Using Buried Directional Receivers in High-Frequency Seafloor Studies

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Abstract. Knowledge of acoustic arrival angle can be useful for studying penetration mechanisms and for estimating sediment sound speed dispersion. The arrival angle of the acoustic field penetrating the water-sediment interface, however, is difficult to measure using sparsely distributed pressure sensors. The arrival angle, as well as amplitude information, can be unambiguously obtained by measuring particle motion with directional receivers. An experiment was conducted off of Elba Island, Italy, to assess the feasibility of a novel technique that uses high-frequency accelerometers to measure the directionality of acoustic arrivals. Measurements of acoustic penetration into a sandy seafloor were obtained over a wide frequency range (2.5 to 29 kHz) using off-the-shelf accelerometers, adapted for use in marine studies. The sensors that were developed are suitable for the penetration studies for which they were devised, but their angular resolution would limit their application in dispersion studies. Insights from this experiment will guide the design of new directional sensors that are suitable to study dispersion.

INTRODUCTION

There have been repeated experiments [1, 2, 3] demonstrating "anomalous" acoustic penetration into the seabed below the critical angle (i.e. beyond that predicted by elastic wave theory for smooth seabeds). Modeling and penetration experiments have suggested various causes for the anomalous penetration including a Biot "slow" compressional wave [2] and scattering from interface roughness [4]. Chotiros [2] used 20 kHz data obtained on a sparse buried array of hydrophones to estimate the direction and speed of acoustic waves by intensity superposition and interpreted the results as evidence of the Biot slow wave. Thorsos et al. [4] showed that scattering, essentially straight down from the water-sediment interface, could also account for subcritical penetration. For an array of receivers such as that used by Chotiros [2], the scattered field could essentially mimic the slow wave. The fact that one cannot distinguish between the competing mechanisms of a Biot slow wave and interface scattering, points out the difficulty in using sparsely distributed pressure sensors to measure arrival angle. Direct measurements of the arrival angle of acoustic waves penetrating the seafloor using accelerometers (or other types of vector sensors) should be able to conclusively distinguish between the two subcritical penetration mechanisms by illuminating not just *when* the signal arrives but *from which direction*. The refracted

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Biot slow wave (typical speed 1200-1300 ms^{-1}) would arrive from a grazing angle between approximately 30º and 45º, whereas scattering by the rough water-sediment interface can arrive over a wide range of angles controlled by the ripple wavelength, water/sand speed ratio, and incident angle [4].

In analyzing their sediment acoustic penetration data, Maguer et al. [3] noted that a lower sound speed than that measured on ground truth cores was required to fit the experimental observations to model calculations. Laboratory measurements of sound speed are made by transmitting acoustic signals a known distance through the sediment core and core liner. This is typically done at a much higher frequency, e.g. 200 kHz, than the experimental data under consideration, 4 and 10 kHz in the case of Maguer et al. [3]. The discrepancy between *in situ* and ground truth measurements was attributed to sound speed dispersion [3] and later confirmed experimentally [5]. More recent investigations [6, 7] have also confirmed sound speed dispersion for a sandy site off of Panama City, Florida. Although comparisons between measurements and predictions of dispersion based on Biot theory have been promising, they have not been conclusive to date due to uncertainties both in parameter estimation and acoustic measurement techniques [6].

As a complement to these techniques [6], sediment sound speed could be measured using buried directional receivers. The angle to which sound is refracted when transmitted across the water-sediment interface is a function of the sediment sound speed. Therefore, the angle at which an acoustic pulse arrives at buried directional sensors, measured as a function of frequency, can be used to make estimates of sound speed dispersion. Sediment to water sound speed ratios at the SAX99 experimental site have been estimated to range between 1.09 below ~500 Hz to 1.15 above 50 kHz [6]. These ratios yield an approximate difference in arrival angles at low and high frequency of 10-15º (Fig. 1), depending upon how close one can work to the critical angle and avoid interference between the refracted and evanescent fields. The angular resolution required to estimate sound speed dispersion would be approximately ±1.5º (Fig. 1a). By contrast, the angular resolution required to distinguish penetration mechanisms is less stringent, approximately ±5º, unless one happens to receive arrivals at an angle at which both penetration mechanisms can occur (30-45º).

To establish the feasibility of using buried accelerometers in the aforementioned seafloor studies, the concept was evaluated during a sea-trial in 1999, the Acoustic Penetration Experiment (APEx99). Two fundamental capabilities must be demonstrated. First, the sensors must be able to achieve the respective angular resolutions required for penetration and sound speed dispersion studies. In Fig. 1, the arctangent of the ratio of the on-axis/off-axis response is used to predict the angular resolution capability of the sensor that may in turn be compared with the anticipated requirements for the seafloor studies. Second, the sensors must be sufficiently sensitive in the frequency band of interest and not be limited by self-noise. Uni-axial accelerometers were selected because of their sensitivity at high frequency. They were buried in orthogonal pairs in order to decompose the acoustic arrivals into vertical and horizontal components. The following section concerns the issues relevant to the design of a sensor package and calibrations of the on-axis and off-axis sensitivity. Results from APEx99 are then presented, followed by a discussion of the measured *in-situ* angular response and the viability of this technique for seafloor studies.

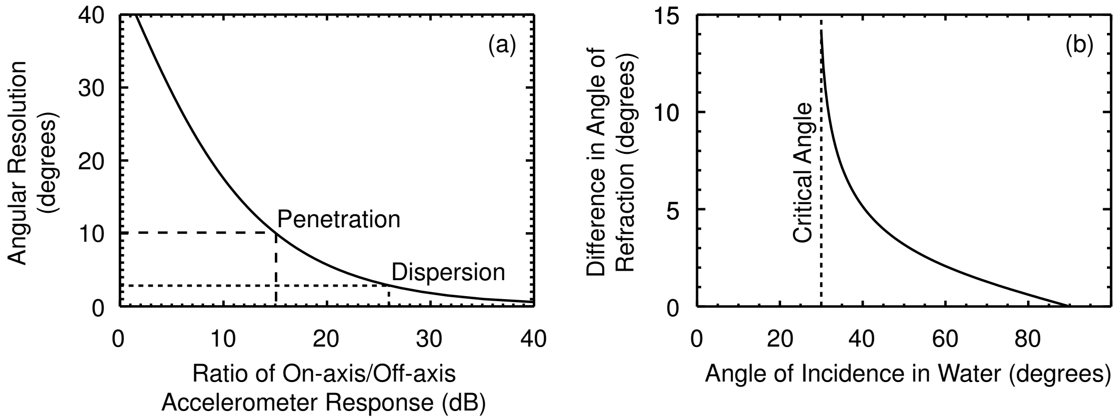

FIGURE 1. (a) Estimated angular resolution as a function of the ratio of on-axis to off-axis accelerometer sensitivity. Penetration (long dash) and dispersion (short dash) measurement requirements are superimposed. (b) Difference in angle of refraction for sediment/water sound speeds ratios of 1.15 and 1.09 as a function of grazing angle.

THEORETICAL CONSIDERATIONS

Several criteria governed the design of the buried directional receivers used in this study. The ideal receiver should have a high sensitivity to forcing on its axis of response, sufficient, for example, to detect arrivals scattered downward from the seabed by a pulse incident at a shallow grazing angle. Meanwhile, in order to be effective at discriminating the angle of arrival, it should be relatively insensitive to off-axis forcing by translational motion, and to rotational motion, as this would manifest itself as a spurious on-axis translational component. It should be rigid within the frequency band of interest and thus free of any internal resonances. It should also be compact such that an orthogonal pair of receivers could be located within a fraction of an acoustic wavelength of each other in order to measure the acoustic field at that point in the seabed.

The directional receiver that has been developed consists of an accelerometer fastened to a thin disk by a mounting stud (Fig. 2). The disk ensures that it is well coupled and oriented in the medium in which it is placed. The mass of the coupling disk is approximately ten times that of the accelerometer, as per the manufacturers recommendation, and such that the accelerometer has a minimal effect on the motion of the object to which it is attached. The accelerometers were manufactured by Endevco Inc. and two versions of the same model were used, 7259A-25 and 7259A-100 with sensitivities of 25 and 100 mvg^{-1} respectively. They have a wide bandwidth with an amplitude response that is flat from 10 Hz to 50 kHz with a deviation of less than 1 dB. As they are not designed for underwater applications, the sensor housing and connection to the 1 mm diameter conducting cable had to be potted. This presented some difficulties, as the potting compound did not bond readily with the Teflon coating of the cable.

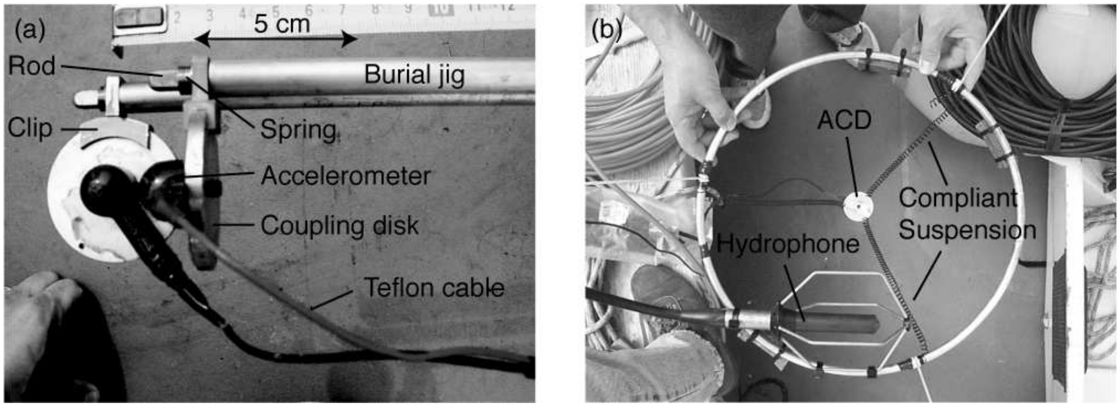

FIGURE 2. (a) Pair of uni-axial accelerometers mounted to coupling disks that are orthogonal to each other. The sensors are attached to the burial jig using clips on the edges of the disks. Springs temporarily fix the clips to the inner, square, rod of the burial jig. The sensors are released when the square rod is retracted. (b) The accelerometers are calibrated individually in water by mounting them on a frame using very soft springs. A hydrophone is also attached to the circular frame.

Specifying the dimensions and composition of a coupling disk is challenging as conflicting design requirements are encountered: maximum on-axis sensitivity requires minimal inertial mass; insensitivity to rotational motion requires maximum disk radius; minimizing internal resonances requires a thick disk with minimum radius; compact pair of sensors requires minimal disk radius. To elucidate these points and find the optimum compromise, the physics of each of these criteria requires consideration. In what follows, all variables (forces, accelerations, etc…) are assumed to be harmonic with angular frequency $\omega = 2\pi f$. Assuming plane wave propagation, differentiation with respect to time becomes a multiplication by $j\omega$, so if a denotes acceleration, then $a/j\omega$ denotes velocity.

In a Newtonian fluid, the equation of motion for the accelerometer coupling disk assembly (hereafter called the ACD) when freely suspended in water is

$$(a_d - a_w)(m_i + m_a) = -a_w(m_i - m_w) - D \tag{1}$$

where a_d and a_w are the accelerations of the coupling disk and the surrounding water respectively, m_i, m_a, and m_w are the inertial mass of the assembly, the virtual (or added) mass of water it entrains, and the mass of water it displaces (values in Table 1). The term $(a_d - a_w)$ represents the acceleration of the disk relative to the water and D is a drag force that is insignificant because the particle velocities are near zero.

The ACD is forced on its axis of sensitivity (perpendicular to the face of the ACD) by an acoustic pressure

$$p = \rho c u = \frac{\rho c}{\omega} a_w, \tag{2}$$

where ρ is the density of water, c is the speed of sound in water, and u is the particle velocity in water. Combining Equations (1) and (2), we find that the ratio of the response of an accelerometer to the incident pressure is

$$\frac{a_d}{p} = \frac{\omega}{\rho c} \frac{(m_w + m_a)}{(m_i + m_a)}. \tag{3}$$

Although the intrinsic frequency response of the accelerometer is uniform as a function of frequency from 10 Hz to 50 kHz, in accordance with the manufacturers specifications, the response of the ACD increases as a function of frequency (Fig. 3), behaving as $20\log_{10}(\omega)$. The sensitivity of the ACD can be increased by reducing its inertial mass. From this standpoint, a coupling disk manufactured with aluminum would be preferable. The theoretical resonance frequency of an aluminum disk would also be higher though still within our measurement band (Table 1). However, the threaded holes for the accelerometer stud mount on the aluminum disks could not withstand the calibrated torque required to fix the accelerometers onto the coupling disk–a crucial and unexpected requirement to minimize the resonance at approximately 13 kHz associated with the stud (Fig. 3).

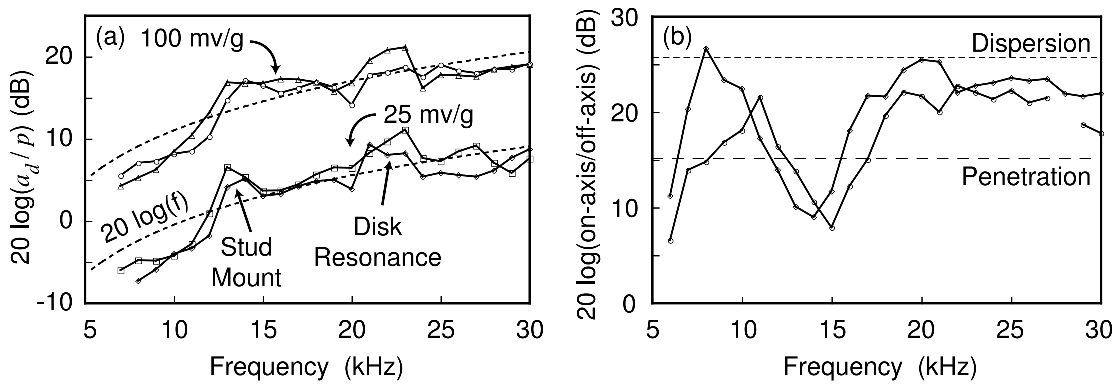

FIGURE 3. (a) On-axis response of four ACDs calibrated individually in water using the setup in Fig. 2b. The overall trend of the data follows 20 log(f) as expected. The resonance around 13 kHz is due to the stud used to mount the accelerometer to the coupling disk. (b) Ratio of on-axis to off-axis response of two ACDs to acoustic pressure in water. The horizontal lines are the minimum ratios required in order to achieve the angular resolution requirements for dispersion and penetration studies (from Fig.1).

For the case of the ACD freely suspended in water, it is straightforward to estimate the received pressure that is required to exceed the self-noise[2] of the accelerometer, 8 x 10^{-3} ms^{-2} for the 7259A-25 and $5x10^{-3}$ ms^{-2} for the 7259A-100. Using the higher self-noise value for the 7259A-25 and the appropriate values for m_i, m_a, and m_w in Equation (3), an incident pressure of 139 dB re 1 μPa would be required at 3 kHz and an incident pressure of 119 dB re 1 μPa would be required at 30 kHz. These incident pressures are readily attainable using sources used in this experiment (ITC-3013, ITC-2007, and Simrad TOPAS with maximum source levels of 185, 189, and 213 dB re 1 μPa respectively).

When the ACD is buried in the seabed, it is more difficult to estimate its response. For an initial estimate, Equation (3) may still be used, but one must treat the seabed as a higher density fluid. In this case, an incident pressure of 143 dB re 1 μPa would be required at 3 kHz and an incident pressure of 123 dB re 1 μPa would be required at 30

[2] More often than not, accelerometers are limited by their self-noise rather than by ambient noise.

kHz. Equation (3) can be extended to include the effects of a reaction force within the seabed. For sake of brevity, these equations are not shown but the effect is to decrease the response of the ACD, thus higher incident pressures are required.

It is necessary for the ACD to be relatively insensitive to off-axis forcing. The manufacturers specification for the accelerometers is 5% of the on-axis sensitivity, or an on-axis/off-axis ratio of -26 dB. Considering the response of the ACD in water, Equation (3) may continue to be used, however, the added mass, m_a, will be considerably lower as the cross sectional area is much smaller. As a consequence, the inertial mass term will dominate, further reducing the transverse sensitivity of the ACD compared to the on-axis sensitivity. However, the ACD may be limited by its response due to rotational motion, rather than by its transverse sensitivity.

TABLE 1. Properties of the accelerometer coupling disk assembly.

Variable	Units	Stainless Steel	Aluminum
r, Radius	m	0.022	0.022
t, Thickness	m	0.004	0.004
m_i, Inertial Mass	kg	0.050	0.016
m_w, Mass of water displaced	kg	0.006	0006
m_a, Added mass, on-axis of a disk ($8/3\rho_w r^3$)	kg	0.029	0.029
m_a, Added mass, off-axis of a sphere ($2/3\pi\rho_w r^3$)	kg	0.0003	0.0003
β factor (see text for details)	Not applicable	0.340	0.195
Inertial response, $(m_w+m_a)/(m_i+m_a)$	dB	-7.24 dB	-2.82 dB
Theoretical resonance frequency of disk	Hz	22121	24442

The importance of rotation may be estimated by considering the value of

$$\beta = md^2 / I \tag{4}$$

where m is the sum of all mass terms (inertial and added/virtual) and I is the sum of all inertia terms (including added/virtual) multiplied by d^2, the square of the moment arm. To avoid problems with rotational motion [8], the inertial terms must be greater than the mass terms and/or the moment arm must be as small as possible, i.e. $\beta \ll 1$. Since the added moment of inertia of the disk increases as a function of the disk radius raised to the fifth power [8], this term quickly begins to dominate. For a coupling disk made of stainless steel and a radius of 0.22 m (Table 1), a value of $\beta=0.34$ is predicted in water. Calibrations in water (Fig. 3b) show that the ratio of on-axis/off-axis response is suitable for penetration studies, except at the frequencies that are effected by the stud mount (Fig. 3b). A β factor may be calculated for an ACD buried in a higher density fluid seabed, however, this does not account for the stiffness of the seabed (angular spring constant). This would serve to further resist any rotational motion of the ACD and increase the on-axis/off-axis response ratio.

SENSOR PERFORMANCE

In April and May 1999, two pairs of ACDs were deployed in a sandy sediment in a water depth of 12 m as part of APEx99 in Biodola Bay, Elba Island, Italy. Driven initially by penetration questions and later by sound speed dispersion issues, the goals of the APEx99 experiment included evaluating the feasibility of using vector sensors such as accelerometers in higher-frequency seafloor studies. Directional sources on a movable, telescopic tower and moored omni-directional sources transmitted pulses over a range of frequencies (2.5-29 kHz) at a variety of grazing angles: above critical for *in situ* calibration; at critical to study interaction of refracted and evanescent waves, and subcritical to measure acoustic penetration into a sandy seafloor. The well-characterized site [3] had a sand layer thickness of approximately 2 m, a bulk density of 1920 kgm^{-3}, and a compressional wave speed estimated at 1720 ms^{-1} (measured at 200 kHz from diver cores). The sand had a mean grain diameter of $\phi = 2.25$ (0.21 mm) with a standard deviation of 0.6 ϕ (~0.1 mm). The water sound speed was measured with a CTD to be 1530 ms^{-1}, thereby creating a critical angle of approximately 29º.

The vertical and horizontal acceleration of the ACDs in response to a pulse of sound can be used to measure the angle of arrival by examining the orientation of the major axis of the elliptical motion (Fig. 4). The analysis can be repeated for different pulses to measure arrival angle as a function of frequency (Fig. 5a). The width of the minor axis of the ellipse (Fig. 4a) indicates that some signal is not arriving in phase. (Phase quadrature between components would yield a circular particle motion.) The physical separation of the ACDs introduces a phase shift that one can correct as a function of frequency, but this requires some *a priori* knowledge about the angle of arrival and the properties of the seabed. As these are the very quantities to be measured, an iterative approach is required in some cases. However, phase shifts do not change the orientation of the major axis; they broaden the minor axis and degrade the ability to discern the major axis (Fig. 5b). The simultaneous arrival of acoustic signals from multiple directions is of greater concern. This may change the amplitude of the components and bias estimates of the angle of arrival.

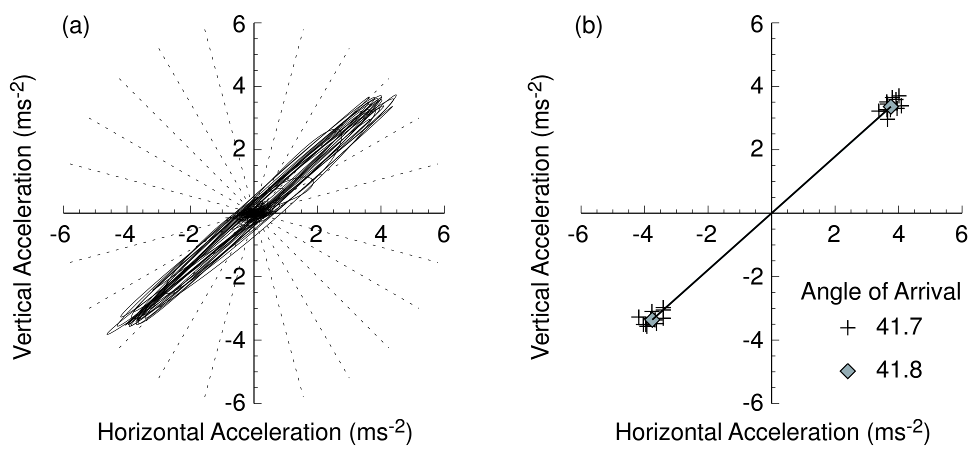

FIGURE 4. (a) Sample hodogram of particle acceleration on ACDs at 50 cm depth for a 2 ms pulse of sound at 16 kHz, incident upon the seabed at a grazing angle of 49.4º. The pulse is refracted to approximately 41.8° as anticipated based on the sound speed ratio (b) Diagonal line represents the best fit to the angle of arrival, following the peak amplitude of both components on cycle-by-cycle basis (plus symbols) and fitting a sine wave, in a least squares sense, on a ping-by-ping basis (diamonds).

CONCLUSIONS

One of the main goals of the APEx99 experiment was to test the feasibility of using vector sensors such as accelerometers to study acoustic penetration into sediment at high frequency. The orthogonal pair of uni-axial accelerometers devised for penetration studies is suitable for that application; however, their angular resolution (as revealed by the scatter in Fig. 5a) is not sufficient for dispersion studies. Design improvements to make vector sensors more amenable to dispersion studies will include: improved angular resolution; co-located pressure for purposes of calibration as well as intensity and impedance processing; and tri-axial accelerometers in a single body to avoid ambiguities due to phase separation between receivers.

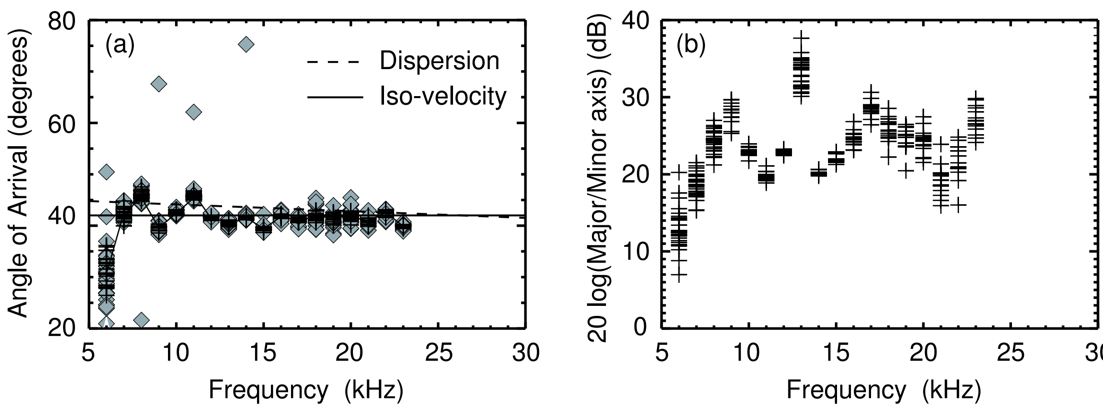

FIGURE 5. (a) Angle of arrival as a function of frequency (25 pings per frequency). The lines are the anticipated angle of arrival for an iso-velocity sand (solid) and for a linear sound speed dispersion from 5-30 kHz for water/sediment sound speed ratios ranging from 1.09-1.15 (dashed). Poor performance at 6 kHz is due to low signal-to-noise. The variability from 8-11 kHz is related to the *in situ* calibration. (b) Ratio of major and minor axes of the hodogram ellipses as a function of frequency.

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