MEASUREMENTS AND SIMULATIONS OF ACOUSTIC PROPAGATION LOSS IN THE BALTIC SEA

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Abstract: *Between 2002 and 2007 FWG has carried out four sea trials at different locations of the western Baltic Sea. These were BAROC 2002 near Landsort and Gotland and UCAC 2006, VOICE 2006 and UCAC 2007 east of Bornholm. Altogether quite a large number of runs with different configurations of source and receiver and different environmental conditions were analysed. Important processing outputs are transmission loss (TL) and channel impulse response as function of acoustic propagation distance. The data add to FWG's existing transmission loss data base which is largely based on experiments performed before 1990. Improvements of the experimental equipment as well as of the processing techniques allowed us to probe the acoustic channel more thoroughly than previously possible. This provides new opportunities to validate but also to pinpoint shortcomings of existing sound propagation models. In particular, our focus is on a possible improvement of the stochastic ray tracer SIPSI / MOCASSIN developed by FWG. In this paper we give an overview of the sea trials and compare measured and modelled transmission loss for a few situations.*

Keywords: *propagation loss, transmission loss, Baltic Sea, SIPSI, MOCASSIN*

1. INTRODUCTION

Before 1990 FWG (Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik) had conducted a long term programme on measuring sound propagation in the Baltic. The motivation for this programme is described in [1]. The standardised experiments used air-dropped explosives as sound source and yielded propagation loss (TL) in one-third octave bands using spectral analysis procedures. The vertical resolution, that is the hydrophone spacing, was about 10m and the horizontal spacing about 1 nautical mile. The data were applied to the validation of a range dependent acoustic propagation model which has become the core, called SIPSI, of the German Navy's sonar performance model MOCASSIN. A key feature of SIPSI is stochastic ray tracing. This method uses a Monte Carlo approach for the stochastic change of ray directions and was found to be a very effective way of accommodating the acoustic forward scattering which is caused by variations of the sound speed in the water column [1]. In line with the incoherent transmission loss data from the experiments, with the model's stochastic approach and with operational conditions and needs, the model calculates incoherent TL only and requires only one sound speed profile to be specified.

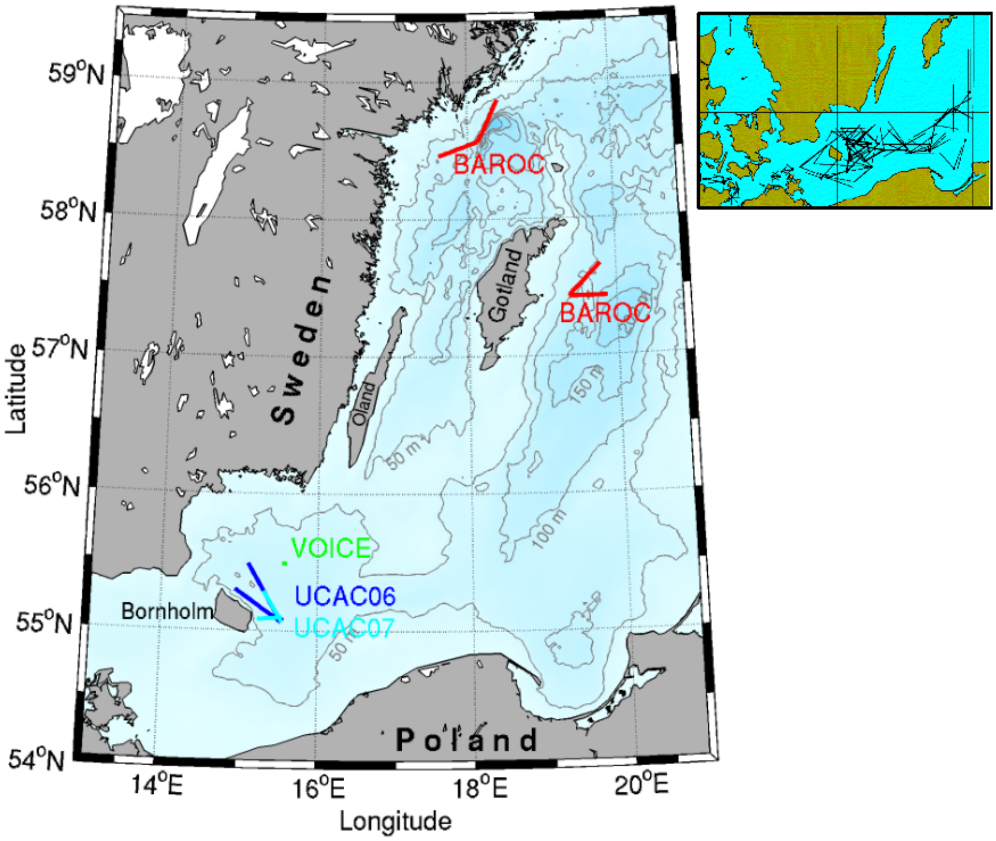

Fig.1: Left: Tracks of the TL runs of the sea trials BAROC02, UCAC06, VOICE06 and UCAC07. BAROC took place near Landsort and near Gotland. VOICE06 used a fixed acoustic range with a comparatively short distance between source and receiver. Top right: FWG's transmission loss runs performed in the Baltic Sea before 1990 [1].

Using new equipment and new processing techniques FWG resumed TL measurements in 2001. In the Baltic Sea four sea trials have been carried out so far (Fig. 1). These were

BAROC in May 2002 near the Swedish coast at Landsort and near Gotland [2, 3, 4, 5, 6], UCAC06 in August 2006, UCAC07 in August 2007 near Bornholm [8, 10] and VOICE06 in November 06 also near Bornholm [7]. The objectives of these sea trials were not identical. In fact, for UCAC obtaining TL was more a by-product rather than the primary goal as the main motivation of these trials was to develop and test underwater communication methods. Nevertheless, some portions of the trials were devoted to the measurement of TL and these used the same acoustic equipment (with the exception of VOICE06), followed the same measurement procedures and employed identical or at least comparable processing techniques. Here we will describe only the salient features of the TL experiments. Details may be found in [2, 3, 4, 5, 6].

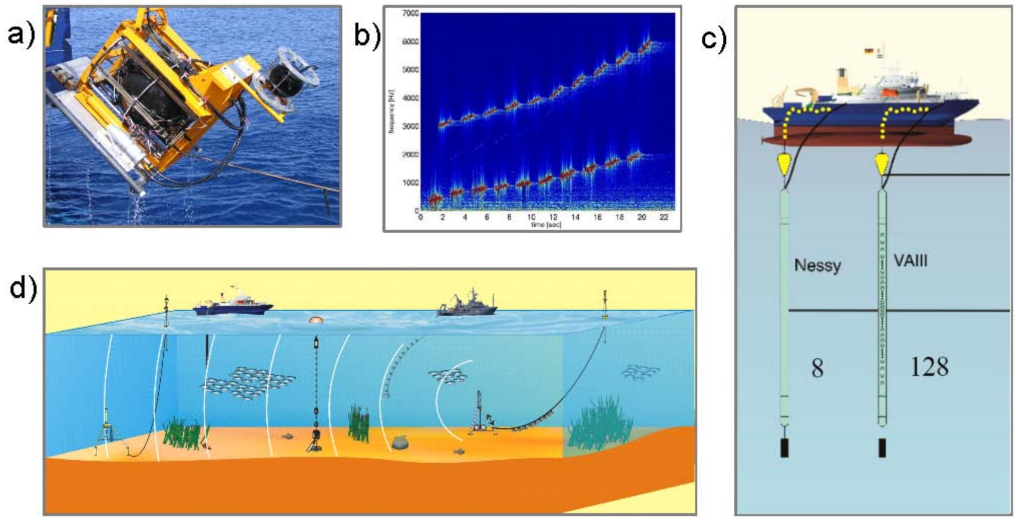

Fig.2: a) Towed transducer frame used during the UCAC trials with two omni-directional transducers for different ranges of frequency. b) Spectrogram of the sequence of twenty one second duration LFMs as used for the BAROC experiment. c) Schematic of the receiver systems deployed from the anchored WFS Planet during the UCAC sea trials. A NESSY hydrophone chain consisting of up to eight omni-directional hydrophones with a vertical spacing of 10m and/or the VAIII, a nested, vertical array of 128 hydrophones distributed over a length of 38m, were used. d) Schematic of the fixed range experiment VOICE06 with stationary source and receiver towers.

For the BAROC and UCAC trials one vessel was anchored deploying a NESSY hydrophone chain or the Vertical Array III (VAIII) or even both (Fig. 2c). A second vessel towed a frame holding two (UCAC) or three (BAROC) transducers. Towing was along a straight line away from the receiving vessel (outbound Run) or back on the same line towards it (inbound Run). Track length varied between 20km to 60km. For the TL measurements a sequence of about twenty “narrow band” LFMs (bandwidths were 200Hz or 400Hz) plus up to four “broad-band” LFMs (bandwidth of 3500Hz) was transmitted at intervals varying between 60 and 180 seconds. With a tow speed of about 5 knots this translates into a horizontal resolution of 150m to 450m. The received signals were analysed using matched-filter techniques which yielded both impulse responses and signal levels as function of distance between source and receiver and as a function of 20 centre frequencies between about 400Hz and 5000Hz. It was investigated whether the new TL data are comparable with the ones obtained by the previous method [1]. Differences do exist. However, being understood they cause little problems.

One issue with the TL versus distance data obtained using a towed sound source is that, because of the slow tow speed compared to the speed of sound, the effects of spatial and temporal variability cannot be separated. This difficulty becomes particularly troublesome in areas with high spatial variability of the environment and/or whenever a high sea-state caused movement of the transducer. Although this issue was recognized right from the beginning, tight cruise schedules and logistics allowed to perform only a few measurements with a stationary or drifting sound source (e.g. [5] for BAROC or Fig. 6 below). The trial VOICE06 is special as it was entirely focused on the temporal variability and therefore used completely stationary systems which were deployed on the sea-floor (Fig. 2d). It furthermore used a smaller number of LFMs [7].

It should be understood that if one wants to go beyond just measuring the temporal variability of acoustic propagation, that is if one wants to relate the acoustic to the environmental variability, one is forced to put significant effort in doing environmental measurements. For BAROC and VOICE06 extra vessels were tasked with accessing the environment and lots of extra environmental measurements were performed and data gathered [2, 3, 4, 7]. For the UCAC trials this was not possible.

Compared to the older TL measurements the new sea trials improved the quality of the data in many ways: the horizontal and vertical (for the VAIII) resolution is much improved, TL data are supplemented by impulse response functions and the amount of supplementing environmental data has increased greatly. This helps to discover and explain effects which previously were not accessible, and it may discover deficiencies in the modelling that can no longer be 'explained' with measurement uncertainty and/or lack of environmental input.

2. MEASUREMENTS AND SIMULATIONS

Of the four sea trials **BAROC** has so far been analysed most [2, 3, 4, 5, 6, 9]. The sound speed field at the Landsort site near the Swedish coast showed a well developed sound channel with strong spatial variability as consequence of a series of cold and warm water fronts [Fig. 3]. At the Gotland site the variability was less pronounced, but still significant, particularly at the depth of the sound channel (see [4, 9]). We investigated the effect of the spatial variability by analysing measured TL curves from four Runs at Landsort and two Runs at Gotland with different receiver and source depths and for frequencies of 400Hz, 1300Hz and 5000Hz. Altogether 144 measured TL curves were used. Simulations were performed with SIPSI and with MOCMULTI which is an extended version of SIPSI. MOCMULTI was developed by FOI to do 2D and 3D propagation modelling in the Baltic [6].

When forward scattering is the important process at work, then there is no difference between the two models. This is the case, for instance, when the sound source is located inside and the receiver above the sound channel (or vice versa). When the sound speed field has a strong deterministic component, MOCMULTI has got advantages over SIPSI. Fig. 3 shows such a case and another is described in [9].

We now turn to the UCAC sea trials. **UCAC06** used the VAIII chain as receiver ranging from about 15m to 53m and **UCAC07** the NESSY chain ranging from 10m to 60m. Other parameters as the transmitter configuration, calibration settings, the position of the receivers, the tracks and the LFMs were identical. We did not have a CTD-chain but carried out repeated CTD-casts from the receiving ship and also a few CTD's and XBTs along the tow track. For both trials the observed oceanographic conditions were typical for Baltic Sea summer conditions, but they were not identical (Fig. 4).

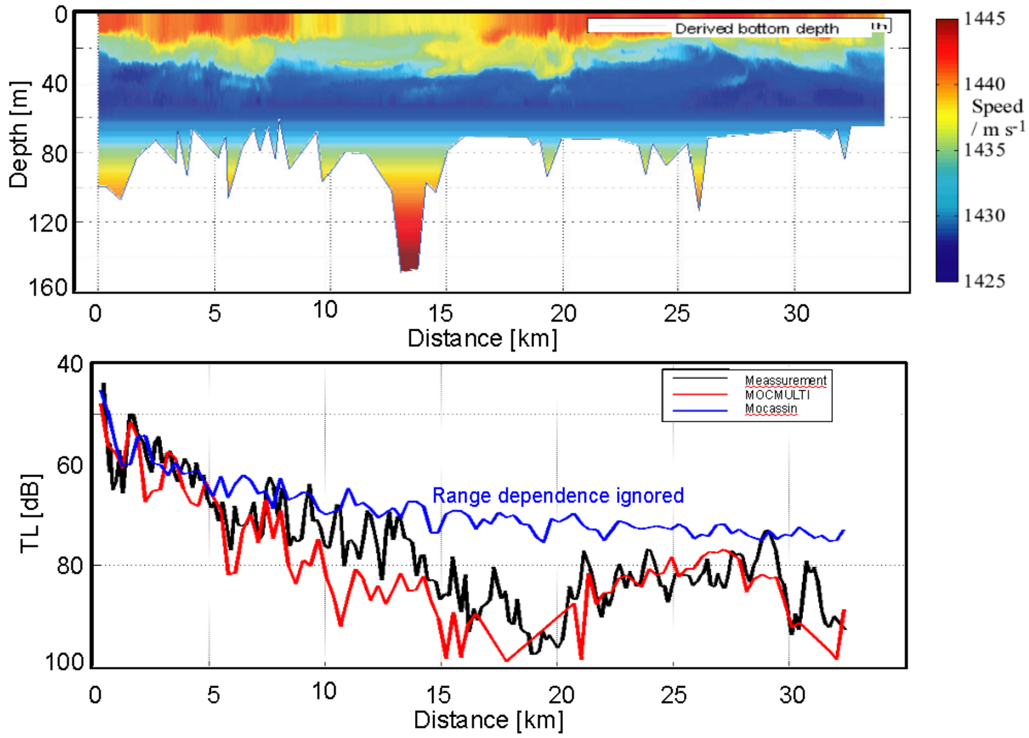

Fig. 3: Top: Contour of sound speed measured with a towed CTD-chain during BAROC at site A near Landsort. For the sound propagation simulation the sound-speed contours were extended from the last CTD-chain sensor at about 50m to the sea-floor. Bottom: Measured and modelled (blue: SIPSI */ MOCASSIN, red: MOCMULTI) TL curves for a frequency of 1300 Hz and source and receiver depth of 30m.*

During UCAC06 there was a very sharp thermocline and the sound speed minimum was about 1427m/s at a depth of 30m to 35m. During UCAC07 the sound speed minimum was only about 1435m/s, it was about 10m deeper, and the thermocline change was more gradual. Compared to BAROC the observed variability of the sound speed profiles was small.

The TL curves are as expected with a large TL for the hydrophones in the surface layer and a much lower TL for those inside the sound channel (Fig. 4). Furthermore the UCAC06 and UCAC07 TL curves are quite similar. We note quite a bit of variability on the TL curves. One could think the movement of the transducer frame induced by the movement of the towing vessel to be a possible explanation. However, the same amount of variability is also observed for a nearly stationary vessel (Fig. 5). A similar observation is described in [5] for the BAROC experiment. We may therefore assume that the variability is caused by the natural variability of the sound speed profiles.

We performed simulations with SIPSI for several runs of UCAC06 and UCAC07 using four different frequencies. Since we did not have a 2D sound speed field we did not use MOCMULTI except to test whether a range-dependent sound speed field, which we derived from the CTD profiles and one or two XBT casts done along the track, would have a significant effect. It did not. The modelled TL curves for Run A05 (UCAC06) show good agreement with the measurements for 3400Hz (Fig. 5) and 5400Hz. We emphasize that a deterministic model would not be able to correctly predict the TL outside the sound channel with only one sound-speed profile given as input. SIPSI performs here very well. For lower frequencies (900Hz and 1300Hz, not shown here) the modelled TL was too small for distances larger than 30km. Diffraction effects not included in the ray modelling might explain this (see also [6]).

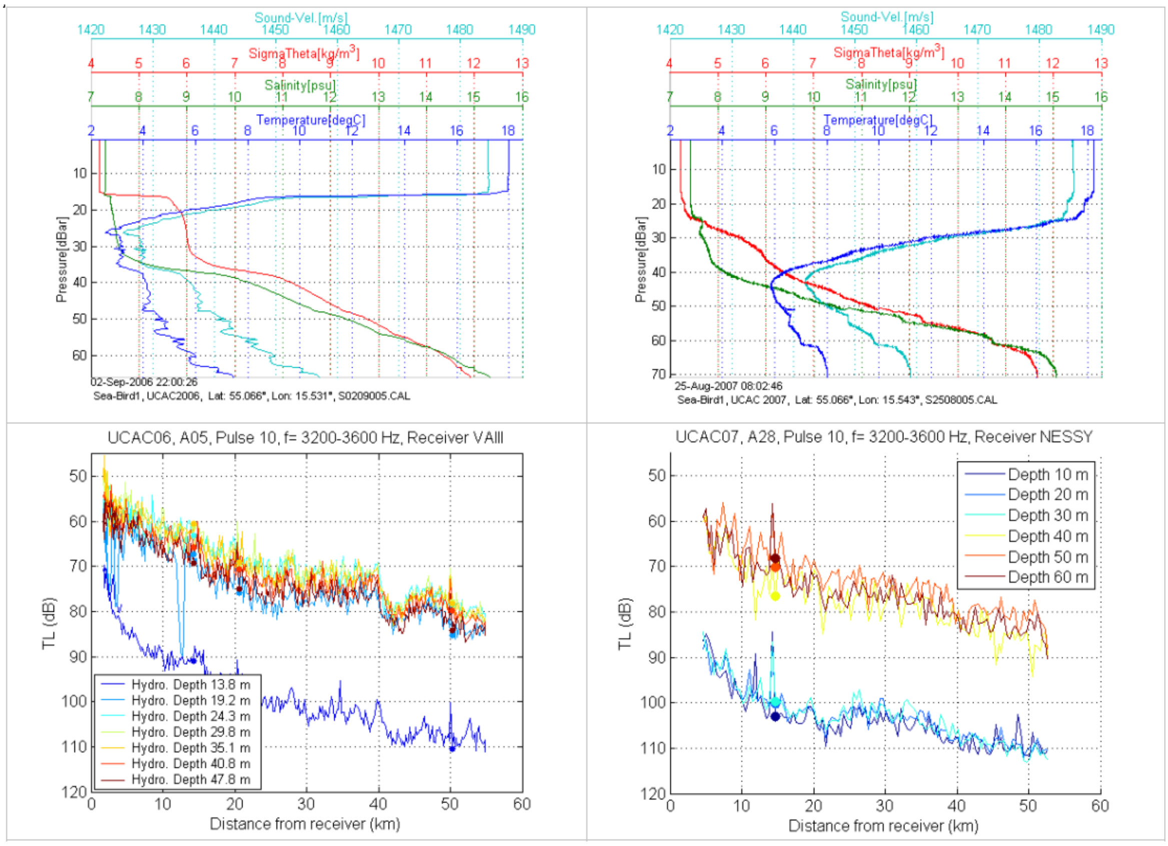

Fig. 4: Top: Typical temperature, salinity, density and sound-speed profiles for UCAC06 (left) and UCAC07 (right). Bottom: TL curves for a centre frequency of 3400Hz. The source was towed at the centre of the sound channel [10]. The tow tracks of A05 (UCAC06) and A28 (UCAC07) are identical.

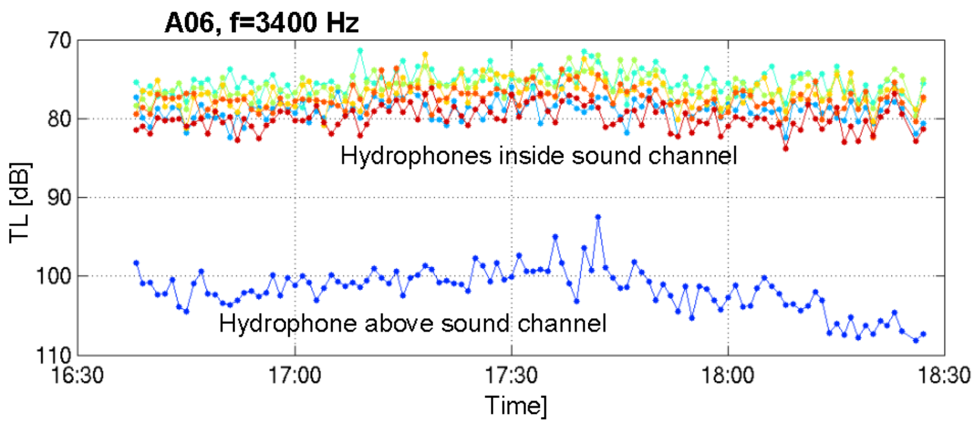

Fig. 5: Measured transmission loss during run A06. The tow ship drifted only about 50m during 90 minutes. Run A06 was performed 20 minutes after the end of Run A05. The propagation distance was about 51km. The hydrophones depths are those of A05.

Surprisingly we were not able to achieve the same level of agreement for Run A28 of UCAC07 (Fig. 6) although we varied many parameters (sea-floor, sound speed profile, transducer depth, receiver depth, matched filter procedure). A calibration problem can be ruled out. One parameter which, for some runs, can be used to improve the agreement is the value of SIPSI's diffusion constant which determines the amount of forward scattering. However, we were not able to find one single optimum value which would improve the agreement for all combinations of source depth, receiver depth and frequency. It was already argued in [6] that a solution might be to extend SIPSI's ray diffusion approach for situations with large thermocline steepness [11]. Furthermore, diffusion might be frequency dependent. Consequently, we might end up with a diffusion function rather than a constant.

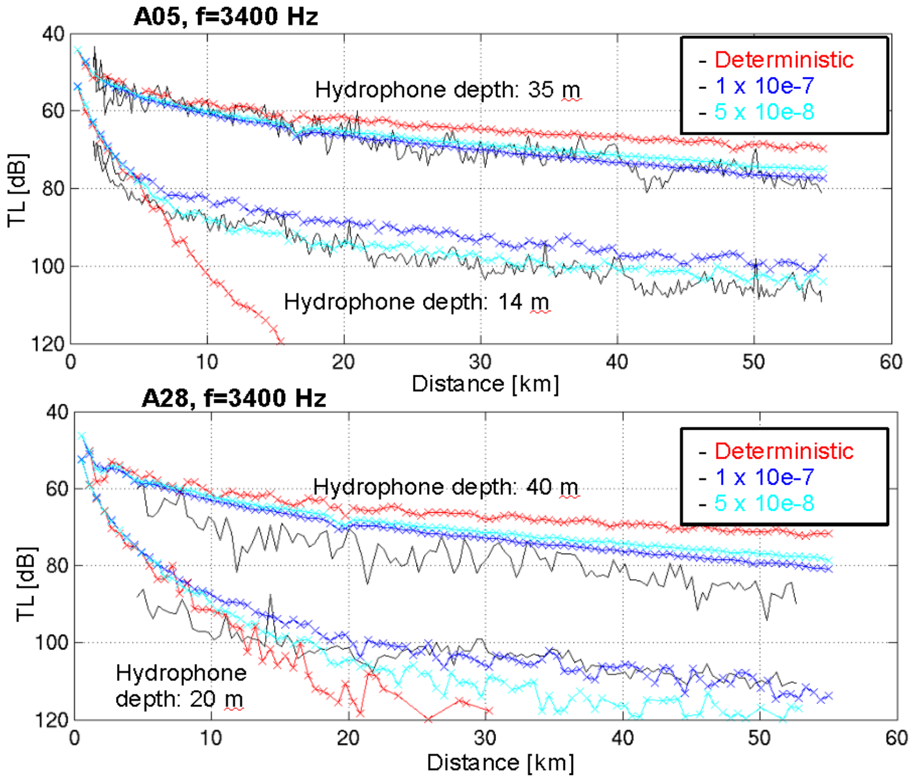

Fig. 6: Measured (black) and modelled (red, blue, and cyan) TL curves for two hydrophone depths, one above and the other inside the sound channel. The centre frequency was 3400 Hz. Modelled curves are shown for deterministic mode and two different diffusion constants. Smaller values mean less forward scattering. The deterministic mode is without scattering. A value of 10e-7 is recommended for the Baltic.

3. SUMMARY

We have given an overview of four relatively recent transmission loss experiments that were carried out by FWG and partner institutes between 2002 and 2007 in the Baltic Sea. In contrast to FWG's earlier transmission loss experiments [1] the main processing method has been the matched filter method. The acoustic channel could be probed in greater detail and the variety of different measurement configurations with respect to source and receiver depths, frequency, and (summer) environmental conditions allows a comprehensive test of a sound propagation model. The comparison with SIPSI yields a mixed bag of good, satisfactory and some unsatisfactory agreements. The last may, for example, be caused by an unsatisfactory representation of the environment or by the neglect of diffraction effects. The first problem is operationally unavoidable and the second inherent to the ray approach. Nevertheless, some improvement might also be possible by modifying SIPSI's ray diffusion approach in cases with high gradient thermoclines [6, 11]. The charm of this approach would be that the amount of environmental input to SIPSI and hence also to the operational model MOCASSIN would not increase.

4. ACKNOWLEDGEMENTS

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