BROADBAND ACOUSTIC SIGNAL VARIABILITY IN TWO “TYPICAL” SHALLOW-WATER REGIONS

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Successful sonar performance predictions in shallow-water regions are strongly dependent on accurate environmental information used as input to numerical acoustic prediction tools. The sea-surface and water-column properties vary with time and this time variability of the ocean introduces fluctuations in received acoustic signals. The lack of knowledge of the environmental changes results in uncertainty in predictions of the acoustic propagation. SACLANTCEN has recently conducted two experiments to quantify the impact of the time-varying ocean on broadband acoustic propagation in “typical” shallow-water regions. Extensive oceanographic data were collected during the acoustic transmissions. Broadband acoustic signals were transmitted every minute over a fixed propagation path up to 18 h. The signals were received on a vertical array at fixed ranges of 1 to 10 km from a moored source. The variability of the oceanographic and acoustic data is presented for the two experimental areas. Numerical modelling of the sound propagation using the measured environmental data is shown and compared to the acoustic data. The possibility of predicting the received signals with an extensive knowledge of the underwater environment is discussed.

1 Introduction

Sound propagation in the ocean depends strongly on the actual location. In shallow-water regions the seabed properties are known as the key parameters that affect the sound propagation. However, experimental data from repeated acoustic transmissions over fixed propagation path in particular shallow-water regions shows significant impact from the time-varying ocean on the sound propagation as variability in transmission loss (TL) and signal arrival time. Prediction of sound propagation in shallow water is generally performed by assuming a time-invariant ocean. This assumption is sufficient for certain shallow-water regions as numerical modelling of the sound propagation has been performed successfully by using “frozen” environmental inputs [1–3]. Experiments conducted in particular shallow-water regions show significant variability in acoustic data.
caused by changes in the oceanographic conditions with time [4–6]. Sudden increase in TL at particular frequencies, amplitude fading and arrival-time variability of received time series were detected during these experiments, and this variability in the acoustic data is most likely caused by the presence of internal waves. Successful prediction of sound propagation in these time-varying environments cannot be achieved without uncertainty unless detailed spatial and temporal information about the environment is available.

In May 1997 SACLANTCEN conducted the PROSIM’97 experiment south of the Elba Island, Mediterranean, in April/May 1999 the ADVENT’99 on Adventure Bank, Mediterranean, and the ASCOT’01 experiment in June 2001 off the coast of Massachusetts Bay, USA. Only data from ADVENT’99 and ASCOT’01 are presented in this paper. The ADVENT’99 experiment was conducted in very benign conditions on the Adventure Bank, Mediterranean with very weak tidal effects. Cores, seismic surveys and model-based geoacoustic inversion results [7] indicate a sandy-like sediment layer overlying a harder sub-bottom. Acoustic Linear-Frequency-modulated (LFM) signals were transmitted every minute from a bottom-moored sound source for up to 18 h. The acoustic signals covered a frequency band from 200–3800 Hz, and the signals were received on a 64-element vertical array at 2, 5 and 10 km range (recover/deploy for each range). Extensive oceanographic data were collected during the acoustic transmissions to correlate changes in the environment with changes in the received acoustic data. In particular, a 49-element Conductivity-Temperature-Depth (CTD) chain was towed by ITNS Ciclope continuously along the 10-km track acquiring range- and depth varying sound-speed structures. Each of the CTD structures are separated by 1 h. The weather conditions were favorable during the acoustic transmissions with maximum significant sea surface wave height of 1.5 m [7].

The configuration of the ASCOT’01 experiment was similar to ADVENT’99. However, the location of the experiment was known a priori to have a more variable environment than for the ADVENT’99. Strong tidal effects are present and the moorings of the sound source and vertical array were close to the continental shelf. These conditions can create strong internal waves affecting the acoustic signals over time. The source, receiving array and signals were the same as in ADVENT’99 with source-receiver separations of 1, 2, 5 and 10 km. The bathymetry is more range dependent than for ADVENT’99 with changes up to 12 m within 2 km. The acoustic signals were transmitted every 30 s for up to 12 h. There was no seismic survey or corering performed along the propagation tracks limiting the knowledge of seabed properties and layering structure of the bottom. However, U.S. Geological Survey [8] has performed analysis on acoustic backscatter intensity measured in the ASCOT’01 area, and the result from this analysis shows rapidly changing sediment properties corresponding to a mixture of sand and gravel.

2 Oceanographic data

There are 3 environmental factors that are considered as main contributors affecting the fixed-path acoustic propagation over time: (1) tidal effects, (2) water-column sound-speed fluctuations, and (3) scattering from the bathymetry and seabed. The tidal effects during ADVENT’99 are considered negligible, as the tide in the Mediterranean is less than 0.5 m. Direct measurement of the tide was not performed during the ASCOT’01 experiment but the tidal stations Boston Harbor and Boston Light are located relatively close to the experimental area. The tide amplitude and phase are almost the same for Boston Harbor.
and Boston Light. Although the 2 stations are separated by only 20 km it is assumed that the measured tide is representing the tide at the ASCOT’01 site about 80 km from the Boston tidal stations. The water depth varies around $\pm 1.2$ m with a period of 12 h.

The time-, range- and depth dependent sound-speed structures along the propagation tracks were measured by a towed CTD-chain. A total of 18 sound-speed sections were acquired during the 18-h acoustic transmission along the 10-km for ADVENT’99. Only 7 sound-speed sections were acquired along the 10-km track during ASCOT’01 for a 10-h transmission period. Sound-speed profiles measured at different times along the 10-km acoustic track is shown in Fig. 1.

There is a clear difference in the sound-speed structures from ADVENT’99 (upper panel) and ASCOT’01 (lower panel). The water column of ADVENT’99 is almost isovelocity with only a few m/s change in sound speed over depth. The sound-speed is also very weakly range-dependent with a tendency to divide the track into a low and high sound-speed region. The sound-speed structures from ASCOT’01 show typical downward refracting profiles along the track. The water column in this area is clearly more range dependent than ADVENT’99 with indications of soliton-like features in the upper part of the water column. The scattering of the acoustic field from the seabed may change in time as the sound-speed profiles change. This change of sound-speed alters the insonification of the seabed and may cause additional fluctuations in the received acoustic signals. The scattering characteristics of the seabed is considered range dependent while the tidal effect and water-column sound-speed are both time and range dependent. The bathymetry along the 10-km measured by a single-beam echo-sounder is shown together with the sound-speed structures in Fig. 1. The water depth changes by a few metres for ADVENT’99 along the 10-km track, while it changes up to 12 m within a couple of km in range and
significant roughness is observed for ASCOT’01. The impact of the bathymetry changes on the acoustic propagation is stronger for ASCOT’01 than ADVENT’99.

3 Acoustic data

The acoustic data received on the moored VLA have been processed for transmission loss (TL) (low level) and for establishing ping-to-ping correlation (high level) used as measures to assess the acoustic fluctuation with transmission time. The arrival structure of the matched-filtered (MF) time-series across the VLA at 10 km and at 3 different transmission times is shown in Fig. 3 for ADVENT’99 (upper panels) and ASCOT’01 (lower panels). The first 2 figures in the upper and lower panel of Fig. 3 show signals separated by 1 min, and the last figure in the upper and lower panel is signals received 1 h later. The received signals are stable at 1-min separation but after 1 h clear changes in the arrival structure can be observed. Especially for the ASCOT’01 data changes in individual multi-path arrivals appear as a focusing-defocusing effect. The time-varying ocean causes these fluctuations of the acoustic signals. Note that the time dispersion of the ASCOT’01 data is significantly longer than for ADVENT’99 indicating a higher sound speed in the bottom at the ASCOT’01 area. In this case steeper and later arriving multi-paths are trapped in the water column caused by the higher critical angle of the bottom. The effect of the tide is only observable for the ASCOT’01 data as the tide in the Mediterranean is negligible. The tide alters the absolute arrival time of the multi-paths as the water depth changes. This change in arrival time is larger for the steep and late arrivals as these paths travel longer (or shorter) distances than the shallow paths before arriving at the VLA.

TL is considered as a robust but low level processing of the acoustic field. The TL has been calculated for all received signals in both experiments as calibrated source signatures were available. The TL is averaged in a 10 Hz frequency band around the centre frequencies 250, 550 and 750 Hz. In addition, the signals are averaged over transmission time resulting in mean TL and standard deviation over depth for a 12-h transmission period (Fig. 2).

In general, the TL is higher for the ADVENT’99 area (upper panel) for all frequencies than for ASCOT’01 (lower panel). However, the standard deviation of the TL is almost the same for both experiments and for all frequencies regardless the difference in the environmental conditions. The standard deviation of the TL also increases with increasing frequency as expected and the deviation reaches ±5 dB at 750 Hz. Correlation of time series to assess variability is a much stricter measure than TL. Matched-Field Correlation (MFC) is applied to illustrate signal similarity and how fast the signals degrade over transmission time. The MFC is using a standard Bartlett processor as the correlator between two signals [7]. One of the signals received early during the transmissions is denoted as a reference signal. This reference signal is correlated with all the subsequently received signals and normalized with the total energy in the two signals. The correlator has a value of 1 for two similar signals and 0 for totally un-correlated signals. The MFC is calculated for all transmitted signals in the frequency band from 200–800 Hz and for each discrete frequency obtained through the Fourier transform of the time series. The correlation is shown in Fig. 3 for 2, 5 and 10-km propagation range obtained during the ADVENT’99 (upper panels) and ASCOT’01 (lower panels).

The ADVENT’99 data show a high correlation between the received signals for all
Figure 2. Time and frequency averaged TL from ADVENT'99 (upper panels) and ASCOT'01 (lower panels) received at the 10-km propagation range. The TL is averaged over a 10-Hz band around 3 centre frequencies of 250, 550 and 750 Hz. The solid line and black-shaded areas are the mean and standard deviation respectively over a 12-h transmission period.

Figure 3. Matched-Field Correlation of an early received signal with the subsequently received signals from ADVENT’99 (upper panels) and ASCOT’01 (lower panels) for 10-h transmission time. The correlation is shown for 2, 5 and 10-km propagation range in the frequency band from 200 to 800 Hz. At higher frequencies and longer ranges the signals start to de-correlate within 1 h of transmission. This de-correlation is caused by changes in the environment, which have more impact at higher frequencies and longer ranges as the signals propagate through a larger amount of water mass. The de-correlation time for the received signals during the ASCOT’01...
experiments is much lower than for the ADVENT’99 data. The ASCOT’01 data de-correlate in less than 2 h regardless of propagation range but the de-correlation time is slightly longer at lower than at higher frequencies. At later transmission time, high correlation can be observed within a short period and for particular frequencies. The frequencies where high signal correlation appears depend on the time of transmission (5 and 10-km track in Fig. 3 lower panels). High correlation of the signals along the 2-km track is observed for a large frequency band after 5 and 9 h of transmission. This indicates significant changes in the environment for a period during the transmissions, and then the environment returns close to the initial condition. The MFC clearly shows that the ASCOT’01 environment is significantly more time and range varying than the ADVENT’99 environment, which has severe impact on broadband sound propagation in this region. Prediction of sound propagation in the ASCOT’01 environment is extremely difficult without a detailed spatial- and temporal description of the environment.

4 Model-data comparison

Fully range-dependent acoustic propagation modelling has been performed for both the ADVENT’99 and ASCOT’01 scenarios to assess the feasibility of predicting the acoustic signals by including the detailed measurements of the underwater environment in the modelling. The measured range-dependent bathymetry, tidal effects, sound-speed profiles varying in time and range, and geoacoustic properties from inversion of the acoustic data are used as input to the propagation model. High-fidelity geoacoustic inversion was achieved for the ADVENT’99 data, and an excellent agreement between acoustic modelling results and data was obtained in frequency, range and time [7]. The bottom properties for ASCOT’01 are known with less confidence than for ADVENT’99. Acceptable geoacoustic inversion results have only been achieved along the 2-km track. These bottom properties are assumed range-independent out to 10 km for the modelling purposes. The propagation model used is the coupled normal-mode model C-SNAP [9]. The model-data comparison of the tidal effect is shown in Fig. 4 as the MF signals received at 84-m depth over transmission time. There is good agreement between data and model with the correct model prediction of the tidal effect of the late multi-path arrivals. Note the slightly higher amplitude of the late arrivals in the modelling results compared to the data. This discrepancy in amplitude due to insufficient knowledge of the bottom properties.
The modelled TL for centre frequencies of 250, 550 and 750 Hz is shown in Fig. 5 together with the experimental data at a range of 10 km. The same averaging in frequency and time is applied to the modelling results as for the data. There is a fairly good agreement between model and data of the mean TL levels but the modelling results are not completely matching the interference structure in depth. The standard deviation of the TL data is also captured by the propagation model by including the measured time- and range varying environmental properties.

The modelling of signal correlation over transmission time follows the same tendency as observed in the data (Fig. 6). The correlation time is 2 h for frequencies around 300 Hz, but the correlation time decreases as the frequency increases. These features in the modelling results can only be achieved if a good representation of the environment is available.

In general, the time- and range varying properties of the measured acoustic field for the ADVENT’99 and ASCOT’01 experimental sites are predictable if detailed information
about the environment is available. The acoustic propagation model includes the main
time- and range dependent features observed in the acoustic data. The uncertainty in
predicting sound propagation in shallow water is mainly a question of predicting the
state and changes in the environment accurately rather than the reliability of acoustic
propagation models.

5 Conclusions

Oceanographic and acoustic data have been presented from the 2 shallow-water fixed
propagation path experiments ADVENT’99 and ASCOT’01. The ADVENT’99 was con-
ducted under benign conditions while the ASCOT’01 environment was known a priori
to be hazardous for sound propagation. The ASCOT’01 environment is more time- and
range dependent than ADVENT’99 which is reflected in the variability of the received
acoustic signals. These results demonstrate the diversity of broadband sound propagation
in two “typical” shallow-water regions. Successful prediction of sound propagation in
the ADVENT’99 and ASCOT’01 region is achievable provided a detailed spatial and
temporal environmental description is available. The uncertainty of predicting the sound
propagation during ADVENT’99 and ASCOT’01 is not introduced by the acoustic prop-
agation models but rather the prediction of the underwater environment.

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