Stationary underwater channel experiment: Acoustic measurements and characteristics in the Bornholm area for model validations

Ivor NISSEN[1], Iwona KOCHAŃSKA[2]

[1]Bundeswehr Technical Center for Ships and Naval Weapons, Naval Technology and Research (WTD 71), Research Department for Underwater Acoustics and Marine Geophysics (FWG) building, Kiel, Germany, IvorNissen@Bundeswehr.org

[2]Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, Department of Marine Electronic Systems, Poland, iwokocha@pg.gda.pl

The underwater acoustical channel is time-variant, and even on small time scales there is often existing no 'acoustical frozen ocean'. Popular is the use of WSSUS-channel transmission modeling (Wide-Sense Stationary Uncorrelated Scattering) for the stochastic description of bandpass signals in GSM mobile phones with moving participants; since this results in a halved number of model parameters. For underwater sound applications such as detection, navigation and communication this approach provides limited a-priori-knowledge for adaptive algorithms with moving cooperative participants. The FWG of the WTD71 is collecting phase-accurate channel measurements from different sea areas in different time and application scenarios, with moving and stationary communication nodes since 2001. This paper presents a SIMO experiment from 2010, with a high precision continuous observation period of eleven hours using two stationary bottom nodes, mostly uncoupled from the influence of surface waves and from the sea floor. Transmitter and receiver node with a distance of two nautical miles between them were stationary installed on the bottom in shallow waters in the Bornholm Basin of the Baltic Sea. The sound speed has been measured continuously in the water column with a moving measurement chain. The question for this experiment was: Is the WSSUS-property fulfilled in water, when participants communicate motionless with negligible current, bottom influence and movements of the surface? The answer is: No, not in this experiment.

Keywords: Underwater communications, stationary time, WSSUS indication

1. Introduction

In a highly dynamic environment like the underwater world, technical systems should be adaptive. Each detection ping, any navigation or communication click represents a measurement and can estimate the transmission channel characteristics, with high costs, energy consumptions and bandwidth. In situ measurements cannot show the complete picture. Model-based knowledge is needed additionally, for example in non-linear distance measurement approaches by using travel times, if the line of sight path is missing. How stable is the sound channel through time and space? How fast it is changing? How many measurements are needed? Should we constantly re-measure the transfer channel, or sufficient sampling of it in certain intervals for channel estimation and modeling?

An important class for the description of linear *time variant* channels with multi-path propagation are stochastic models based on the WSSUS assumption. Given are the transmit signal s, the received signals r and the time variant impulse response h with the relationship:

$$r(t) = n_m(t)(hs)(t) + n_a(t) = n_m(t) \int_{\mathbb{R}} h(t,\tau)s(t-\tau)d\tau + n_a(t), t \in T \subset \mathbb{R}$$

Without loss of generality the multiplicative noise n_m and additive colored noise component n_a should be one respective zero. The communication systems use synchronization techniques like the cycle prefix, or Doppler filter banks, in combination with resampling to remove the main Doppler shift. After this compensation, the time spread and Doppler spread increases the error probability. If we assume, the channel impulse response is constant in the time interval $T' \subset T$ (time-invariant), it is possible to calculate the Fourier integral $R(f) := \int_T r(t)e^{-2\pi \hat{\imath} f t}dt$, similar integrals S for s and H for h and we can substitute the convolution by the product $R(f) = H(f)S(f)$. In the case of a 'non-frozen' channel with no rapidly varying impulse response this is not possible. The theory of time-variant filters based on the work of Lotfi Zadeh [1], Thomas Kailath [2], and Philip Bello [3], and for the shallow water channel based on Rolf Thiele's work [4] provide the following non-separable equation:

$$R(\xi) = \int_B H'(\xi - f, f)S(f)df,$$

with the so called bi-frequency-function H' (please refer to [2]). In theory the Doppler power spectrum has to be in symmetric [13]. In a formulation as weak stationarity, based on Boltzmann's ergodic hypothesis, where statistical relationships are constant over differences of time realizations, this implies the broad use of WSSUS-based transmission channel modeling for the stochastic description of bandpass signals in GSM mobile phones with moving participants. In the case of shallow water sound channels we can say: 'Due to the very slow change of oceanographic states it can be assumed that the [shallow water] transmission channel behaves over periods of about an hour sufficiently ergodic' [4, page 17]. On the other hand, it can be assumed that the 'WSSUS assumption is violated for many real [underwater acoustic] channels.' [6], [7, figure 3], similar to terrestrial applications with high-speed vehicles like transrapid trains [8]. To resolve this problem, Bello introduced the concept of 'quasi-stationarity'. A finite time duration is established, during which the stationarity assumption holds. But, what is the limitation of this finite time, what kind of influence dominates this effect, the Non-WSS or Non-US? The community assume, Doppler shifts generated by the movements of the transmitter and receiver and the surface motion; an asymmetric spectra results from different surface behaviours. This was our motivation for the following investigations. A stationary experiment over 11 hours was performed by FWG in the Bornholm basin of the Baltic Sea in March 2010 with precise environment measurements (RUN A40), to show the time-varying effects of surface- and medium-influence with stationary communication nodes.

2. Measurements: stationary SIMO experiment 'RUN A40'

On the 8^{th} to 9^{th} March 2010 a stationary SIMO experiment (Single In - Multiple Out) was performed in the Bornholm Basin with a transmit tower and a receive tower, both with a height of 5 meters, fixed installed on the sea floor to reduce the time variance. Both stations are the end of the acoustic measuring range in a water depth of 75 m with a distance of $3680m$ (about 2NM, 6 $\%_0$ deviation). A short description of the experiment can be found in [5]. The transmit tower was equipped with a spherical transducer of the type ITC 4008 with a resonance frequency of 5.5 kHz, the receiving tower was equipped with a line lance array using seven equidistant placed hydrophones in a distance of $32 \pm 0.5cm$ (the eighth channel was used for the trigger signal to calculate the exact travel time). Both devices could be controlled via buoys interactively, the transmit and receive activities are triggered by GPS. The bottom hydrophone (No 1) was placed $2.42m$ over the seabed. In the middle of the experiment range a 300 kHz ADCP (turtle) was placed to measure the current. It was observed, that the current in the water column was minimal in the time segment between 19.30h and 6.30h looking over the complete week, this defines the duration of the experiment run A40, see figure 6. A waverider buoy was anchored outside of the range, which makes it attest-able that the wave height starts with $h_{\frac{1}{3}} \approx 1$ to $2.5m$ in the end. The water surface provides only one impact on the time variability, see figure 7, the second one was the sound speed. Moreover Microcat CTD probes were installed at the transmitter and receiver to measure continuously the temperature and the salinity. The measurement range was installed away from busy shipping lanes at the edge of a restricted area to minimize the ambient noise. The source level of the ITC 4008 was chosen in an iterative process to have a signal to noise ratio of 20-25 dB. In March, at this place, exists a strong layer with higher sound speeds at the sea floor, which bent the sound energy to the surface. This results in a low interaction with the sediment. Finally, the variation of both components are out of human control, neither the sea state, nor the 3D sound speed field in the water column. The latter one is varying between $1420m/s$ to $1440m/s$. Seven circumnavigations with the research ship FS PLANET in ovals around the range were performed in the eleven hours, towing a vertical chain containing 85 CTD-sensors in different depths to measure simultaneously the precise 3D temperature and salinity field, see figure 9 in the appendix. An animated sequence with the measured and interpolated speeds can be found in [9].

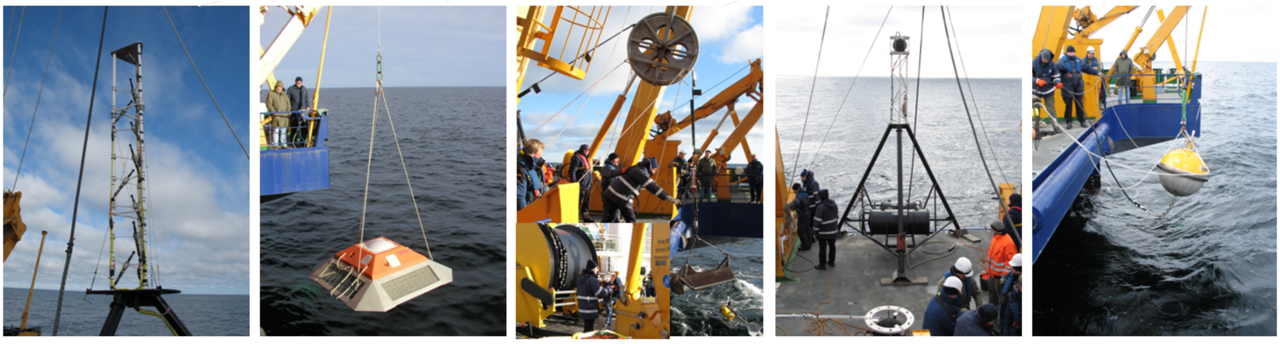
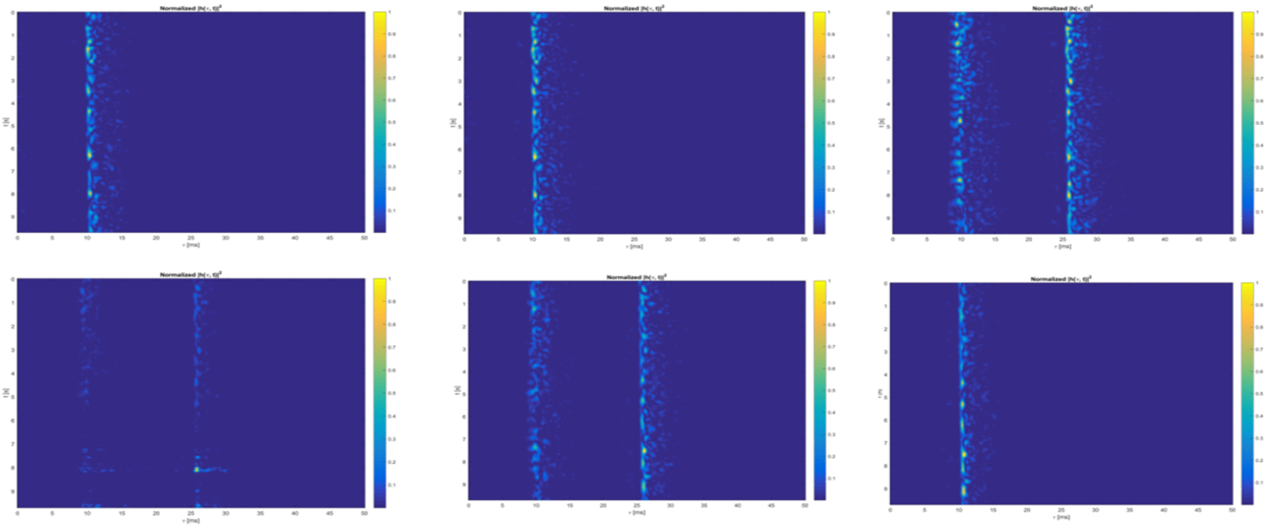


Fig. 1. Photographs of the equipment used during RUN A40. From left to right: receive tower with seven hydrophones, ADCP turtle, towed CTD chain with 85 sensors, transmit tower, and waverider buoy.

Every 15 minutes in the eleven hours, a frame with different channel probe signals was transmitted continuously in the frequency band $2.1 - 5.6kHz$. Each probe signal frame with a length of 4 minutes 30 seconds contains five LFM sweep collections, an OFDM multi carrier signal with 512 Hadamard pilot and a cycle prefix of 0.9 [10], a single carrier PRBS [11, PN1, V.A. Table 1] and a synthetic pseudo random noise sequence, all with a length of 30 seconds separated by silence. With the PRBS sequence, the acoustical channel was measured in total 41 times with a length of 41 * 30 seconds in all seven hydrophones in the frequency band from 2.1 to $5.6kHz$. For the design of the PRBS, pseudo noise random M sequences are needed, the feedback taps for the register shift are taken from Dixon [12]. For the generation of the PRBS M-sequence it was assumed that the channel is constant in the observation time duration of minimal $T' = 30/205s = 146ms$. Using the correlation of the transmitted PRBS-probe signal, and the recordings for each time segment one impulse response measurement can be determined. This sequence length can be used for tracking relatively changes of the underwater acoustic channel, but it is not suited to monitor geometric echo structures longer than $|T'|$. Note, that these Doppler sensitive PRBS signals are processed with a bank of Doppler-shifted replicas of the underlying M-sequence. In the case of multi-path with one chosen Doppler shift, this results in a Doppler spread. Using the measured sound speed interval a wavelength can be estimated between $[1420m/s/5600Hz, 1440m/s/2400Hz] = [25cm, 60cm]$. The concatenation generates an evolution of the impulse responses. If the WSSUS assumption is fulfilled, this is equivalent with the formulation $H(f) = R(f)/S(f)$ using the transfer function [10, sections 4.3, 4.4 (channel archive)], [11, equation 2].

3. In situ channel characterisation of run A40

The measurable time spread was limited to the observation time T', in this measurement configuration to $146ms$. In total $41 * 7 = 287$ Delay-Doppler-Power spectra can be determined over the 11 hours. These spectra show a time spread of maximal approximately $16ms$. In the figure 2 an evolution of the impulse response for the multi-path structure in 30 seconds is shown. The seven pictures illustrate the diversity in the hydrophone spacing of $32cm$ in a snapshot (same $30s$) with a surface introduced jitter, please see the animated sequence in [9].



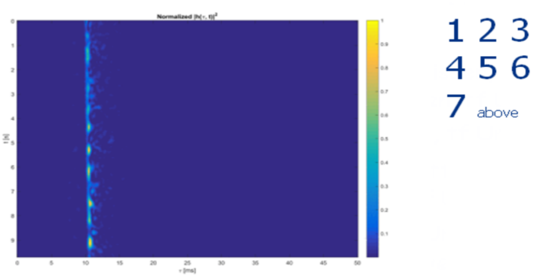


Fig. 2.
Time evolution in the 30 seconds time slot 8/41. The seven evolutions are hydrophone No 1 (near the sea floor) 2 3 . 4 5 6 . 7 (above). In the hydrophones 3, 4, and 5 in the case of two ray clusters the delay spread is $16ms$. The impulse response evolution of hydrophone 4 shows a strong fading of the broadband signal.

One calculated Doppler power spectrum collection for the seven hydrophones is given by figure 3. The Doppler power spectrum has to be symmetric [13, page 270], as a consequence of the so called Clarke/Jakes assumption. The main part of all calculated spectra in the A 40 experiment, however, is antisymmetric. On the other hand some symmetrical Doppler power spectra exist, which can be seen in the graphic for the hydrophone 7 in this time slot.

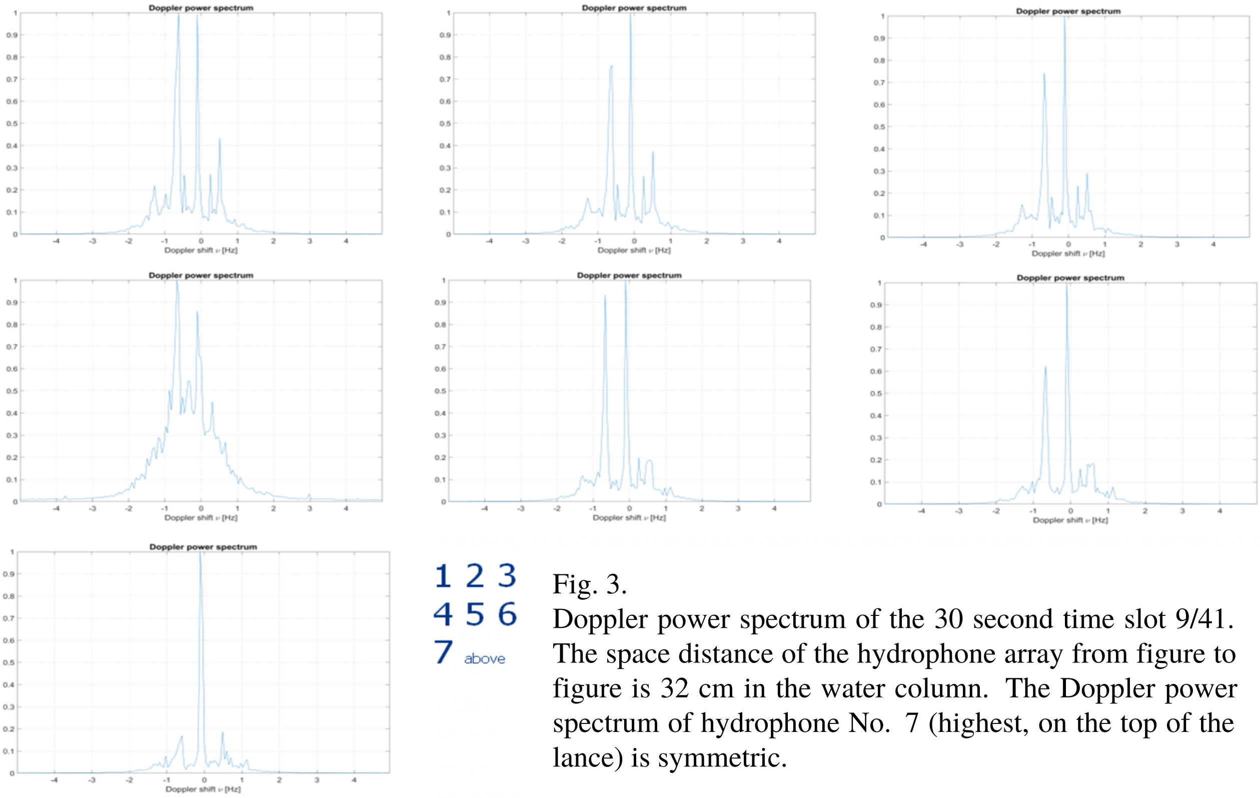


Fig. 3.
Doppler power spectrum of the 30 second time slot 9/41. The space distance of the hydrophone array from figure to figure is 32 cm in the water column. The Doppler power spectrum of hydrophone No. 7 (highest, on the top of the lance) is symmetric.

The stationary time and stationary bandwidth are two important channel characteristics derivate from the Delay Doppler power spectrum. For A40 both values can be calculated for all 30s frames. These are collected in the table 8 in the appendix, and presented in the form of the number of similar impulse responses in figure 4. Starting with significant stationary times in the area < 16 seconds, in the first 33% of the run, coupled with a strong sound layer at the sea floor and a wave high $h_{\frac{1}{3}} < 1.5$. After this first third with increasing wave height and a homogeneous sound field, the stationary time breaks down under the observation threshold of $146ms$, a typical magnitude of multi carrier symbol times in communication systems. This effect is starting at the sea floor. In the last third the stationary time is equal or shorter than the observation time. It seems to be correlated with antisymmetric Doppler power spectra. Shorter M-sequences for the probing of acoustical channels reduce the monitor horizon of the geometric echo structure. For example, a minimal length of $10ms$ for a frozen ocean is not helpful, typical time spreads are two, up to three, magnitudes higher. With this effect run A40 covers a wide span of realizations, only with the variation of the transmission medium. This implies a correct measurement installation, a correct probe calculation and a violation of the general assumption of WSS and US. But - what kind of influence dominates this effect, the Non-WSS or Non-US? We need an indicator function for an in situ calculation, in the modem, to choose the correct model.

Both components WSS and US can expressed via the new indicators [7], [5]:

$$(Ind_{WSS}, Ind_{US}) :=$$

$$\left(\sqrt{\frac{\underset{\tau}{mean}\ \underset{\Delta t}{max}\ E\{E\{H_i(t,\tau)|H_i(t+\Delta t,\tau)\}|E\{H_q(t,\tau)|H_q(t+\Delta t,\tau)\}\} \cdot \underset{\tau}{mean}\ \underset{\Delta t}{max}\ E\{E\{H_i(t,\tau)|H_q(t+\Delta t,\tau)\}|E\{H_q(t,\tau)|H_i(t+\Delta t,\tau)\}\}}{1+\underset{\tau}{var}\ \underset{t}{mean}\ |H(t,\tau)|}},\right.$$

$$\left.\sqrt{\frac{\underset{t}{mean}\ \underset{\Delta \tau}{max}\ E\{E\{H_i(t,\tau)|H_i(t,\tau+\Delta\tau)\}|E\{H_q(t,\tau)|H_q(t,\tau+\Delta\tau)\}\} \cdot \underset{t}{mean}\ \underset{\Delta \tau}{max}\ E\{E\{H_i(t,\tau)|H_q(t,\tau+\Delta\tau)\}|E\{H_q(t,\tau)|H_i(t,\tau+\Delta\tau)\}\}}{1+\underset{t}{var}\ \underset{\tau}{mean}\ |H(t,\tau)|}}\right)$$

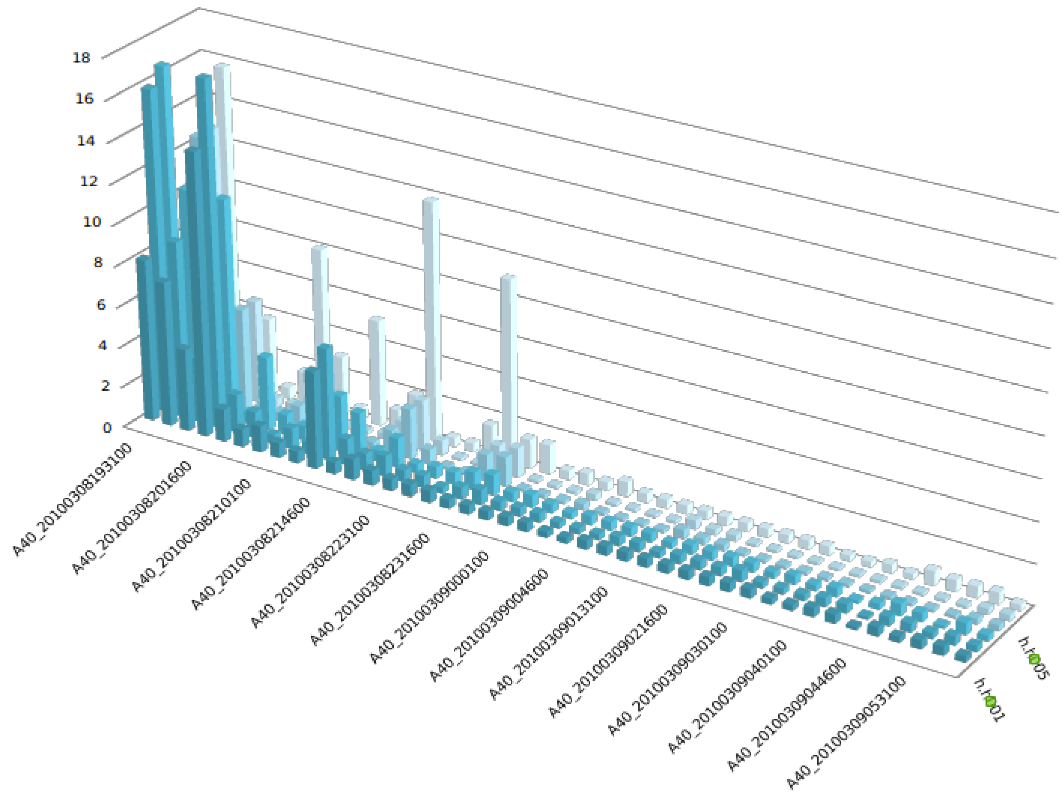


Fig. 4. Stationary time of the run A40 as number of impulse responses multiply with the observation time 0.1457s.

Both indicators can determine in situ on the receiving modem how to chose the correct model, and to help the transmitter after the relaying of the values. The channel in this experiment is Non-WSS but US, the last as a result of the reduced influence of the sediment on the transmission process. The first third shows, in figure 5 with the green dots, the same situation: A higher stationary part is at the beginning of the experiment, decreasing with the time (blue and red dots). The calculation method details can be found in [7].

4. Insufficient evolution modeling

Without modeling knowledge, the modem has no chance in this situation to estimate the node distance based only on travel time. There is no Line Of Sight (LOS). The observed travel time of the GPS-triggered signals was between $2.620s$ and $2.638s$, for the LOS-distance of $3680m$ this means $2.556s$, and thus a detour of $40m$ to $118m$. A travel time modeling, using for example the sound propagation model MOCASSIN (MOnte CArlo SchallStrahlen INtensitäten), of the stationary experiment calculates in the hydrophone depth with only one given reference sound speed profile, the values of the following table 1:

ray	travel time [s]	hydrophone depth [m]	intensity [-]	travel distance [m]	integrated sound speed [m/s]
a	2.6321	74.9934	0.04837799	3760.4278	1428.6447
b	2.6844	74.9878	0.00413327	3828.8495	1426.3222
c	2.6332	74.9433	0.04467838	3762.0598	1428.6939
d	2.6844	74.9371	0.00414643	3828.8135	1426.3137
e	2.5914	74.8988	0.12385749	3723.7129	1436.9549
f	2.6571	74.8855	0.01434075	3791.6655	1427.0098

ray	travel time [s]	hydrophone depth [m]	intensity [-]	travel distance [m]	integrated sound speed [m/s]
g	2.5707	74.8594	0.38968162	3708.3704	1442.5722
h	2.6319	74.8449	0.05892624	3759.7690	1428.4873
i	2.6116	74.8425	0.14297891	3739.6101	1431.9496

Similar values can be determinate with *bellhop*. The main problem with the calculations is the time invariance. A frozen ocean in the model without current and surface activities cannot describe the reality. At the beginning of the acoustic experiment is a single path in the 30s-impulse response evolutions visible [9], often by a $2ms$-ray cluster superimposed. The wave height was in this period lower than $1.5m$. Looking into the figure collection 9 [9] over the eleven hours the last third of the experiment time was homogeneous speed without a strong layer (blue and red points in figure). The diffuse multi path cluster in the time evolutions is a result of the slightly increasing sea state, over a number of reflections. The difference between the first scattering center path of $d_7 = 8 \times \sqrt{(d0/8)^2 + 70^2} \approx 3722.36m$ and the second path $d_9 = 10 \times \sqrt{(d0/10)^2 + 70^2} \approx 3745.98m$ confirmed an delay of $(d_9 - d_7)/1420m/s \approx 16.5ms$. The muddy seabed has only a little influence on the transmission process with the strong layer.

The current in the order of $0.1 - 0.2m/s$ compared to the sound speed of $1420 - 1440m/s(< 0.1\%_0)$ is the origin for the Doppler spread component. The ratio of the integrated sound speed of the rays h and i in the table is 1428.4873 / 1431.9496 = 0.997.

This knowledge cannot be generated by the standard modem, because of the lack of accurate time synchronization, and the nonlinear behavior of the acoustical channel.

5. Conclusion

This shallow water communication experiment - run A40 - has shown, as a counter example, that even in stationary scenarios of underwater communication links the WSSUS assumption can be violated. In-stationary scenarios are not only the situation with moving platforms, also the moving medium is involved in the process. Run A40 is neither stationary in wide-sense, nor is it constant over time differences. The channel is time variant and it is changing faster than $146ms$ even with fixed installations at the sea floor. Doppler asymmetries and symmetries are found in the same time slot in distances of $32cm$. A wind-driven surface influence was not recognized. The Doppler spread generated by multipath and sound speed changes in the medium over time can be the main contribution. Therefore it is essential for UAC designers to take into account the limitations of the WSSUS concept. Multi carrier symbols are changing in the symbol time. With the new developed indicator pair it is possible to split in situ between WSS and US to use it in the modem.

The hydro-acoustic modeling-community of practice is looking for simplifications of the wave equation for a useful processing time on today's computers. As part of this school of practice we are using only one sound speed profile over depth, with additional stochastical variations and some surface sub models. MOCASSIN is a result of this simplification step. But the sound speed field depending on the position (latitude, longitude), depth and time and the surface waves coupled with the wind, has to model with the Navier-Stokes equation as input for the acoustical wave equation. This simple experiment shows, that the model instruments are insufficient with a moving and varying medium.

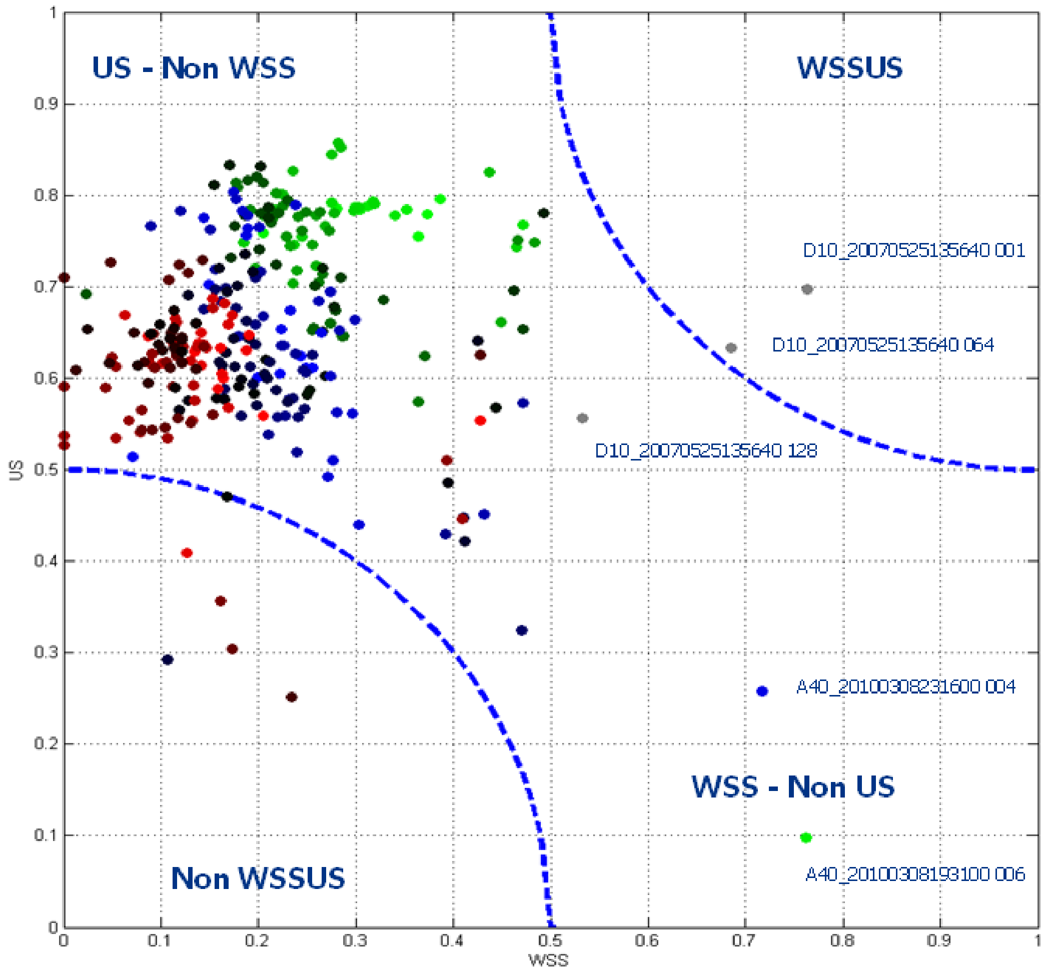


Fig. 5. Plot of the indicator with WSS and US component for every 30s frame over the eleven hours. Green dots represents the channel stationary and scatter behavior of the first third of the run, in blue dots the run situation in the second third in the middle of the run time and in red the last third from 66% to the morning 6.30h. The three gray dots represent a drifting short-range measurement in the Mediterranean Sea (CCUP 2007, Run D10 20070525135640) at the surface, in the middle and at the bottom of the water column as a reference of a quasi fulfilled WSSUS channel.

Acknowledgement

Gratefully acknowledge to Dr. Frank Gerdes for his work on the virtual ocean measure-ment and the crew of the sea trial for their help and contribution for this important data set.

References

[1] Lotfi A. Zadeh, *Frequency Analysis of Variable Networks*, Proceedings of the IRE, 38:291, 1950.
[2] Thomas Kailath, *Sampling Models for Linear Time-Variant Filters*, Technical Report 352, MIT, 1959.
[3] Philip A. Bello. *Characterization of Randomly Time-Variant Linear Channels.* IEEE Transactions on Communications Systems, Volume:11, Issue: 4, December 1963.
[4] Rolf Thiele, *Anwendung der Theorie zeitveränderlicher Filter zur Beschreibung des Flachwasser-Schallkanals*, Dissertation, Universität Hannover, 1972.
[5] Ivor Nissen, Iwona Kochańska *Hydroakustik-Messung im Bornholmbecken zur lokalen Stationaritätsmodellierung beim Unterwasserschallkanal*, DAGA Aachen, 2016.

[6] Paul A. van Walree, Trond Jenserud, Morten Smedsrud *A Discrete-Time Channel Simulator Driven by Measured Scattering Functions.* IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 26, NO. 9, DECEMBER 2008

[7] Iwona Kochańska, Ivor Nissen *Limitations of WSSUS modeling of stationary underwater acoustic channels.* Hydroacoustics Vol. 19, 2016.

[8] Franz Hlawatsch, Gerald Matz *Wireless Communication over Rapidly Time-Varying Channels*, 2011.Ivor Nissen, Iwona Kochańska *Filmsequenzen für den Beitrag Hydroakustik-Messung im Born-holmbecken zur lokalen Stationaritätsmodellierung beim Unterwasserschallkanal* Supplementary resources, Researchgate, https://www.researchgate.net/publication/303603968.

[9] Ivor Nissen, *Pilot-Based OFDM Systems for Underwater Communication Applications*, in Proc. Conf. on New Concepts for Harbour Protection, Littoral Security and Underwater Acoustic Communications, Istanbul, Turkey, July 2005.

[10] Wolfgang Jans, Ivor Nissen, Erland Sangfelt, Connie-Elise Solberg, Paul van Walree *UUV -Covert Acoustic Communications - Preliminary Results of the First Sea Experiment.* UDT 2006, Hamburg.

[11] R. C. Dixon, *Spread-Spectrum Systems*, 2^{nd} ed., John Wiley Sons, p. 87, 1984.

[12] John Sadowsky, *On the Correlation and Scattering Functions of the WSSUS Channel for Mobile Communications*, 1998.

1. Appendix

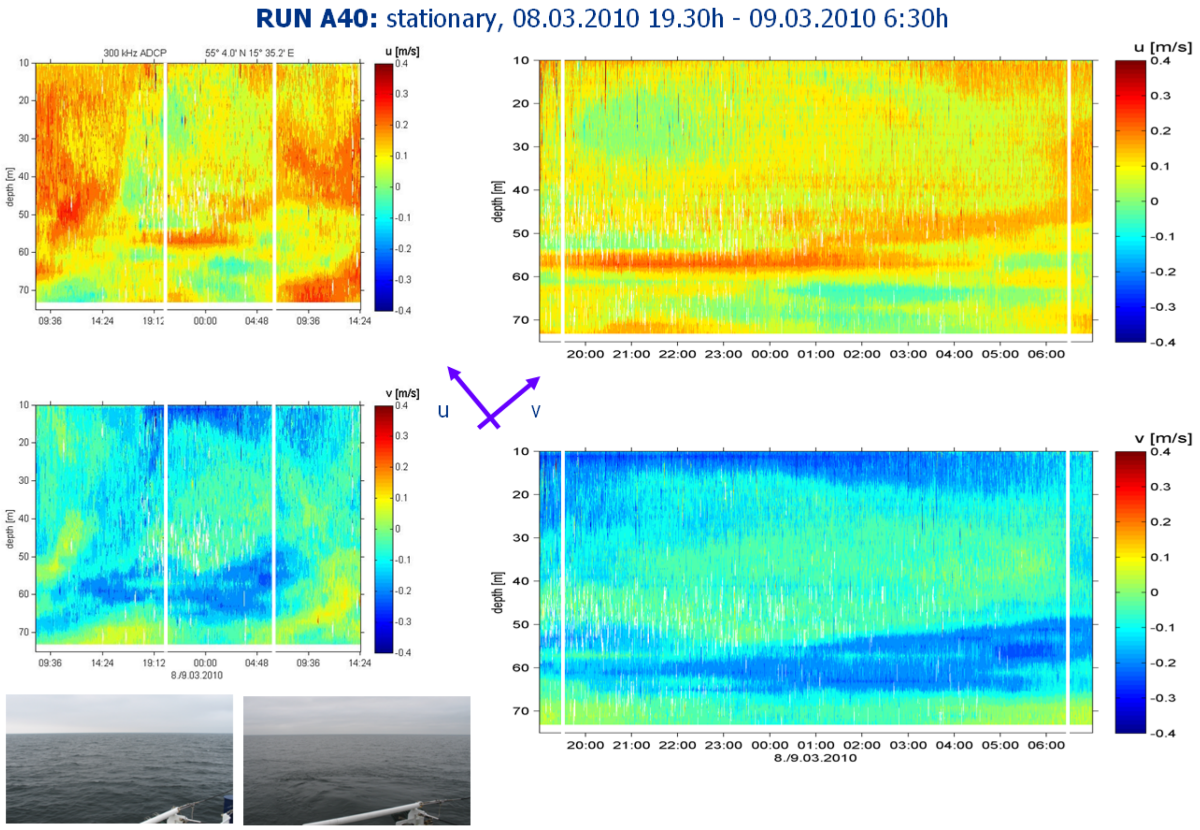


Fig. 6. Current measured with the 300 kHz ADCP in the middle of the acoustical range.

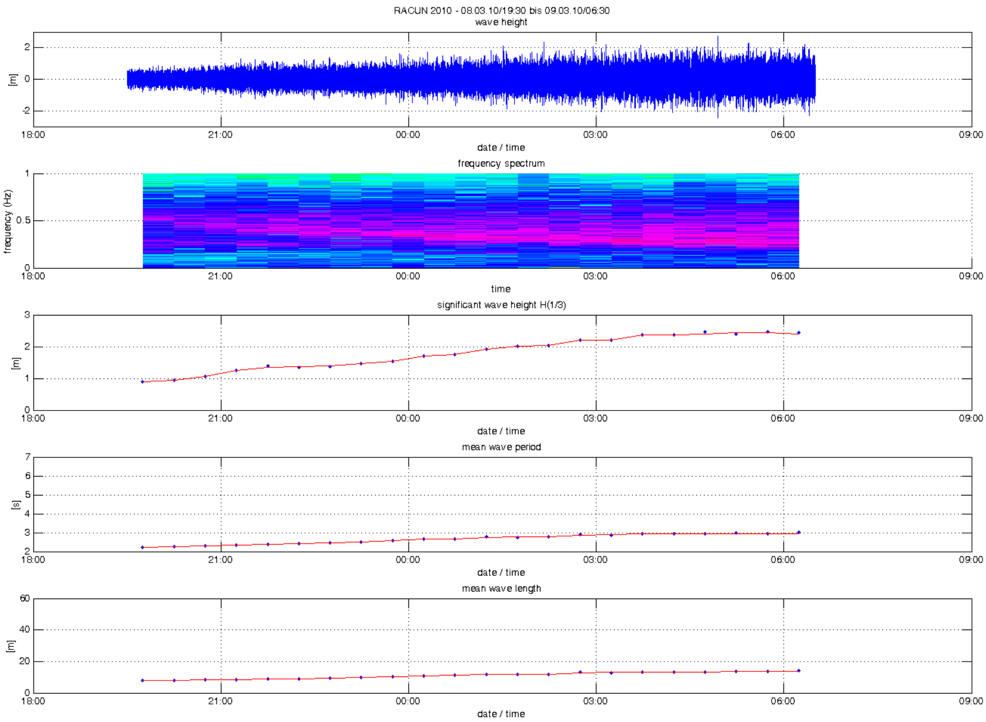


Fig. 7. Wave height measured with the waverider buoy outside of the acoustical range.

30s-Probe	h.h001	h.h002	h.h003	h.h004	h.h005	h.h006	h.h007
A4020100308193100	8.0135	15.8813	16.6098	0.1457	0.1457	0.1457	14.2786
A4020100308194600	7.1393	8.742	10.9275	13.113	13.113	15.7356	10.9275
A4020100308200100	4.0796	3.2054	1.0199	1.1656	1.1656	1.8941	1.7484
A4020100308201600	13.9872	17.0469	10.9275	5.0995	5.0995	3.7882	3.3511
A4020100308203100	1.6027	1.8941	0.5828	0.4371	0.4371	0.5828	1.3113
A4020100308204600	0.8742	1.3113	3.6425	0.4371	0.4371	1.6027	0.8742
A4020100308210100	1.3113	0.4371	1.0199	1.0199	1.0199	8.0135	10.9275
A4020100308211600	0.7285	1.0199	0.7285	0.1457	0.1457	2.914	4.6624
A4020100308213100	0.5828	0.5828	0.5828	0.1457	0.1457	0.5828	4.225
A4020100308214600	4.8081	5.5366	2.7683	0.1457	0.1457	5.2452	6.5565
A4020100308220100	0.5828	1.3113	2.1855	0.2914	0.2914	1.0199	3.4968
A4020100308221600	1.0199	0.8742	0.5828	1.1656	1.1656	2.0398	0.8742
A4020100308223100	0.7285	1.0199	1.457	2.4769	2.4769	11.8017	4.9538
A4020100308224600	0.5828	0.5828	0.4371	0.7285	0.7285	0.4371	0.4371
A4020100308230100	0.5828	0.5828	0.5828	0.1457	0.1457	0.4371	0.4371
A4020100308231600	0.5828	0.2914	0.5828	0.1457	0.1457	1.6027	2.914
A4020100308233100	0.4371	0.5828	0.8742	1.3113	1.3113	9.0334	3.0597
A4020100308234600	0.4371	0.7285	1.0199	1.457	1.457	1.457	2.0398
A4020100309000100	0.4371	0.4371	0.4371	0.1457	0.1457	1.457	1.8941
A4020100309001600	0.4371	0.4371	0.5828	0.1457	0.1457	0.4371	0.4371
A4020100309003100	0.4371	0.4371	0.4371	0.1457	0.1457	0.5828	0.5828
A4020100309004600	0.2914	0.2914	0.2914	0.2914	0.2914	0.4371	0.5828
A4020100309010100	0.2914	0.2914	0.4371	0.1457	0.1457	0.7285	0.5828
A4020100309011600	0.4371	0.2914	0.4371	0.1457	0.1457	0.4371	0.4371
A4020100309013100	0.4371	0.4371	0.4371	0.1457	0.1457	0.4371	0.7285
A4020100309014600	0.4371	0.4371	0.4371	0.1457	0.1457	0.4371	0.4371
A4020100309020100	0.4371	0.2914	0.2914	0.4371	0.4371	0.4371	0.4371
A4020100309021600	0.4371	0.4371	0.4371	0.2914	0.2914	0.4371	0.4371
A4020100309023100	0.4371	0.4371	0.4371	0.2914	0.2914	0.4371	0.2914
A4020100309024600	0.4371	0.4371	0.4371	0.1457	0.1457	0.4371	0.4371
A4020100309030100	0.4371	0.5828	0.4371	0.1457	0.1457	0.4371	0.4371
A4020100309031600	0.4371	0.2914	0.2914	0.1457	0.1457	0.4371	0.4371
A4020100309033100	0.2914	0.2914	0.4371	0.1457	0.1457	0.4371	0.4371
A4020100309040100	0.2914	0.2914	0.2914	0.1457	0.1457	0.2914	0.2914
A4020100309041600	0.4371	0.4371	0.4371	0.1457	0.1457	0.2914	0.2914
A4020100309043100	0.4371	0.4371	0.1457	0.1457	0.1457	0.4371	0.4371
A4020100309044600	0.1457	0.1457	0.2914	0.1457	0.1457	0.2914	0.2914
A4020100309050100	0.4371	0.4371	0.5828	0.1457	0.1457	0.7285	0.7285
A4020100309051600	0.2914	0.4371	0.4371	0.1457	0.1457	0.5828	0.2914
A4020100309053100	0.4371	0.2914	0.1457	0.1457	0.1457	0.5828	0.4371
A4020100309054600	0.4371	0.4371	0.5828	0.2914	0.2914	0.5828	0.4371
A4020100309060100	0.2914	0.2914	0.2914	0.2914	0.2914	0.2914	0.2914

Fig. 8. Stationary time of the run A40 as number of impulse responses multiply with the observation time 0.1457s. Note, the PRBS sequence can track channel changes to the length of the M sequence. Low values in the order of the observation time T' seems to be correlated with antisymmetrical Doppler power spectra. The columns h.h001 to h.h007 denote the consecutive hydrophones.

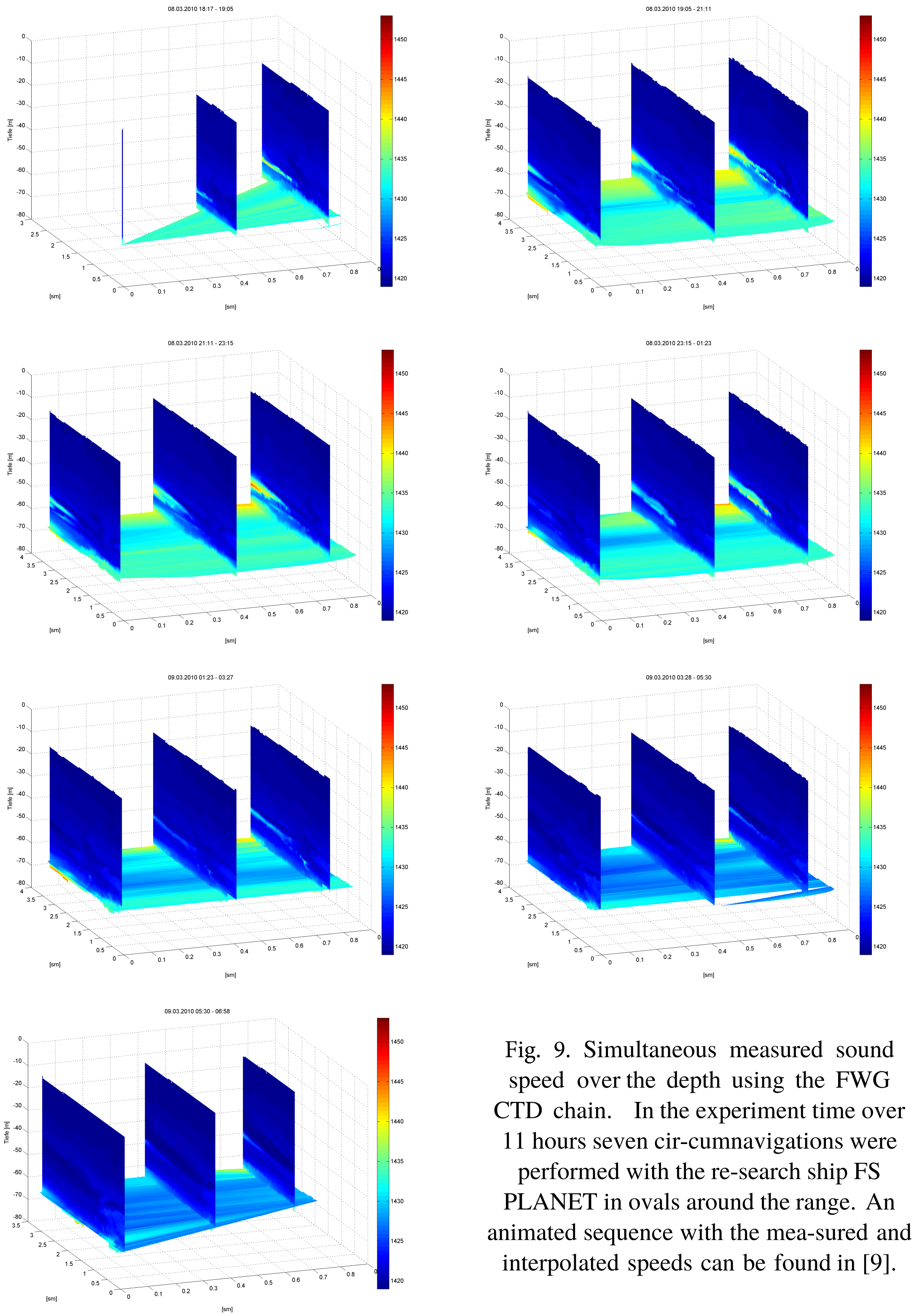


Fig. 9. Simultaneous measured sound speed over the depth using the FWG CTD chain. In the experiment time over 11 hours seven cir-cumnavigations were performed with the re-search ship FS PLANET in ovals around the range. An animated sequence with the mea-sured and interpolated speeds can be found in [9].