μPa RMS) allows recording low-level signals as well as the intense biosonar signals from sperm whales (Fig. 10).

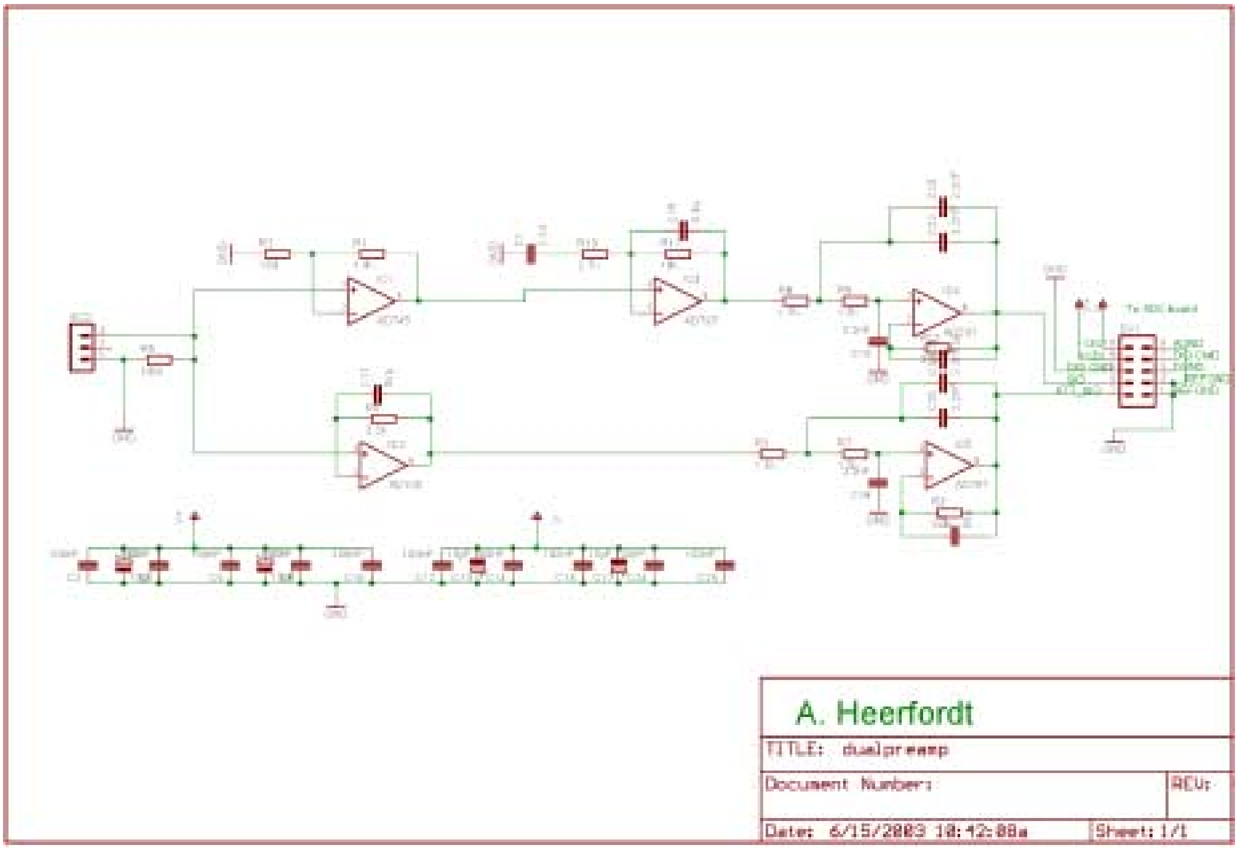

Fig. 10. The two-channel low-noise preamplifier.

After digitization the data are multiplexed into the upwards data stream. The multiplexing of signals is handled by a Xilinx XCS10 Field Programmable Gate Array (FPGA). The multiplexed electrical data stream is converted to an optical data stream by a fiber-optic transceiver (Agilent HFBR5205) using Manchester encoding (Fig. 11). At the receiving end the clock signal is recovered from the data stream with a Vectron TRU050 Phase Locked Loop oscillator (PLL), and the Manchester signal is decoded in the FPGA. From the downwards data stream a number of bits are de-multiplexed in each canister and used as commands to control the electronics or to generate an analog signal through an AD766 16-bit digital–to-analog converter (DAC). This analog signal is amplified and fed to an external piezoelectric transmitter. Presently a home-made pinger, tuned to 13 kHz, is used. The maximum source level of the transmitted signal is 146 dB re 1 μPa RMS at 1 m, which should be sufficient to exceed the hearing threshold of whales up to at least several kilometers. The purposes of the transmitter are to attract a whale, to simulate prey echoes, and to calibrate the array shape by estimating the inter-hydrophone distances.

The depth and slant of the array are presently monitored with two autonomous Star-Oddi CTD depth sensors, which are attached to the bottom and top canisters. Also a 3-D accelerometer is placed in the middle canister, reporting the slant through the fiber-optics. Additionally a strong acoustic impulse is emitted from time to time from the surface. When repeated reflections from the bottom and the surface can be detected, it helps to determine the depth of the individual hydrophones. Neither the slant of the array nor the exact depth of the hydrophones are important for measuring beam directivity.

Onboard the vessel the data stream is converted to a 16-bit parallel data stream (Fig. 12). An absolute time signal accurate within 35 μs and a position, both derived from the Global Positioning System (GPS, ad modum Møhl et al., 2001), are added to the data stream. Thus, the hydrophone

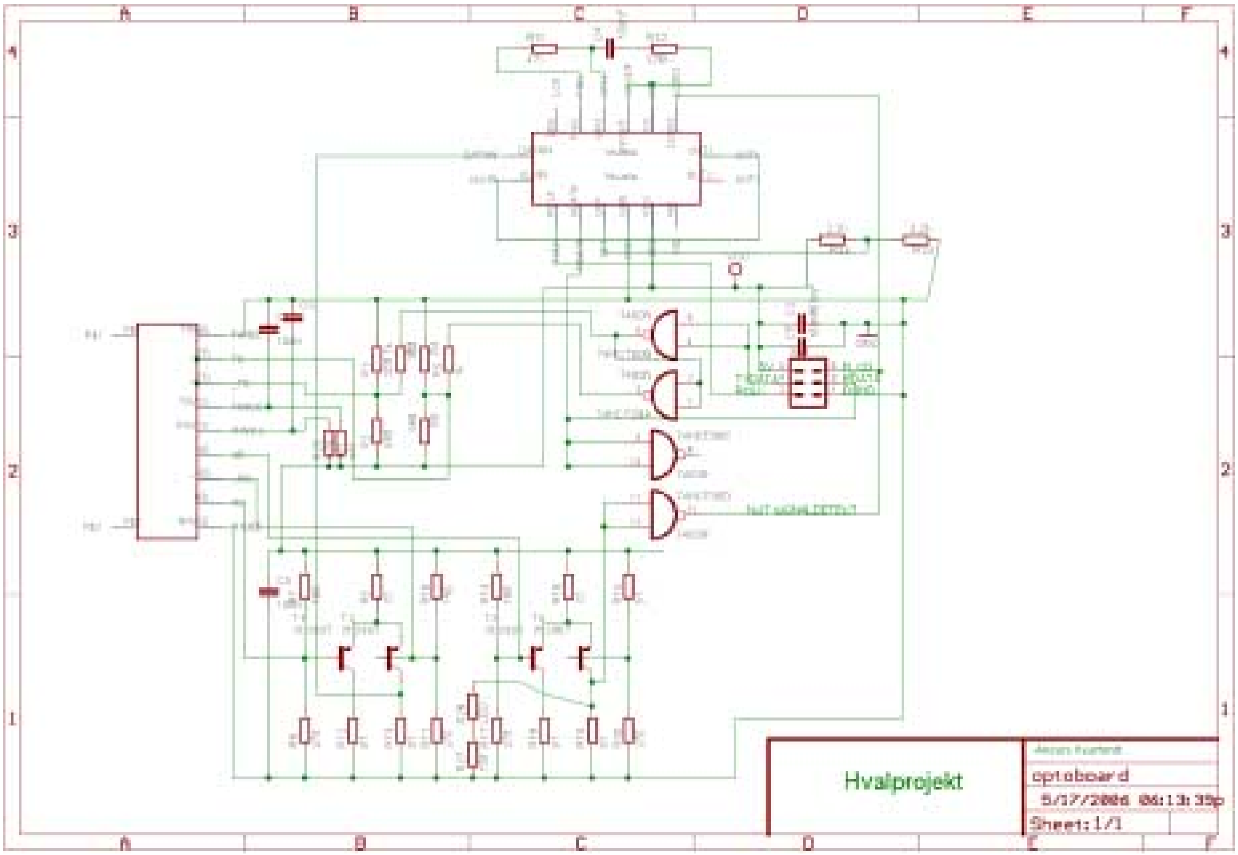

Fig. 11. The fiber-optic interface with PLL and clock/data separation.

signals are annotated and can be synchronized with independent recording units on other vessels. An IBM-compatible PC running Linux (Red Hat version 7) with a 2-GHz CPU, 330-MB RAM, a 200-GB hard disk, and the Adlink IO-card PCI-7300Ab receives the 16-bit parallel data stream and writes it to a hard disk as is in chunks of 650 MB that will fit onto CD-ROMs. Each file record covers a period of $3\frac{1}{2}$ min. Any one of the hydrophone signals can be extracted from the upstream data and be listened to for monitoring in real time. The recorded data are accessible through a wireless local area network on the vessel, and with custom-built software the data stream can be split into a number of sound files, one for each hydrophone. This can take place while the next chunk of data is being recorded. Assuming the array is truly linear and vertical, that the sound velocity is constant and known, and that the depth of each hydrophone is known, the time-of-arrival difference for a sound signal between the hydrophones can be used to calculate the distance and the depth of the sound source using the algebraic method described by Spiesberger and Fristrup, 1991. The array will, however, be curved and not strictly linear, and the single accelerometer is insufficient to determine the 3-D geometry of the array. Modeling the curvature of the array in 2-D with a simple curve and using a general least-squares fitting method such as the Levenberg–Marquardt method (Marquardt 1963) the curvature of the array and the position of the whale can be fitted to the data for a single click, and a better localization of the whale is obtained.

8. Example of a recording

In 2003, 2004, and 2005 recordings of deep-diving sperm whales were made in the Bleik Canyon off of Andenes, Norway (69°N/15°E). The results of the recordings will be described in separate publications. Here a single example is given.

Fig. 8 shows an example of a recording of a sperm whale click on five hydrophones of the array. The middle track has been edited to suppress

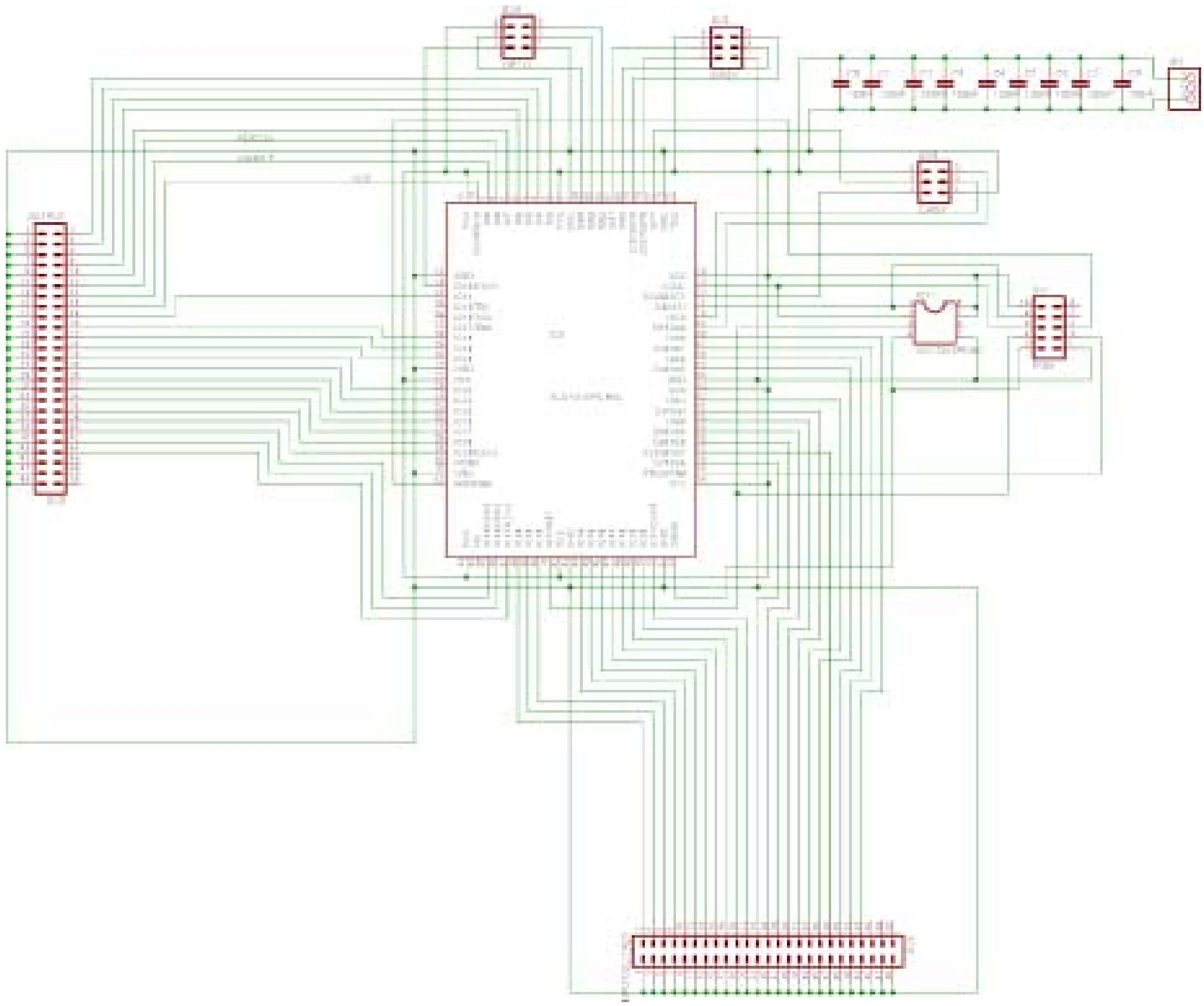

Fig. 12. The interface to the Adlink IO-card with 16-bit parallel data streams in both directions.

hydrodynamic noise due to water movement around the hydrophone. All tracks have identical full-scale deflections. The whale is apparently directing a focused beam of acoustic energy towards the 650-m canister (with the pinger) from a distance of around 2.5 km. The amplitude is highest on the canister with the pinger and smallest for the canisters furthest away from the pinger. Usually the amplitude in a series of recorded sperm whale clicks as seen from one hydrophone will slowly increase and then decrease as if the whale is slowly scanning from side to side with fixed output. But in the series, of which the shown example is a part, the first click has maximum amplitude on the canister with the pinger as if the whale from the very beginning of the series directed its beam on the pinger.

9. Discussion and conclusions

We find that the approach is feasible; the array can be constructed from off-the-shelf components for a modest budget. The total procurement cost is about 38,000 USD (2004 prices). This breaks down to 13,000 USD for cable, winch, and aluminum materials, 14,000 USD for electronics and 11,000 USD for the hydrophones. Labor is not included.

The system has been operated from a 14-m vessel and produces data with high bandwidth and wide dynamic range. Data are available in real time from any one of the hydrophones and in near real time from the remaining. Prerecorded signals have been transmitted from the pinger and apparently have attracted the sonar beams of the whales. The array is suited for measuring directional properties of deep-sea biosonar signals. 10 deployments to depths between 500 and 950 m have been carried out without mechanical failure of the cable or its connections to the canisters.

Deployment of the array from the present vessel is limited to sea state 3 and below. The movements of the vessel are significant during deployment. It should be considered to suspend the array from a buoy to decouple it from the movements of the ship. The time consumed deploying and retrieving the array hampers rapid relocation in response to the movements of the animals.

Relocation is however possible by towing the array. But with the weight at the bottom of the array, it becomes non-linear during towing, and it becomes difficult to monitor the non-linearity. If the array were to be used for towing, the lead ballast at the bottom should be removed, and the array should be adjusted to neutral buoyancy. A paravane could be used to force the array to a larger depth.

The design could, with minor modifications, be used for other purposes than the study of beam patterns of odontocetes. For example, if the distance between canisters were increased to the maximum of 2000 m, and if electric power via cables were added, the array could be deposited on the seafloor connected to a ship or shore-station and collect data for days or weeks. This would be more suited for localizing whales over a large area or for studies of low-frequency signals.

The array has proven to solve a number of issues facing deep-sea bioacoustics where high bandwidth, wide dynamic range, large aperture, and multiple hydrophones are required simultaneously.

Acknowledgments

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