Overview of Results from the Asian Seas International Acoustics Experiment in the East China Sea

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***Abstract*—The Asian Seas International Acoustics Experiment (ASIAEX) included two major field programs, one in the South China Sea and the other in the East China Sea (ECS). This paper presents an overview of research results from ASIAEX ECS conducted between May 28 and June 9, 2001. The primary emphasis of the field program was shallow-water acoustic propagation, focused on boundary interaction and geoacoustic inversion. The study area's central point was located at 29° 40.67'N, 126° 49.39'E, which is situated 500 km east of the Chinese coastline off Shanghai. The acoustic and supporting environmental measurements are summarized, along with research results to date, and references to papers addressing specific issues in more detail are given.**

***Index Terms*—Propagation, reverberation, seabed, sea surface, shallow water acoustics.**

I. Introduction

THE CENTERPIECE of the Asian Seas International Acoustics Experiment (ASIAEX) consisted of two major field programs conducted in the spring of 2001, one in the South China Sea (see Lynch *et al.* [1]) and the other in the East China Sea (ECS). The intent of this paper is to provide an overview of research results to date of ASIAEX ECS, conducted primarily under the auspices of the U.S. Office of Naval Research and the Natural Science Foundation of China. The U.S., Chinese, and Korean research organizations involved in the 2001 ECS field program are listed in Table I.

The primary goals of ASIAEX ECS were to: 1) identify and elucidate properties of shallow-water boundaries governing propagation and reverberation in the ECS, such as sediment inhomogeniety, sediment roughness, and sea surface roughness and 2) establish a geoacoustic description for the ECS seabed, based on complementary approaches to inverting acoustic propagation and reverberation measurements made in the O(10–10000) Hz frequency range. The ECS study area, jointly approved by the State Oceanic Administration, People's Republic of China, and the Japanese Ministry of Foreign Affairs, was a box defined by 28° to 30° N and 126° 30' to 128° E.

Leading up to the 2001 primary study in the ECS was a pilot study conducted in the spring of 2000 from the U.S. R/V *Revelle* (see Ramp *et al.* [2]), aimed at obtaining environmental data within this boxed area to support the acoustics experiments planned for 2001 (see Table II for the list of organizations involved in the 2000 pilot study). Information on the ECS seabed and subbottom structure derived from this earlier study (see Miller *et al.* [3]) was used to select the final study area for the primary experiment in 2001, involving the U.S. R/V *Melville* and the Chinese R/Vs *Shi Yan 2* and *Shi Yan 3* (Fig. 1). The center point of this area, located at 29° 40.67' N and 126° 49.39'E, is referred to in several papers in this special issue as position M and is located in the northwest corner of the approved box about 500 km east of the Chinese coastline off Shanghai. Position M (Fig. 1) became the designated center of a 30-km-radius circular transect over which broadband, explosive sound sources were deployed for the propagation and reverberation experiments in 2001. (These acoustic sources are often referred to in Chinese technical literature as Wide Band Source (WBS), an acronym for wide band source that is used in several papers in this issue.)

TABLE I
RESEARCH INSTITUTIONS INVOLVED IN THE 2001 ASIAEX EAST CHINA SEA PRIMARY STUDY

INSTITUTION	Country
Applied Physics Laboratory, University of Washington	USA
Dalian Scientific Test & Control Technology Institute	CHINA
Georgia Institute of Technology	USA
Hangzhou Applied Acoustics Research Institute	CHINA
Harbin Engineering University	CHINA
Institute of Acoustics, Beijing	CHINA
Korean Ocean Research and Development Institute	KOREA
Marine Physical Laboratory, Scripps	USA
National Taiwan University	TAIWAN, CHINA
Northwestern PolyTechnical University, Xi'an	CHINA
Ocean University of Qingdao	CHINA
South China Sea Institute of Oceanology, Guangzhou	CHINA
University of Rhode Island	USA

TABLE II
RESEARCH INSTITUTIONS INVOLVED IN THE 2000 ASIAEX ECS PILOT STUDY

INSTITUTION	Country
Florida Atlantic University	USA
Marine Physical Laboratory, Scripps	USA
Naval Postgraduate School	USA
University of North Carolina	USA
University of Rhode Island	USA
Woods Hole Oceanographic Institution	USA

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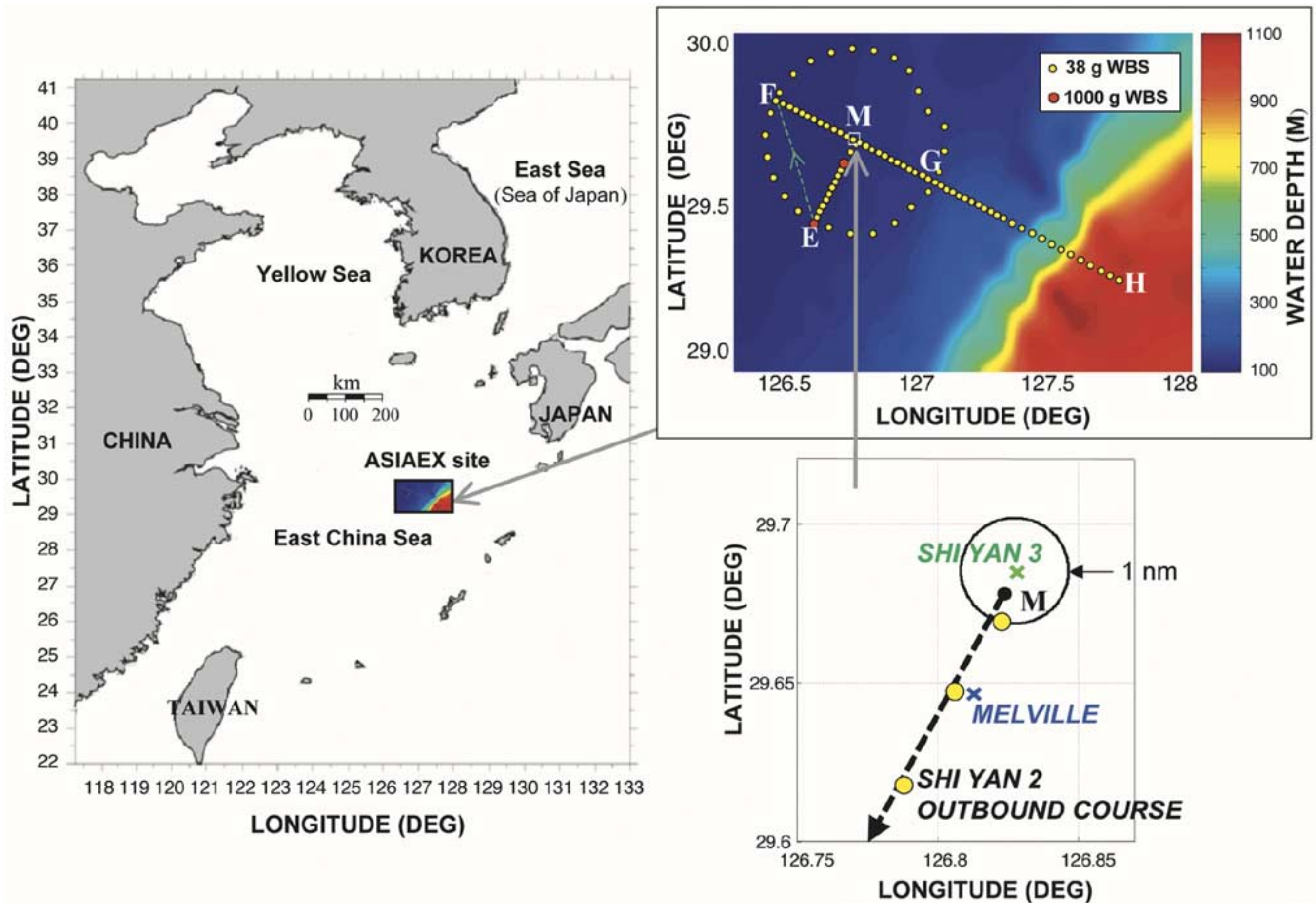


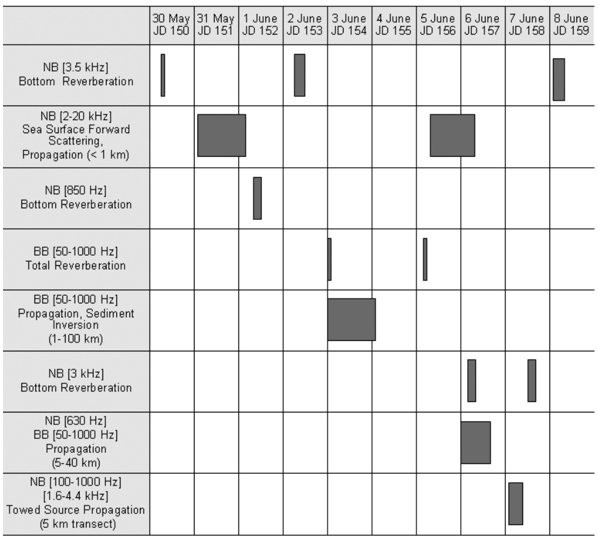
Fig. 1. Location of the ASIAEX ECS experimental site. Clockwise from left: large-scale view reducing to small scale (lower right) showing positions of the R/V *Shi Yan 3* and R/V *Melville* near position M and the outbound course of the R/V *Shi Yan 2*. Upper right panel shows the location of explosive sources (WBS) deployed from the *Shi Yan 2*. Between waypoints F-G and M-E, these sources (38-g) are deployed approximately every 2 km. Yellow circles in lower right panel show positions of the initial three 38-g source deployments by the *Shi Yan 2*.

The final study area and position M were also selected because the bathymetry there was relatively simple and characterized by parallel isobaths oriented southwest to northeast. The water depth was 105 m $\pm$ 3 m for radials extending out approximately 10 km from position M in any direction. Further motivation for selecting this site was its reduced water column variability, desirable in view of the experimental emphasis on boundary interaction. The variability was reduced because of the appreciable standoff distance from the shelf break where the north wall of the Kuroshio resides. Linear and nonlinear internal waves were observed during both 2000 and 2001, but they were neither as frequent nor as energetic as the waves observed in the South China Sea [2].

The area encompassed by the 30-km radius circle in Fig. 1, known as the *large-scale ECS experimental site*, was the primary site for low-frequency, O(10–1000) Hz, propagation and reverberation studies. A subset area of approximately 10 km^2, centered at position M, was the site for mid-to-high frequency, O(1–10) kHz, studies. (Table III summarizes all the major ECS ocean acoustic studies, classified here as either narrow band if the acoustic measurement bandwidth was less than one octave or as broadband if the bandwidth was greater than one octave.) The approach of embedding mid-to-high-frequency acoustic experiments within an area where low-frequency experiments were also conducted served two purposes. The first was to more efficiently allocate limited resources for seabed sampling; for example, the area immediately surrounding position M received substantially more emphasis insofar as coring [3] and measurements of fine-scale bottom relief [4]. The second was to conduct multiple-frequency geoacoustic inversions on the same area of seabed. That is, the inner region about position M was studied using a wide range of frequencies, O(10–10000) Hz. The lower end of this band yielded low-resolution but deep, O (10 m), information about the sediment; the higher end of this band yielded little or no information on the deep sediments, but provided better resolution on upper sediment structure (e.g., layering). A key objective of ASIAEX ECS was to fuse inversion results from such frequency-complementary acoustic experiments. This was achievable at position M, although the process of doing so continues at this writing.

The remainder of this paper provides an overview of results of the environmental characterization (Section II) and results of analysis of ocean acoustic experiments to date (Section III), along with references to papers addressing specific issues in more detail.

TABLE III
CHRONOLOGY OF MAJOR OCEAN ACOUSTIC EXPERIMENTS FOR ASIAEX ECS CONDUCTED BY TEAMS FROM THE U.S. AND CHINA (DATES AND TIMES IN UTC.) EXPERIMENTS ARE CLASSIFIED AS EITHER NARROWBAND (NB) IF THE ACOUSTIC MEASUREMENT BANDWIDTH IS LESS THAN ONE OCTAVE OR BROADBAND (BB) IF BANDWIDTH IS GREATER THAN ONE OCTAVE. THE NOMINAL CENTER FREQUENCIES (FOR NB) OR FREQUENCY RANGE (FOR BB) OF A PARTICULAR EXPERIMENT IS GIVEN IN BRACKETS



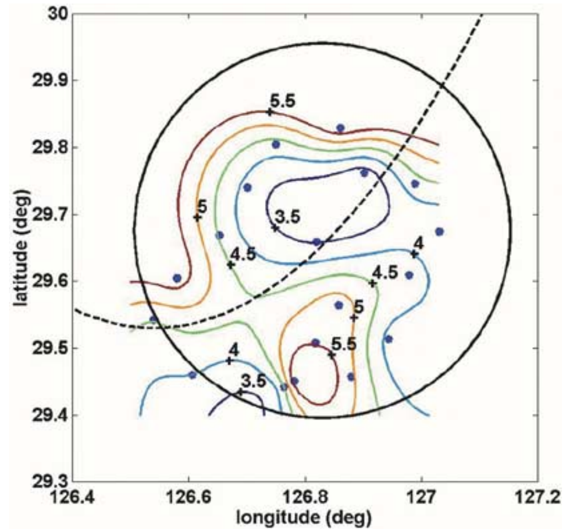


Fig. 2. Contours of the spatial distribution of mean grain size in phi units, based on the coring locations shown by the blue dots (figure adapted from [3]). Phi units are defined as minus $\log_2$ of the grain diameter in millimeters; lower phi values indicate more sandy-like sediments and higher phi values indicate more mud-and-sand-like sediments. The circle has radius 30 km with position M at the center; the dashed line is the historical mud–sand boundary discussed in Miller *et al.* [3] with sand to the southeast and mud–sand to the northwest.

Fig. 3. Frozen video image (courtesy of D. Tang, Applied Physics Laboratory, University of Washington, Seattle) of the seabed taken near position M, showing an example of indentations from bottom-dwelling organisms that are postulated to be responsible for the small-scale relief.

II. OVERVIEW OF RESULTS OF ENVIRONMENTAL CHARACTERIZATION

A. Seabed

Several measurement techniques were used to determine the properties of sediments in the ECS, as described by Miller *et al.* [3]. Within the 30-km-radius circle (Fig. 1), 21 gravity cores were collected from the U.S. R/V *Revelle* as part of the environmental assessment in 2000; additional gravity cores were collected during 2001 from the R/V *Shi Yan 3* during the main experiment and two months later the Taiwanese R/V *Ocean Researcher 2* returned to the experimental site to collect 30 piston cores. The gravity cores and the piston cores obtained samples 25 cm and 2 m deep, respectively. Analysis [3] of the *Revelle* coring set suggests a compressional wave speed in the surface sediment layer varying from near 1600 m/s at core stations located in the northwest quadrant of the 30-km circle to near 1650 m/s at some stations in the vicinity of the circle's center. The spatial distribution of mean grain size (see [3]) derived from the *Ocean Researcher 2* coring set (Fig. 2) points to variation on scales much smaller than that originally depicted by an historical mud-sand boundary discussed in [3]. Subbottom profiling using water-gun and chirp sonars was conducted on the *Revelle* cruise; these measurements indicate that the subbottom structure at the experiment site consists of a thin veneer of sediment of variable thickness directly beneath the sea floor. Near position M the sediment layer is about 1 m thick. Below this layer, there is sediment with relatively uniform acoustic attributes.

The sediment porosity and fine-scale relief measurements (within a 4-m measurement aperture) put the seabed root-mean-square (rms) relief at 0.5 cm in the vicinity of position M [4]. A frozen video image (Fig. 3) taken from the instrument (see [4]) shows an example of the indentations from bottom-dwelling organisms that are postulated to be responsible for the fine-scale relief. Tang [4] has developed a bioturbation model that reproduces the observed mean roughness spectrum. These measurements are necessarily a high-pass filtering of relief and do not capture variability at length scales greater than about 2 m, but are essential for modeling acoustic backscatter in a mid-frequency (3–4 kHz) range. Future work will combine this data with chirp-sonar measurements made in 2000 and 2001. Possible contributors to large-scale relief are trawl marks, observed by side-scan sonar in 2000; however, the degree to which bottom trawling contributed to bottom relief during the 2001 study is unclear.

B. Volume

During the 2001 experiment, sound speed in the water column was measured routinely and at varying intervals by conductivity–temperature–depth (CTD) casts from the *Melville*

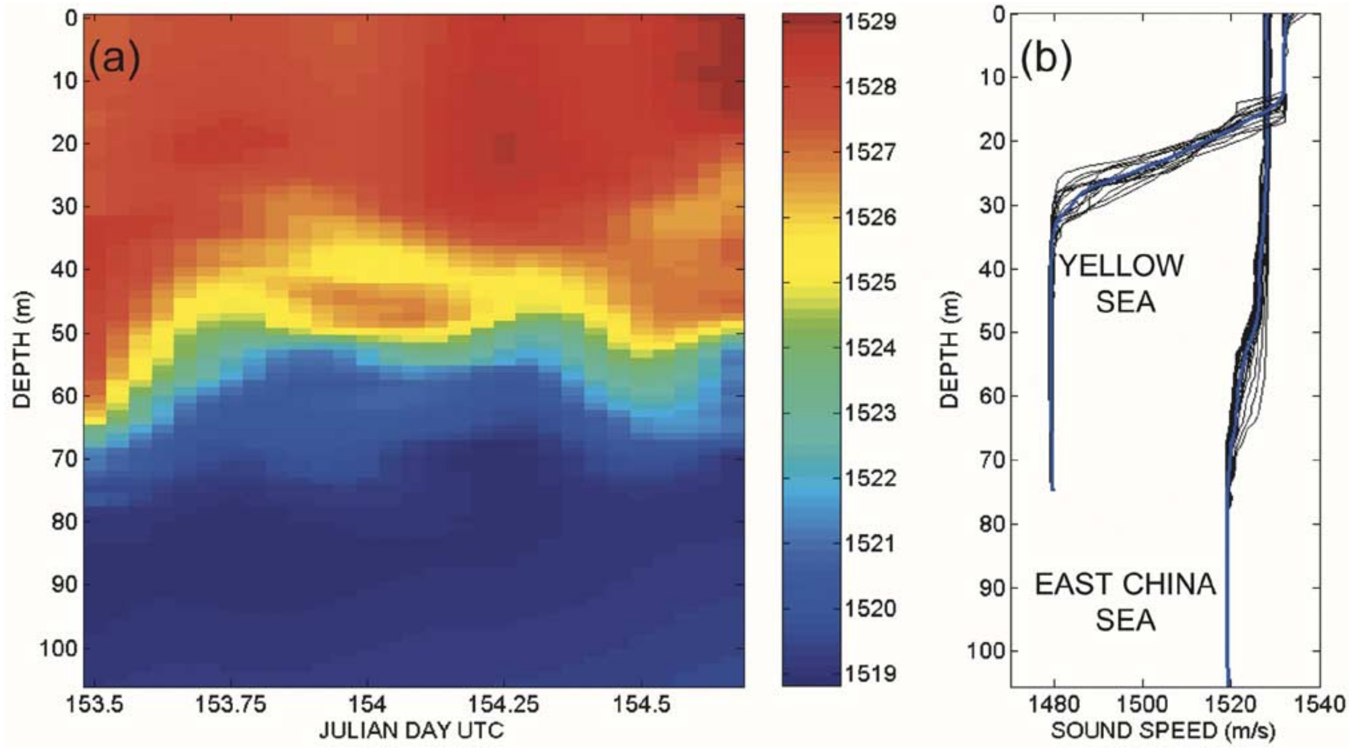


Fig. 4. (a) Example of the time variation in the sound-speed vertical structure for the ECS taken at position M, starting UTC 1200 on June 2 (Julian day 153), as measured by CTD. (b) A 24-h average of the data in (a), compared with an equivalent average of sound speed versus depth taken in the Yellow Sea in August 1996. The thick, blue line is the 24-h average and thin, black lines are individual CTD measurements made hourly.

and the *Shi Yan 3*. Typical time variation in the sound-speed profile for the ECS in late spring [Fig. 4(a)] shows the dominant component of the variance linked to the semidiurnal (M2) internal tide oscillation of the thermocline. (Associated baratropic tidal current magnitudes were approximately 40 cm/s and maximum surface elevation changes were approximately 100 cm.) A comparison of a 24-h average of this data [Fig. 4(b)] with an equivalent average of the sound-speed profile taken in the Yellow Sea in August 1996 [5] shows that the late-spring thermocline in the ECS is truly weak when compared with the late-summer thermocline in the Yellow Sea. The acoustic implication is that the sea surface should have a greater influence on propagation and reverberation in the ECS than in the Yellow Sea. More detail and discussion on the salinity and temperature profiles and the internal wave characteristics of the ECS are presented in Ramp *et al.* [2] and Yang *et al.* [6].

C. Sea Surface

Between May 29 and June 7, 2001, wind speed varied from 1–13 m/s and the rms wave height varied between about 0.1–0.6 m, providing a wide range of sea state conditions for the ASIAEX ocean acoustic experiments conducted in the ECS (Fig. 5). In particular, three acoustic experiments have been subject to closer examination in regard to the impact of concurrent sea surface conditions. Sea state conditions for the WBS detonations on June 3 at 0109, intended primarily for broadband measurements of seabed reverberation, were characterized by an rms wave height and wind speed of 0.1 m and 3 m/s, respectively; for the measurements made on June 5 at 0520, the rms wave height and wind speed had increased to 0.34 m and 9 m/s, respectively. The 24-h broadband propagation experiment involving WBS deployments from the *Shi Yan 2* began in relatively calm conditions, but ended in conditions characterized by rms wave height and wind speed of 0.6 m and 11 m/s, respectively. Finally, the two, 24-h narrow-band measurements, designed specifically to capture acoustic effects of changing sea state conditions, were also successful in sampling a large range of sea state conditions. Time windows for these experiments are indicated in Fig. 5.

III. Overview of Results of Ocean Acoustic Experiments

Considerable progress has been made toward establishing a geoacoustic description of the ECS seabed [3], [7]–[15], based on complementary approaches to inversion. It is important to keep the diversity of acoustic field measurements in mind, representing one-way propagation and two-way reverberation, made at frequencies ranging from $O(10–10000)$ Hz, that have been utilized for these geoacoustic inversions. Such measurements interrogate the seabed in fundamentally different ways. Furthermore, the different approaches to geoacoustic inversion embodied by the degree of parsimony inherent in the inversion forward model, e.g., a half-space representation for the seabed as in [10]–[13], [15] versus a structured seabed representation that includes layers and gradients as in [3], [7]–[9], [14], invariably lead to seemingly different inversion goals and subsequent geoacoustic models for the seabed. (A lucid clarification concerning the basis of differing inversion goals is given in [16].) Still, a fair degree of consistency has emerged. For example, the range of inverted sound speeds corresponding to the water–sediment

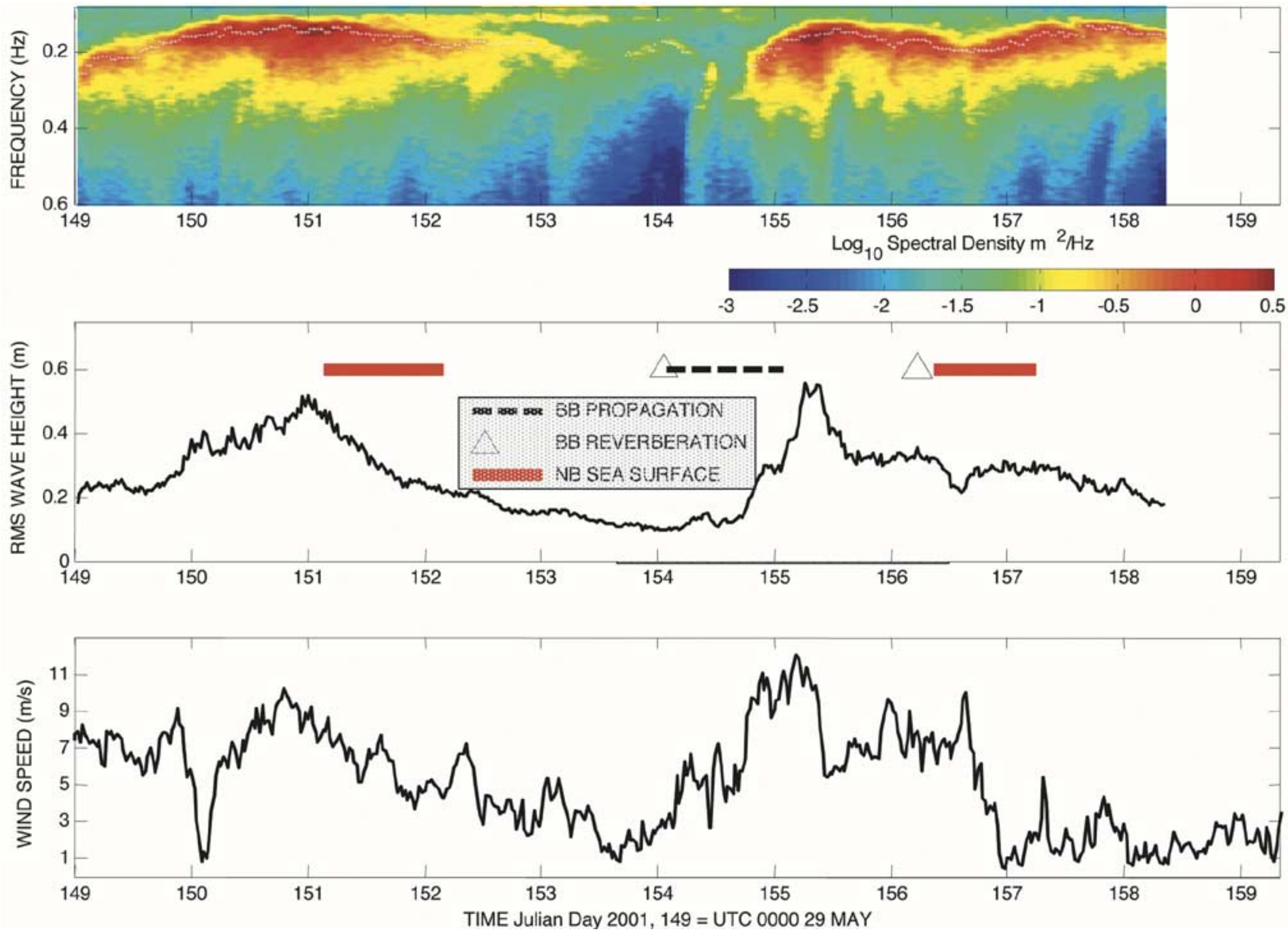


Fig. 5. Time history of the wind and sea surface waves made during ASIAEX ECS. Wind speed was measured from the R/V *Melville's* IMET station and wave data were measured with a directional wave buoy positioned approximately 500 m from the *Melville*. (Top) Contour of directional averaged wave spectra (see [22] for an example of directional wave data), taken every 0.5 h, with white dots showing location of peak frequency. (Middle) Time series of rms waveheight, along with approximate time windows for three acoustic experiments. (Bottom) Time series of wind speed; note that wind-speed data continue slightly beyond the wave buoy recovery time.

interface is 1557–1643 m/s; at a depth of 0.5 m, this range is 1590–1643 m/s and at a depth of 1 m, it is 1600–1650 m/s. This general increase in compressional wave speed with depth into the seabed is consistent with the results of Zhou *et al.* [11], who invert reverberation measurements made in the frequency range 100–1500 Hz based on a half-space representation for the seabed. They obtained an equivalent half-space sound speed that increased with decreasing frequency and their results illustrate how the resolution scales inversely with frequency. For example, the minimum inverted sound speed for the water–sediment interface, 1557 m/s, was obtained with $O(10)$ kHz measurements [7].

In regard to sediment attenuation in the ECS, the ASIAEX results (summarized in Fig. 6) display both linear and nonlinear trends for attenuation as a function of frequency in the 50–500-Hz frequency range. At this writing, these results point to more questions than answers; clearly, understanding and reconciling the frequency dependence poses a challenge for follow-up analysis of ASIAEX data or for future experiments conducted in this same region. This includes the relative importance of shear wave conversion as a loss mechanism for lower frequencies. Furthermore, it will be effective in future work to assign geoacoustic estimates obtained at higher frequencies to the region near the water–sediment interface and geoacoustic estimates obtained at lower frequencies to deeper sediment regions, for a geoacoustic model for the ECS that is robust over a broad frequency range.

From inversion benchmark studies [17], absolute (calibrated) transmission loss has been shown to be an effective metric with which to quantify and compare the performance of inversion results based on different methodologies. In this regard, the transmission loss estimates for ASIAEX ECS described in [12], derived from the propagation measurements made along the three, 30-km length radials EM, FM, and GM (Fig. 1), will be particularly valuable for future benchmarking. (A companion analysis utilizing the same propagation data set [18] demonstrates improvement in the matched-field source localization performance upon inclusion of bottom slope information.) Fig. 7 displays a subset of the transmission loss estimates (along the GM radial) expressed in decibels re 1 m versus range for third-octave center frequencies between 40–2500 Hz.

Modeling and interpretation of ASIAEX bottom reverberation measurements is in large part dependent upon the seabed characterization and such data also requires a substantial

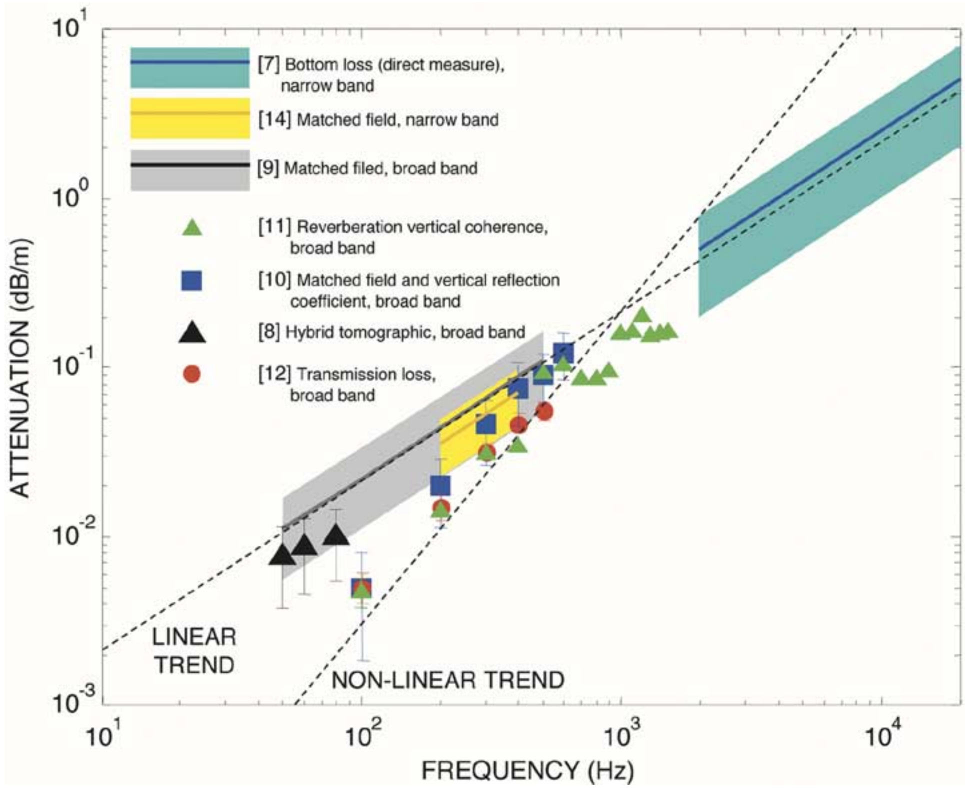


Fig. 6. Results of inversion for sediment attenuation in the ECS. The legend gives a brief description of the inversion approach, with broadband and narrowband defined as in Table III and Section I; reference numbers refer to this paper.

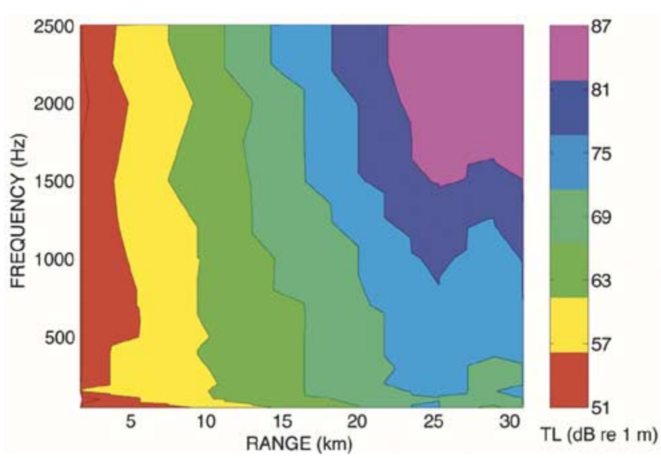


Fig. 7. Transmission loss in decibels re 1 m as a function of range from position M along track MG (Fig. 1) and $1/3$-octave bandwidth center frequency. Both source and receiver depth are 50 m. Data from [12].

degree of processing, interpretation, and modeling (some of the results of which are reported in this issue). Thus far, emerging results [19] have established a link between reverberation from the seabed and fine-scale relief [4] (rather than subbottom inhomogenities) for bottom reverberation in the O(1–10) kHz frequency range.

In terms of the role of sea state in governing the strength and coherence of shallow-water acoustic propagation and scattering over frequencies of O(100–10000) Hz, the following results have emerged thus far. The two 24-h length measurement periods of forward scattering from the sea surface yielded a large data set with which to evaluate energy loss associated with wind-speed-dependent bubbles. Results in [20] show how this loss varies with wind speed and a model is presented that agrees well with ASIAEX data and other archival measurements. This dependence on wind speed is not clearly evident with the ASIAEX data alone; however, when it is combined with the archival data, the dependence is clear (Fig. 8). In contrast to *coherent* surface loss, incoherent loss (or energy loss in Fig. 8) was small and difficult to precisely measure against ordinary statistical fluctuation, for wind speeds up to about 8 m/s. Fig. 8 also illustrates for the ASIAEX conditions and measurement geometry, the poor correlation between energy loss and the Rayleigh parameter $\chi = 2kH\sin(\theta)$, where k is wave number, H is rms wave height, and θ is the nominal sea surface grazing angle. This is expected given that near-surface bubble concentration correlates well with wind speed and poorly with wave height [21]. These results are significant because, in some propagation schemes, coherent loss is interpreted as the entire loss associated with interaction with the sea surface. In such an approach, the χ data in Fig. 8, all of which are $O(10)$, would necessarily translate to large and significant estimates of coherent loss, yet incoherent energy loss was in fact small.

The spatial coherence of sound forward scattered from the sea surface was also measured during ASIAEX. These data have been modeled with an approach that utilizes the van Cittert–Zernike theorem in conjunction with the simultaneously measured sea surface spectral wave properties [22]. The concept of a coherence volume, having applications in underwater acoustic imaging and communication, follows from this approach: for the ASIAEX acquisition geometries and surface conditions and for a 20 kHz source at a depth of 25 m and range

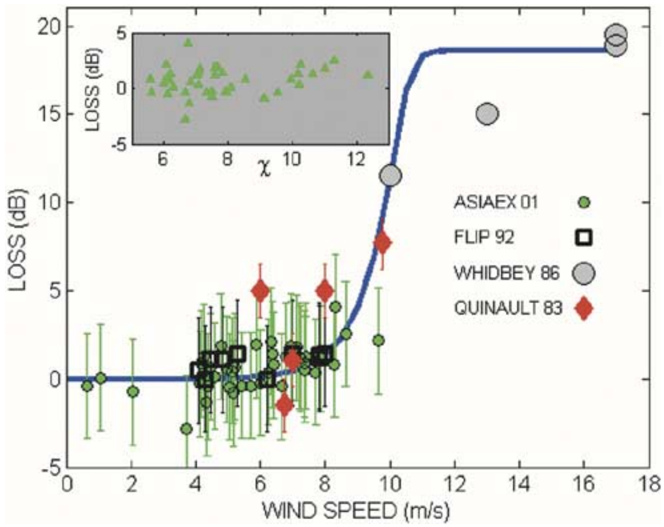


Fig. 8. Estimates of energy loss for a single interaction with the sea surface as a function of wind speed for a nominal sea surface grazing angle of 9° and frequency 20 kHz. Results from ASIAEX and three other experiments are shown (year of the experiment is identified in the legend and additional information given in [20]). Solid, blue curve is a model for energy loss (in [20]) due to attenuation from near-surface bubbles; the model reaches a bound phase (associated with bubble scattering) for wind speeds greater than about 12 m/s. Shaded plot in upper left corner shows same ASIAEX energy loss data as function of the nondimensional (Rayleigh) parameter χ.

of 0.5 km, a coherence volume exists for receivers between depths of 25 and 50 m. This coherence volume relates to the spatial coherence of the sound field arriving via the surface bounce channel and consists of a vertical layer 0.5 m thick and 3 m in each of the two horizontal dimensions or, equivalently, 4–5 m^3.

The experimental observations in [23] show that the significant change in sea surface conditions between June 3 and June 5 (see Fig. 5) impacted the broadband (50–1000 Hz) reverberation measurements during this period. Specifically, significantly *higher* (order 5 dB) mean reverberation levels were observed on June 3, when the rms wave height was 0.1 m and wind speed was 3 m/s, than on June 5, when the rms wave height was 0.34 m and the wind speed was 9 m/s. Mechanisms for this change associated with two-way propagation and reflection loss from the sea surface have been proposed [23].

Whether or not the sea surface has a significant effect on the fidelity of geoacoustic inversions will depend on the sea state, the frequency range, and acoustic measure being inverted. We note that the completed inversion studies reported in this volume involving long-range propagation and multiple boundary interaction have not, as is common, addressed this issue *per se*. Yet, emerging studies [24] suggest, for example, that the aforementioned June 3-to-June 5 change in sea state does impact inversion results. It remains a challenge for future studies involving the ASIAEX ECS data to elucidate and distinguish first order, and higher order, influences of the sea surface on geoacoustic inversion results and their uncertainties.

IV. Concluding Remarks

The results summarized here, and presented in greater detail in this issue, can only be regarded as a subset of the results expected to ultimately emerge from the ASIAEX East China Sea program. Taken together, this diverse set of ocean acoustic measurements, spanning a frequency range from O (10–10000) Hz and representing a large range of temporal and spatial scales, will be brought to bear toward an improved understanding of shallow-water acoustics.

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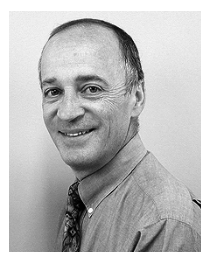

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