AN ACOUSTIC PIPELINE TRACKING AND SURVEY SYSTEM FOR THE OFFSHORE

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Abstract: *Acoustic pipeline surveys with low-frequency echo sounders are mostly done by sailing cross courses. By adding a directional element in the receiving stage a course can be sailed along the pipeline. With such a method a 100 % inspection of the pipe coverage can be obtained with reduced survey time than with cross sailing surveys with limited information about the pipe coverage. The receiving element is an array of 16 hydrophones with optimal acoustic signal processing (Kalman filtering). The position and orientation of the transmitting transducer and receiving hydrophone array are also optimal estimated using a Global Position System and a Motion Reference Unit. The technique will be presented theoretically, supported by simulation and with a play back of the raw data (20 Gbyte) from the 16 hydrophones, GPS and MRU from tests at sea.*

1. INTRODUCTION

In sailing a cross course the echo from the pipe shows as a hyperbola in the survey record, normally presented on screen or paper. In case of a flat sea bottom the pipe coverage is readily obtained from the survey record. The shortest distance of the hyperbola to the sea bottom reflection in the presentation is equal to the pipe coverage, see lower right sub-picture in Fig. 3. The sailing time increases with the number of cross points. When the coordinates of the reflection spot on the pipe can be obtained and presented to the surveyor in an suitable way, but also to the helmsman it will be a great asset for the total survey operation.
The helmsman can then sail the ship a favorable course along the pipe and for the surveyor the precise position of the pipe in the sea bottom can be calculated. With the exact sea depth above the pipe reflection spot the coverage is obtained exactly. The requirement of a flat sea bottom is less stringent than for normal pipe surveys. In cooperation with Boskalis and Innomar a system has been simulated, built and tested.

2. THE SYSTEM

Fig. 1 shows the sensor configuration of such a system. A transducer transmits a (non)linear acoustic pulse which reflects or scatters against the pipe wall. The reflections or echoes are received by the hydrophones.

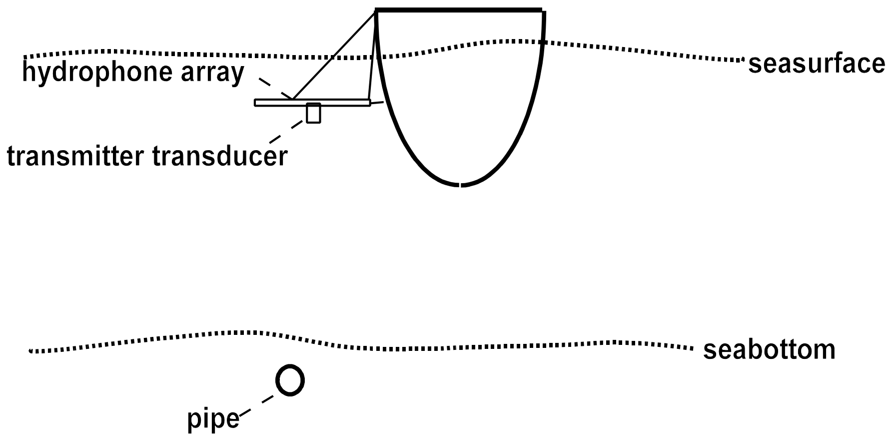


Fig. 1: Ship with transmitting transducer and hydrophone array

The propagation path of a low frequency acoustic pulse transmitted by an echo sounder, reflected against the pipe and received by the k^{th} hydrophone is shown by Fig. 2.

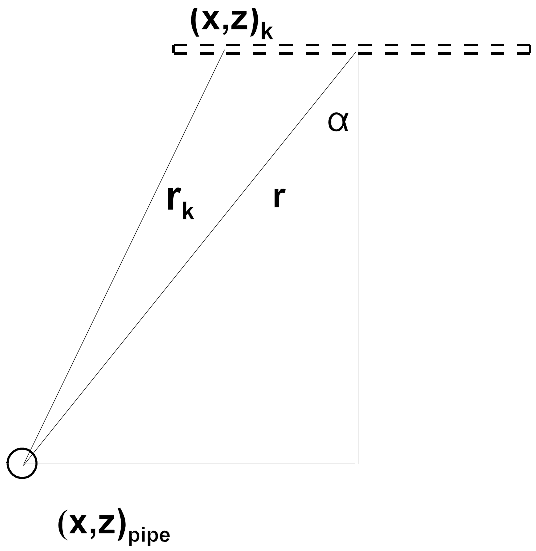


Fig. 2: Propagation path from the middle of the array to position x laying on the array.

The length of the propagation path is

$$\begin{aligned} r_k(\alpha) &= r + \sqrt{r^2\cos^2\alpha + (r\sin\alpha - x_k)^2} \\ &= r + r\sqrt{1 - 2\sin\alpha\frac{x_k}{r} + \left(\frac{x_k}{r}\right)^2} \end{aligned} \qquad (1)$$

For the sake of simplicity we take the same sound velocity c for the water and the soil. The propagation time for the k^{th} hydrophone is

$$\tau_k(\alpha) = \frac{r_k(\alpha)}{c} \qquad (2)$$

Note. The diameter of the pipe can be easily taken into account.
We can combine all hydrophone signals $\boldsymbol{S_k}$ in a cost function to be minimized by a least square method as follows

$$\chi^2 = \sum_l \sum_k |\phi_{k,l} - (\tau_k(\alpha) + l\Delta t)\omega|^2 W_{k,l}, \tag{3}$$

where $\boldsymbol{W_{k,l}}$ the weight of the $\boldsymbol{l}^{th}$ sample of $\boldsymbol{k}^{th}$ hydrophone signal is and $\boldsymbol{\phi_{kl}}$ its phase function of the signal S_k. The parameters to be fitted are $\boldsymbol{r}$, $\boldsymbol{\alpha}$ and $\boldsymbol{\omega}$.
The parameter ω is equal to the momentary or mean radial frequency of the signal and thus may be omitted from the fit procedure.
Since small changes occur in r, α and ω, the cost function can be linearized as follows

$$\chi^2 = \sum_l \sum_k |\phi_{k,l} - (\tau_k + \frac{d\tau_k}{dr}\Delta r + \frac{d\tau_k}{d\alpha}\Delta\alpha + l\Delta t)\omega - \tau_k\Delta\omega|^2 W_{i,k} \tag{4}$$

The parameters are found by varying $\boldsymbol{\Delta r}$, $\boldsymbol{\Delta\alpha}$ and eventually $\boldsymbol{\Delta\omega}$.
The reflection spot is on a cone described by the direction vector

$$R[\cos\alpha\sin\gamma,\ \sin\alpha,\ \cos\alpha\cos\gamma]^T \tag{5}$$

The estimated angle and distance are subsequently used to estimate the offset vector and eventually direction vector of the pipe. A circle on a cone is obtained on which the reflection spot is located. Since the echo is perpendicular to the pipe direction, the angle γ and thus the coordinates of the reflection spot are calculated with the error and transformed into world coordinates. Summarized: the history, system and observations with their errors are taken into account to estimate the new pipe position leading to a Kalman filter procedure. More or less the same applies for an unknown pipe direction vector.

3. SIMULATION

Fig. 3 shows the monitor screen with the pipe and soil simulated and a signal to noise ratio (S/N) of 10 dB . The upper left sub-picture shows the 16 hydrophone signals of the present record. The sea bottom echo is shown by the equal time black responses in the hydrophone signals. The echo of the pipe is shown by the green lines. The lower left sub-picture shows the navigation screen. The red line is the pipe position. The zig-zag line and the arrow show the simulated sailed course of the ship, respectively the present position and orientation towards the pipeline. Every point of the line corresponds with one record of the upper left sub-picture. The transmission rate is 25 Hz.
The lower right sub-picture shows the acoustic record in false colors. This record corresponds with normal survey records. Clearly is shown the hyperbolic curves of the acoustic echoes from the pipe in the sea bottom.

The middle lower sub-picture shows the spectrum of the present record. The moment of the green arrow corresponds with the displayed spectrum and with the small hyphen on the line between the spectrum record and the survey record.
At the upper right in Fig. 3 numbers are produced for testing and operational purposes.

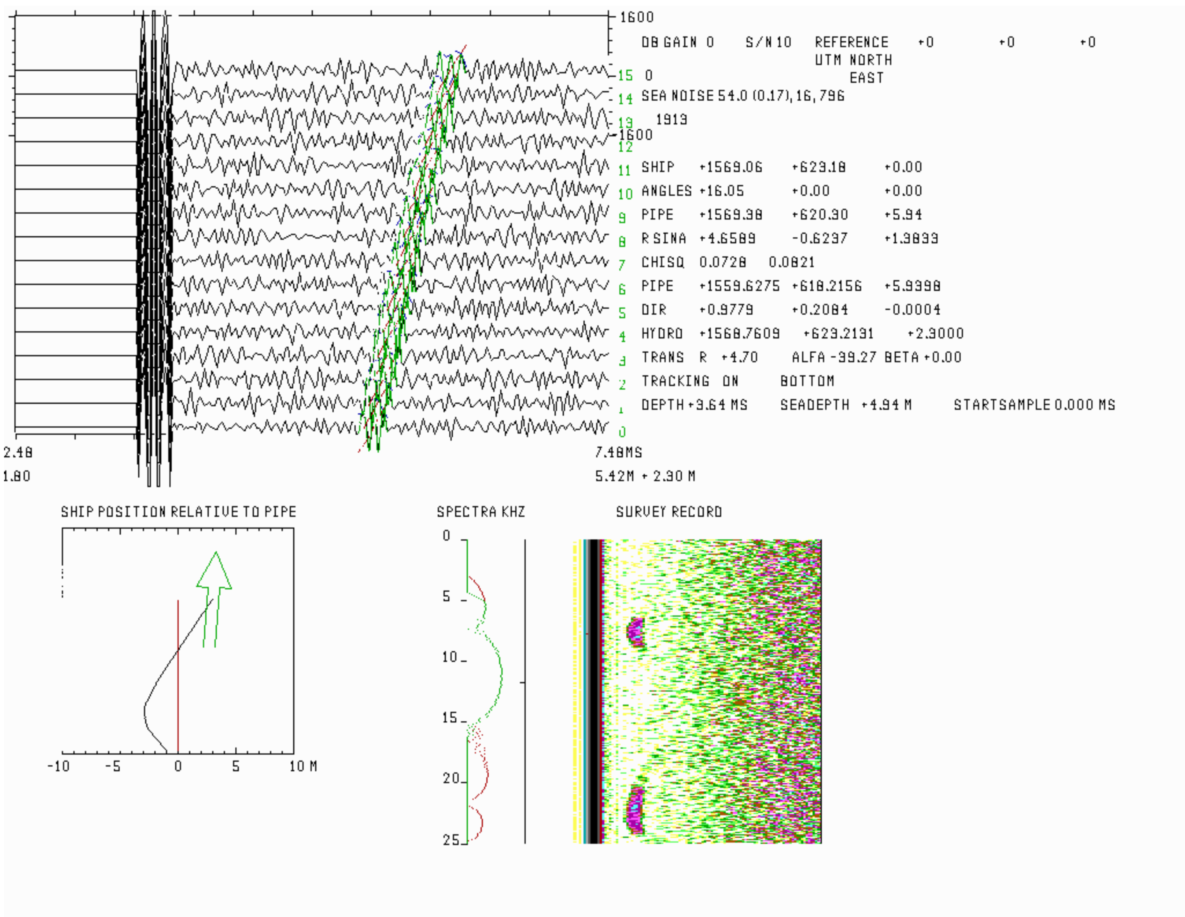


Fig. 3: Screen dump of the monitor display of a simulation with a S/N of 10 dB. See text.

4. A REAL TEST

The hardware is based on a personal computer (pc) with a 2500 MHz Celeron processor with an AD-DA card of Realtime Devices. Transmission rates up to 30 Hz with all realtime graphics, like Fig. 4, are possible. The nonlinear echo sounder SES-96 of Innomar was used as transmitter. The receiving hardware consisted of an array of 16 hydrophones and a filter bank, also supplied by Innomar.

The system is programmed in the C language under 32-bit DOS control with direct graphics control and has a simulation, realtime and play-back mode. For the play-back mode a log mode is incorporated. The position information, based on a Motion Reference Unit (MRU) and a Global Position System (GPS), is estimated by the Kalman procedure in the pc-system. The logged data are all raw data from the hydrophones, the MRU, the GPS and the intermediate results of the signal-processing. Logging is done in realtime and eventually in simulation mode.

Since nonlinear echo-sounder transmitters have a small transmitting aperture, and in this case steering of the beam is possible an estimate for the transmission angle was supplied to the echo-sounder by the pc-system. Also information about the moment of transmission and type of pulse was exchanged via links between the transmitter and the pc-system.

The Eemszinker pipe, located in the Wadden sea, near the Dutch city Delfzijl, was used in the test in 2003. The pipe diameter is 47 inches. The weather and sea conditions were calm.

The pipe position was determined, as a reference and for test purposes, in the classic way, by sailing a cross course. One record was made with a large GPS aerial offset relative to the transmitting transducer and a second record without an horizontal offset.
Fig. 4 shows a screen dump of the monitor display of the realtime operation. A navigation sub-picture has been added at the lower right and a compass card at the top right.

The survey sub-picture shows no noticeable swell.

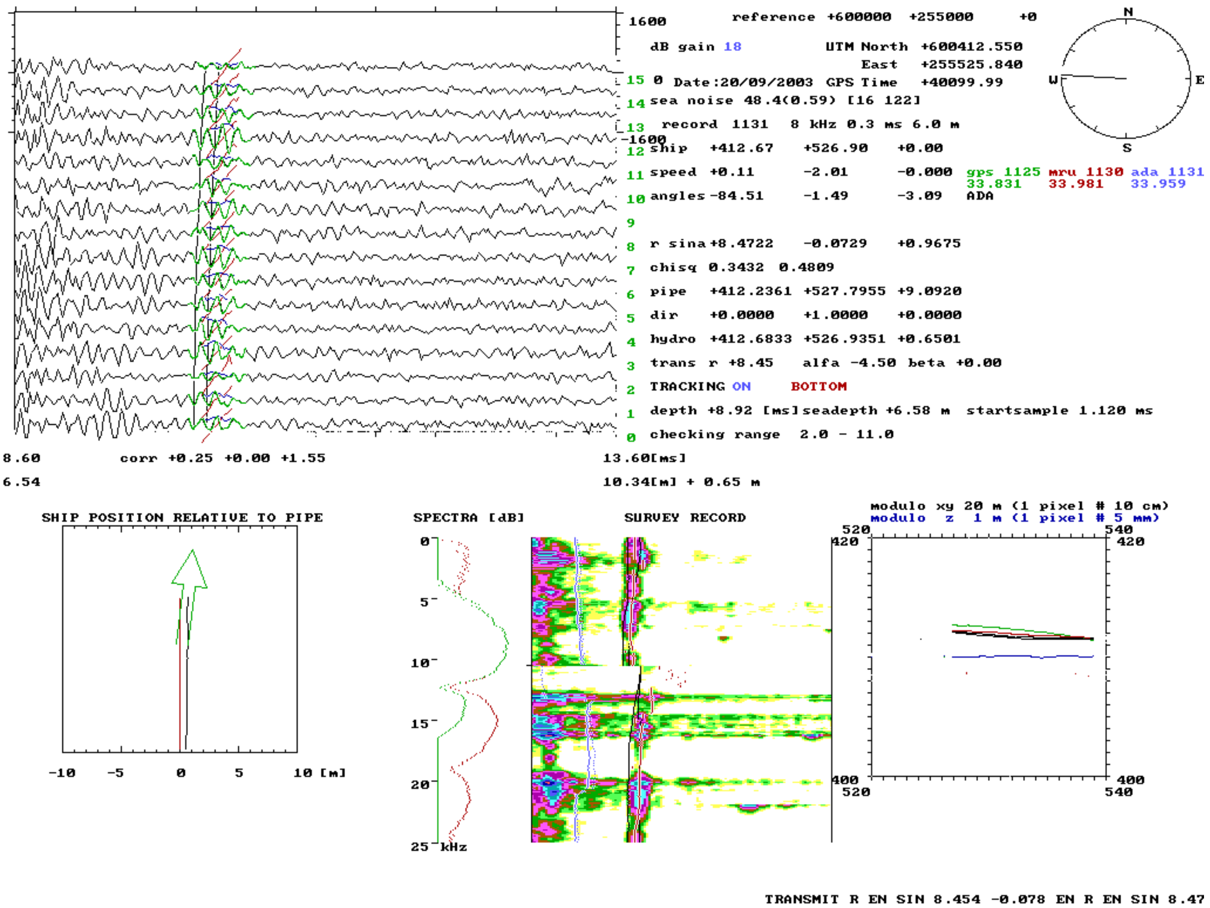


Fig. 4: Screen dump of the monitor display

The upper part of Fig. 5 shows the geophysical record and the lower part shows information about the horizontal positions of some variables.
The real pipe position in the bottom is drawn heavily black in the geophysical record and red in the position record. Clearly is shown the pipe coverage. In the position record the position of the ship is shown by the green line.

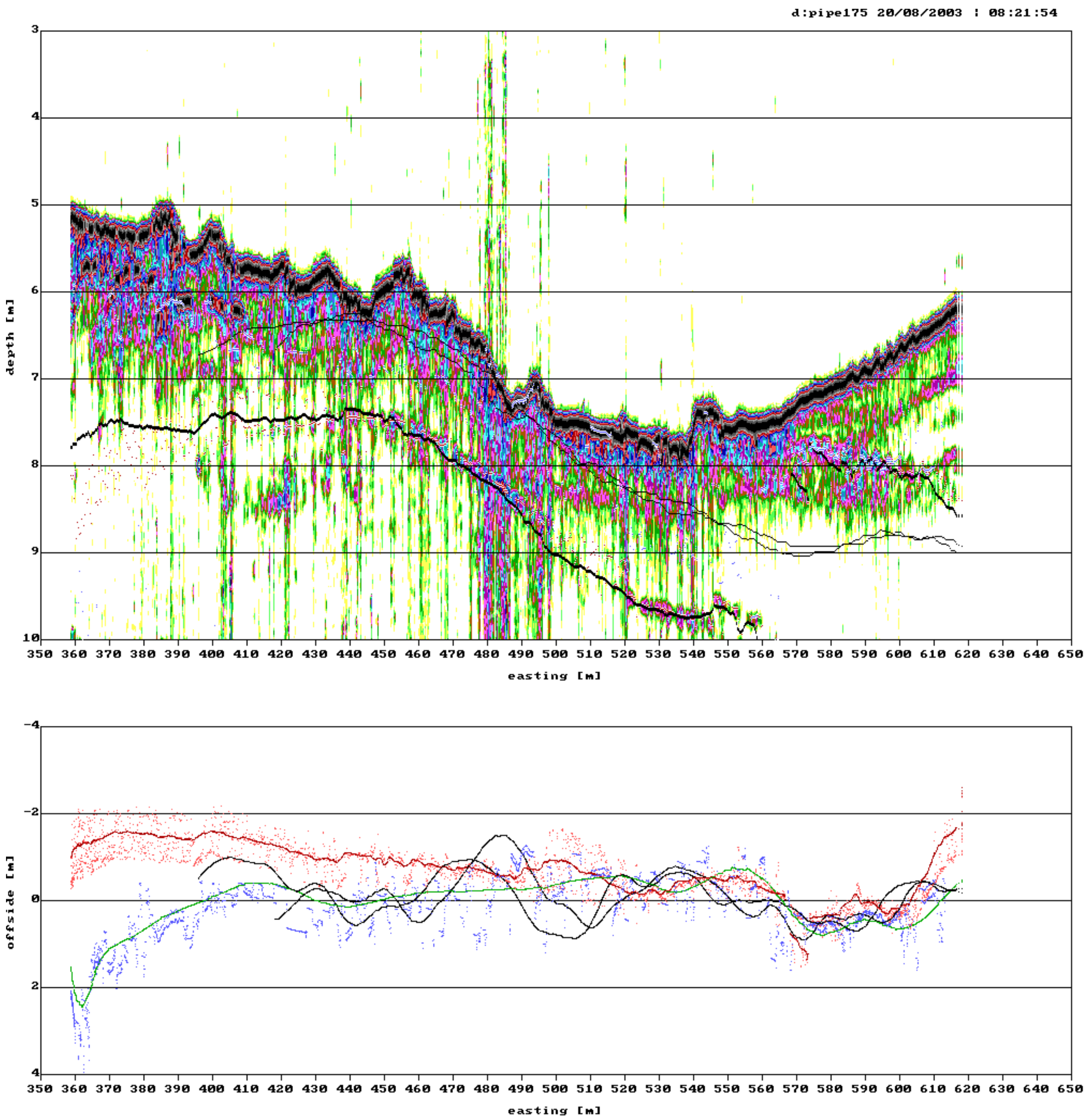
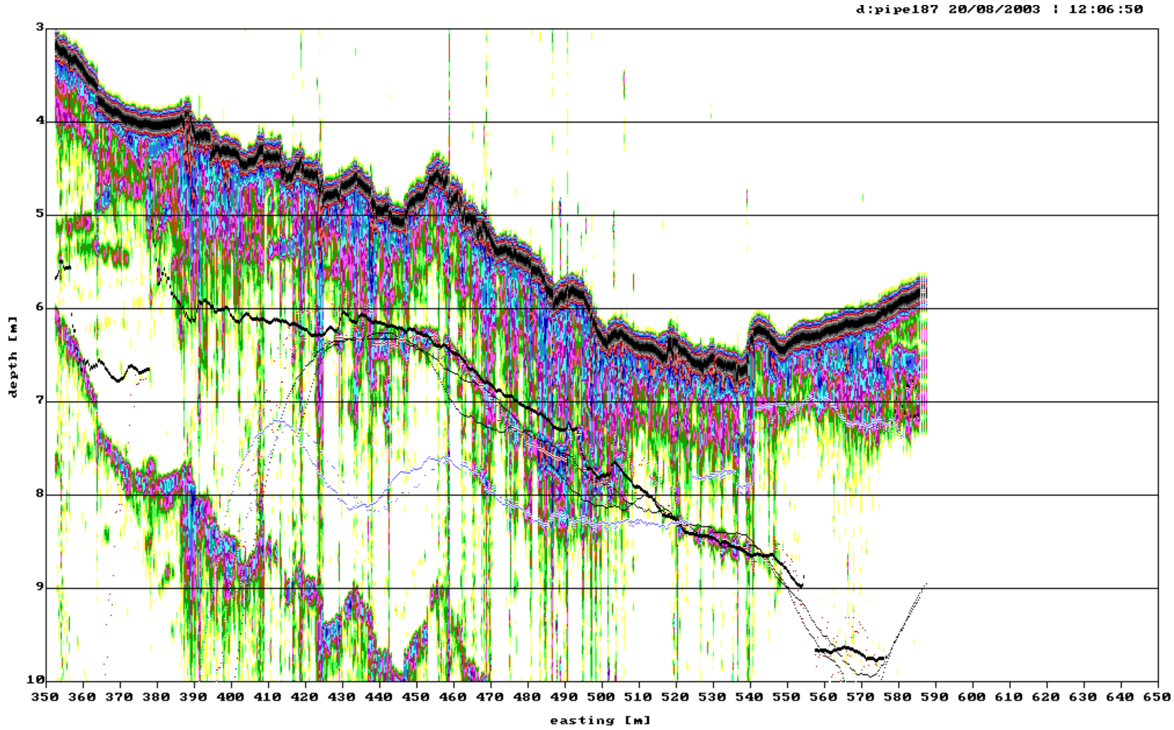


Fig. 5: A geophysical and position record. The sailing directions is westwards (to the left) The geophysical record is created without the use of any steering information.

The lines/dots in both records have the following meaning:

- green line # position of the transducer/array, estimated form the GPS and MRU data
- green/blue line # position of the tranducer/array without GPS data for at least the last 10 seconds
- blue line # position according logged distance r and sin(α) or transmission angle of SES system
- light reddots # estimated pipe position, according estimated distance r and sin(α)
- red line # estimated pipe position, according updated pipe vector after using estimated sin(α)
- thin black lines # pipe position according the two Innomar records
- thick black line # estimated real depth of pipe

In Fig. 6 the sailing course deviates largely from the pipe position, contrary to the course shown in fig. 5. The measured pipe positions of Figures 5 and 6 correspond rather well. At the detection stage varies the correspondence .
The position of the pipe from just the geophysical record is difficult to extract. At the start and also at the end no trace is seen.



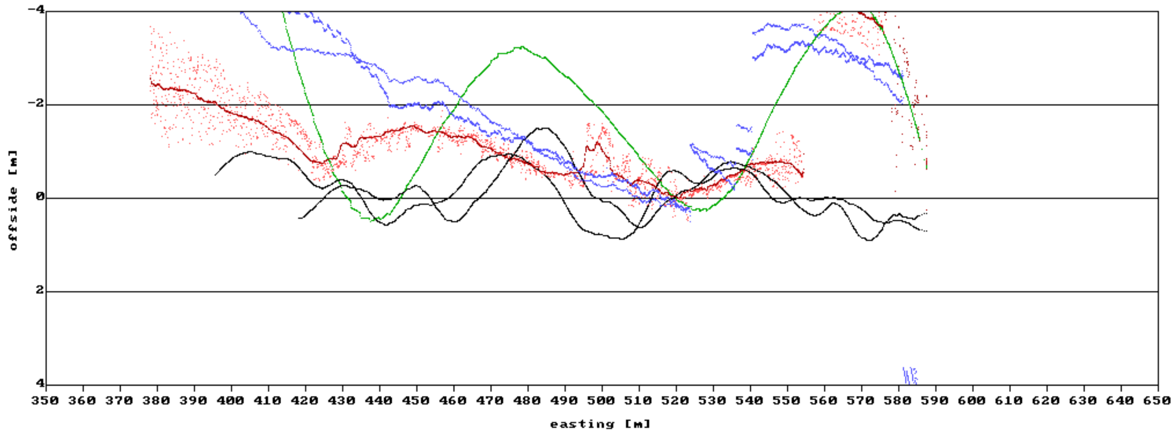


Fig. 6: A geophysical record and position record with a sailing course (green line) not parallel with the pipe. The sailing direction is eastward (to the right).

Although the wrong transmission angle is given to the transmitter during the test, it has hardly any effect on the reception, the signal-processing. The detection and tracking is rather well.

5. CONCLUSION

Already in 1980 a pipe survey system with directivity was envisaged, designed and simulated, based on charge bucket devices. No proven hardware was available at that time. The proven hardware and signal processing technology nowadays make the construction of a low cost pipe survey system possible. Simulation showed that such a system works correctly. Also the test carried out on the Delfzijl Eemszinker shows that the system works correctly, clearly pictured by Figures 5 and 6. The SES-96 system was used as a transmitter. The pc-system can also transmit low frequency (~10kHz) chirps with a large aperture, enhancing the capture range of the system and adding a very low chirp subbottom profiling option together with the tracking of pipes .

6. ACKNOWLEDGMENTS

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