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COMPUTER SIMULATIONS OF BATHYMETRIC SIDESCAN SONAR

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ABSTRACT

Bathymetric sidescan sonar systems offer the potential for high-resolution mapping of the ocean bottom at a substantial reduction in survey cost because of their relative simplicity combined with improved area coverage over multibeam bathymetric systems currently in use. However, data obtained to date from bathymetric sidescan systems are not considered sufficiently accurate to meet the required hydrographic standards. We have used REVGEN, a realistic sonar simulation program, to study the performance limitations of such systems. Here, we report on the statistical behavior of the phase difference between the backscattered return received by vertically separated transducer elements, in the presence of sloping bottom features, volume reverberation and ambient noise.

INTRODUCTION

Bathymetric sidescan systems use an estimate of the phase difference between two or more spatially separated receivers to infer depth ([1]-[4]). A simple system of this type is depicted in Figure 1. The "electrical" phase difference $\Delta\psi$ is related to the declination angle θ by:

$$\Delta\psi = ks\sin\theta \tag{1a}$$

where $k = \frac{2\pi}{\lambda}$ is the wavenumber and s is the distance between the receiving elements. The depth estimate is given by:

$$D = R\sin\theta = R\frac{\Delta\psi}{ks} \tag{1b}$$

where R is the slant range, related to the two-way propagation time t by $R = \frac{ct}{2}$ where c is the speed of sound.

We have performed computer simulations of this system using REVGEN (REVerberation GENerator), a high-fidelity sonar system simulation program [5]. REVGEN creates synthetic reverberation by randomly distributing point scatterers throughout the volume and the boundaries of the "ocean" and coherently summing the individual echoes at each receiver. The program output consists of the in-phase (I) and quadrature (Q) components of this reverberation process. Thus, REVGEN amounts to a direct implementation of the point-scattering model of reverberation [6]. In addition, it affords the user a great deal of flexibility in defining the experimental geometry and sonar system parameters such as beam patterns and transmitted signals. This built-in flexibility allows us to isolate the influence of various system and environmental factors on the performance of the bathymetric sidescan concept. In designing the simulations, guidance has been provided by certain theoretical predictions of the point-scattering model.

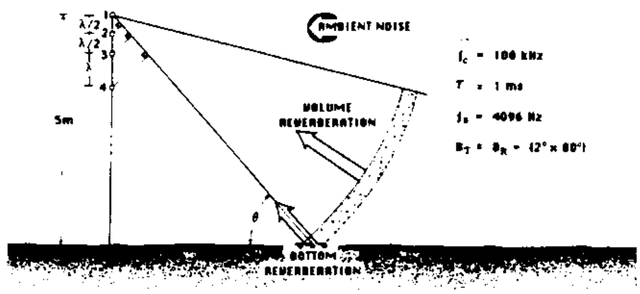

Figure 1. Simulated system geometry.

SPATIAL REVERBERATION CORRELATION AND PHASE ESTIMATION

Knowledge of the statistical character of the phase difference $\Delta\psi$ is essential for predicting the performance of a sidescan bathymetric system. A useful expression is offered by the point-scattering reverberation model [6] which relates the probability density function (p.d.f.) of the phase difference to the crosscorrelation of the received reverberation between two spatially separated receivers:

$$f(\Delta\psi) = \frac{1-|\rho|^2}{2\pi(1-\beta^2)^{3/2}} \cdot \left[\beta\sin^{-1}\beta + \pi\frac{\beta}{2} + (1-\beta^2)^{1/2}\right] \tag{2}$$

for

$$|\Delta\psi - \mu_{\Delta\psi}| \leq \pi$$

and

$$\beta = |\rho|\cos(\Delta\psi - \mu_{\Delta\psi})$$

where $f(\Delta\psi)$ is the p.d.f. of the phase difference, $\mu_{\Delta\psi}$ is the mean of the phase difference and ρ is the crosscorrelation coefficient.

The above indicates that the p.d.f. of the phase difference will become increasingly wide with decreasing crosscorrelation. Therefore, in order to obtain accurate bathymetry from phase measurements, the bottom reverberation return must possess a high degree of spatial coherence.

Spatial correlation expresses mathematically the fact that returns arriving from widely separated angular directions tend to add out of phase at spatially separated receivers. The geometry for the volume backscattered return is depicted in Figure 2a. The two receivers R_1 and R_2 are a distance s apart and vertically aligned. Volume reverberation arrives from a range of elevation and azimuthal angles determined by the directional characteristics of the transmitting and receiving arrays. For omnidirectional transmission and reception, the spatial correlation coefficient of volume reverberation is [6]

$$\rho_V(s) = \frac{\sin(ks)}{ks} \tag{3a}$$

Thus, ρ_V is a decaying function and will tend to zero as the transmitted frequency and/or receiver separation increase.

The geometry for the boundary return is described in Figure 2b. The two receivers lie in the xz plane and the line connecting them forms an angle ϕ_o with the $x-$ axis. In this case, for omnidirectional transmission and reception and for ranges much larger than the receiver separation, the spatial correlation coefficient is given by [6]

$$\rho_B(s) = J_o(ks\cos\phi_o) \tag{3b}$$

where J_o is the modified Bessel function of the first kind. For $\phi_o = \frac{\pi}{2}$ (vertical separation) we have

$$\rho_B(s) = J_o(0) = 1.$$

Therefore, no loss of spatial correlation is suffered for vertical separation of the receivers. This can be explained intuitively, in terms of the lack of vertical extent of the insonified surface patch. For all intermediate values ($0 \le \phi_o \le \frac{\pi}{2}$), a certain loss of coherence is to be expected. Note that in the sidescan geometry this condition will result from a sloping bottom.

The effect of directional transmission can be readily included. Letting $b_T(\theta,\phi)$ be the beam pattern of the transmitting array, we have for volume reverberation

$$\rho_V(s) - \frac{1}{\Delta\Omega_{eff}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{2\pi} b_T^2(\theta,\phi)\cos(kssin\,\phi)d\,\theta\cos\phi d\,\phi \tag{4a}$$

where,

$$\Delta\Omega_{eff} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{2\pi} b_T^2(\theta,\phi)d\,\theta\cos\phi d\,\phi$$

and for boundary reverberation,

$$\rho_B(s) - \frac{1}{\Delta\theta_{eff}} \int_0^{2\pi} b_T^2(\theta)\cos(kscos\,\phi_o\sin\theta)d\,\theta \tag{4b}$$

where,

$$\Delta\theta_{eff} = \int_0^{2\pi} b_T^2(\theta)d\,\theta.$$

According to equation (4a), the volume return will become increasingly correlated with increasing directivity of the transmitting array thus reducing the correlation disparity between the two reverberation types.

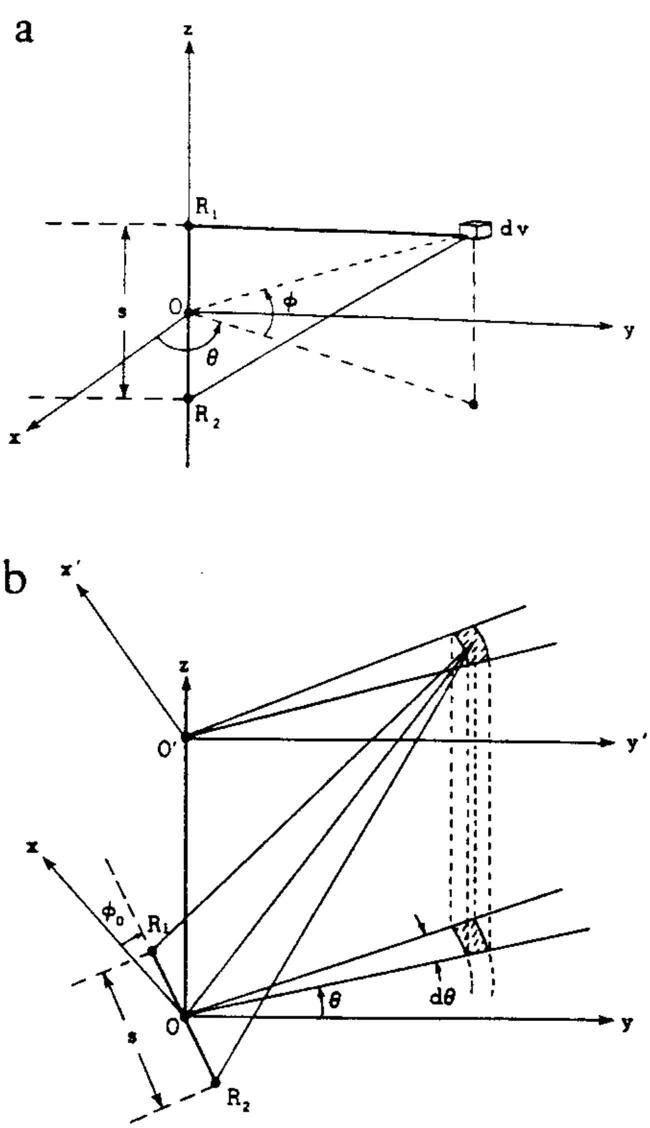

Figure 2. Spatial correlation geometry: (a) Volume reverberation, (b) boundary reverberation.

Based on these theoretical results the following predictions can be made:

i. Sloping bottom features can lead to potentially deleterious loss of spatial coherence for the bottom return

ii. Volume reverberation may be sufficiently coherent as to contribute significantly to the mean phase value thus leading to erroneous bathymetry.

These predictions were tested with REVGEN simulations.

REVGEN SIMULATIONS

The basic simulation geometry is depicted in Figure 1. The depth was set to $5\,m$. Four vertically separated receivers were included but only the first three (1-3) are involved in the results reported here. They are positioned at $\frac{\lambda}{2}$ intervals where $\lambda = 1.5\,cm$ is the acoustic wavelength. A carrier frequency of $100\,kHz$ and a pulse length of $1\,ms$ were used. In each simulation, a sufficient scatterer density was prescribed to insure Gaussian reverberation. Both transmitting and receiving beam patterns were 80° in elevation and 2° in azimuth. The beam patterns were "ideal" with no sidelobes and null response in the direction of the surface. A sound speed profile constant with depth was assumed and no multipath propagation was allowed. The bottom reverberation coefficient was prescribed to vary linearly from $-15\,dB$ to $-60\,dB$ as the grazing angle decreased from 90° to 0°.

Simulation 1 included bottom scatterers only. The phase difference between receiver pairs 1,2 and 1,3 produced from single pings is shown in Figure 3. As expected, for a separation of $\frac{\lambda}{2}$ (receiver pair 1,2) the phase difference is monotonically decreasing with time while for a separation of λ (receiver pair 1,3) a phase reversal occurs at $t = 0.013\,s$ corresponding to a declination angle of 30°. A number of "spikes" are observed reflecting the stochastic nature of the phase difference. A total of 30 such pings were transmitted, with the scatterers rearranged prior to each transmission to insure statistically independent acoustic returns. A phase estimate, produced by averaging over the 30-ping ensemble, is shown in Figure 4a. The corresponding depth estimate is shown in Figure 4b. Note that although the averaged phase appears smooth throughout, the variance of the depth estimate increases with range. This can be understood by modelling the phase estimate as

$$\langle \Delta\psi \rangle = \mu_{\Delta\psi} \pm \sigma_{\Delta\psi}$$

The corresponding depth estimate is (see eq. (1a))

$$\langle D \rangle = \mu_D \pm \sigma_{\Delta\psi}\left(\frac{R}{ks}\right)$$

Therefore, a relatively low variance $\sigma_{\Delta\psi}$ in the phase estimate can result in a significantly "amplified" variance in the depth estimate. As this effect becomes more severe for smaller phase difference values, it argues for increased receiver separation for estimating depth in the outer reaches of the insonified swath. Moreover, additional temporal filtering is probably in order.

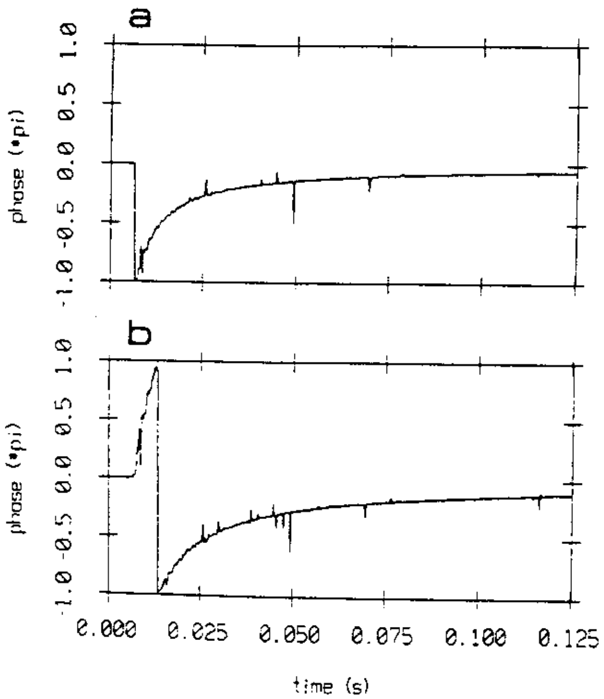

Figure 3. Phase difference time series, bottom reverberation only: (a) Receiver pair (1,2), (b) receiver pair (1,3).

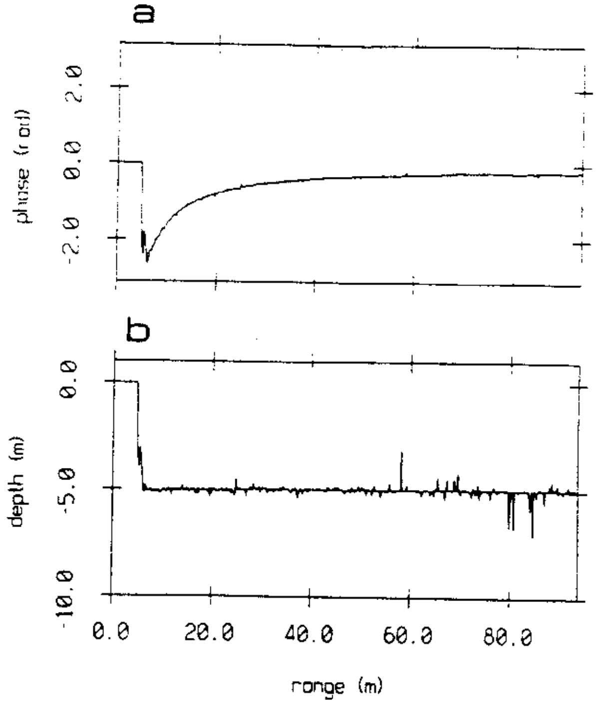

Figure 4. 30 ping average for receiver pair (1,2), bottom reverberation only: (a) Phase difference estimate, (b) depth estimate.

Bottom slope

A question not sufficiently addressed by current bathymetric sidescan system design is the effect of bottom slopes on the accuracy of the depth estimate. Although the assumption of gently sloping sea floor is realistic in many ocean environments, radical departures from this assumption will often be encountered in the real world. Sharply defined features in the bottom profile combined with the typical, vertically wide, sidescan beam pattern could result in significant coherence loss with a corresponding decrease in the accuracy of the phase estimate and therefore bathymetry. Simulation 2 was designed to demonstrate this effect. Three sloping profiles were created on the otherwise flat bottom with slopes of 14°, 76° and 90°. In each case, the slope begins at a range of $20\,m$ where the declination angle θ is $-14°$. Because the current version of REVGEN does not allow for departures from a flat bottom, the profiles were created separately by utilizing the REVGEN option of including individual point targets at arbitrary locations. The targets were randomly arranged on the chosen profiles and their individual target strengths were taken from a Rayleigh distribution. Each profile was insonified 30 times with the simulated bathymetric system, each time with a new (independent) random distribution of scatterers. A phase estimate was produced by ensemble averaging. The associated bathymetric estimates are displayed in Figure 5. In conjunction with bathymetry, phase histograms were created by extracting single slices from the phase difference ensembles at times corresponding to acoustic returns from the sloping portions of each profile. The phase difference histograms together with estimates of the crosscorrelation coefficient between the two receivers are given in Figure 6.

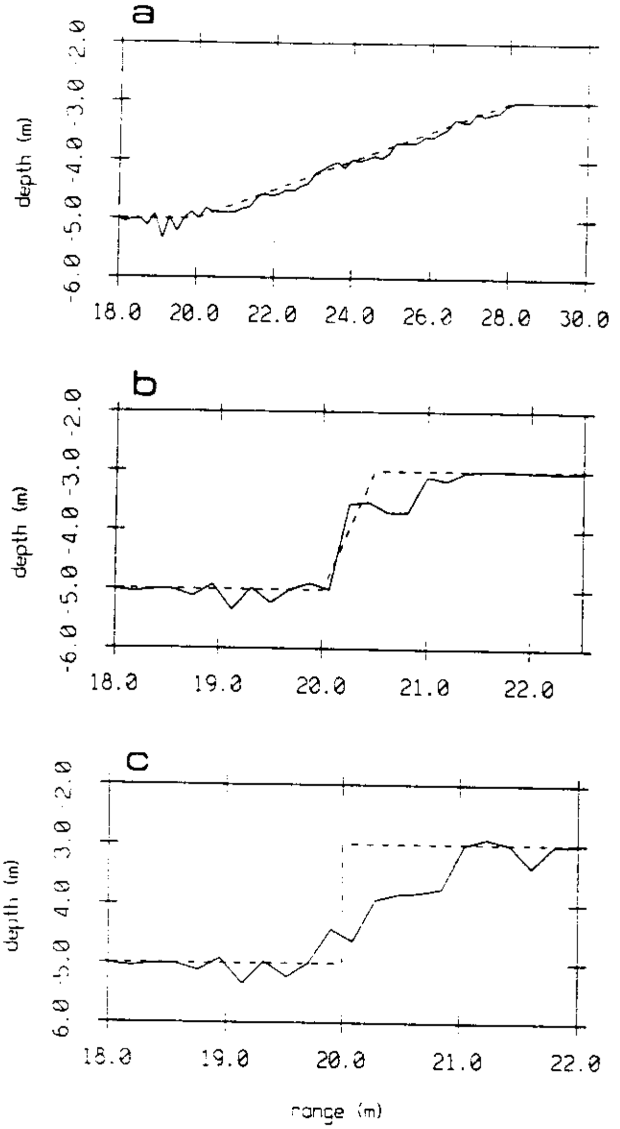

Figure 5. Test bottom profile (dotted line) and bathymetric estimate (solid line): (a) 14° slope, (b) 76° slope, (c) 90° slope.

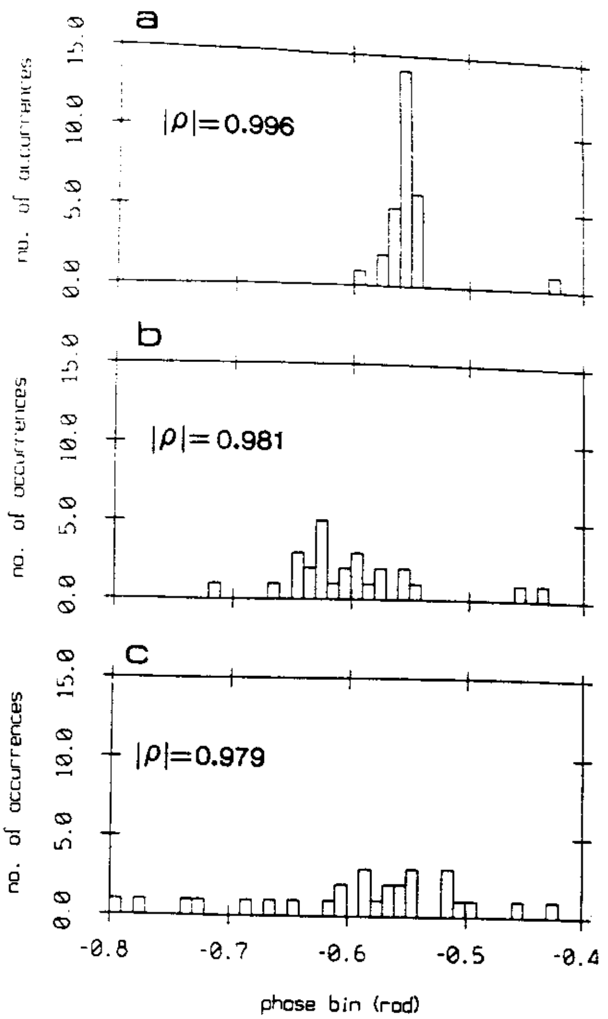

Figure 6. Phase histogram: (a) 14° slope, (b) 76° slope, (c) 90° slope.

The simulation results confirm the theoretical predictions. In the case of the 14° slope the system accurately reproduced the test surface. The 76° slope represents the "critical angle" case where the slope is equal to $\frac{\pi}{2} - \theta$. In this case, the wavefront impinges simultaneously on the entire sloping surface leading to a large insonified area with considerable vertical extent. This in turn leads to coherence loss reflected by the poor reproduction of bathymetry and the widely distributed phase. For slopes exceeding this critical angle, further coherence loss is incurred as the slope and the flat portion of the bottom (for ranges $\leq 20\,m$) will contribute simultaneously to the acoustic return. This was the case for the third test, a bottom profile with a slope of 90°, representing the "worst case" scenario.

Manifestations of this coherence loss and corresponding phase spread have been observed in bathymetric data collected with the SeaMARC II system and was named the "glissando" effect by Blackinton and Hussong [3]. This effect is likely to pose a serious limitation to the performance of the single-beam configuration of bathymetric sidescan systems, particularly in the near ranges where only small slopes are required to give rise to this condition.

Volume reverberation

Simulation 3 examines the effect of volume scattering on the depth estimate. The parameters of Simulation 1 were preserved and volume scatterers were added. The volume reverberation coefficient was set to $-80\,dB$. Figure 7 shows the resulting phase time series for receiver pairs 1,2 and 1,3. The largely random contribution of the volume component can be observed prior to the bottom arrival. The resulting increase in phase variance is more pronounced in the near and intermediate ranges. This is due to the fact that the insonified volume is restricted in the far ranges by the shape of the transmitting beam pattern. Figure 8a shows a 30 ping average for the combined bottom/volume return. The corresponding depth estimate (Figure 8b) displays a considerable bias towards lower depths. This means that the volume return is sufficiently directional to contribute a non-zero mean to the phase estimate. It should be noted that this problem is likely to be more severe when the volume return originates from layered aggregations of biological scatterers as is often the case in the ocean. In that case the volume reverberation return will be more coherent and its contribution to the mean phase more substantial.

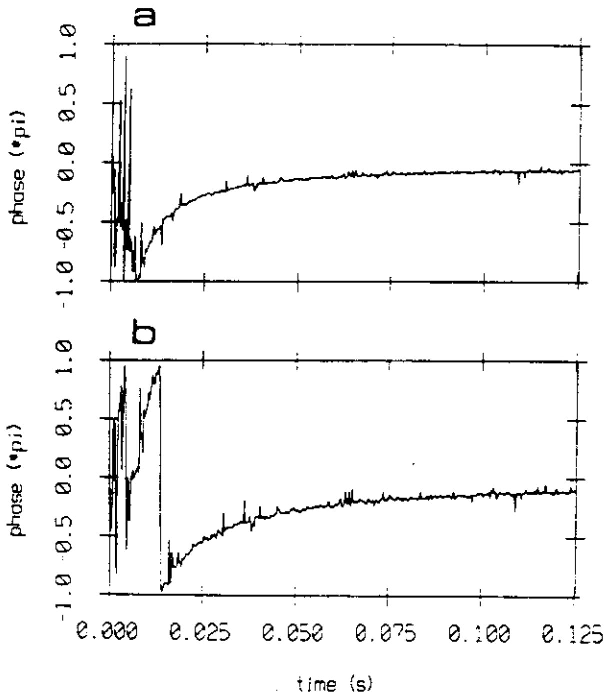

Figure 7. Phase difference time series, bottom and volume reverberation: (a) Receiver pair (1,2), (b) receiver pair (1,3)

Ambient noise

In Simulation 4 we included an ambient noise field with an intensity level of $50\,dB\ re\ 1\mu Pa$ while retaining the volume reverberation component. The noise is completely incoherent between the receivers, thus lacking a preferred direction. As Figures 9 and 10 indicate, ambient noise is likely to become the limiting interference in the far ranges where the reverberation returns have decayed sufficiently. At that point the phase variance increases dramatically and the depth estimate deteriorates.

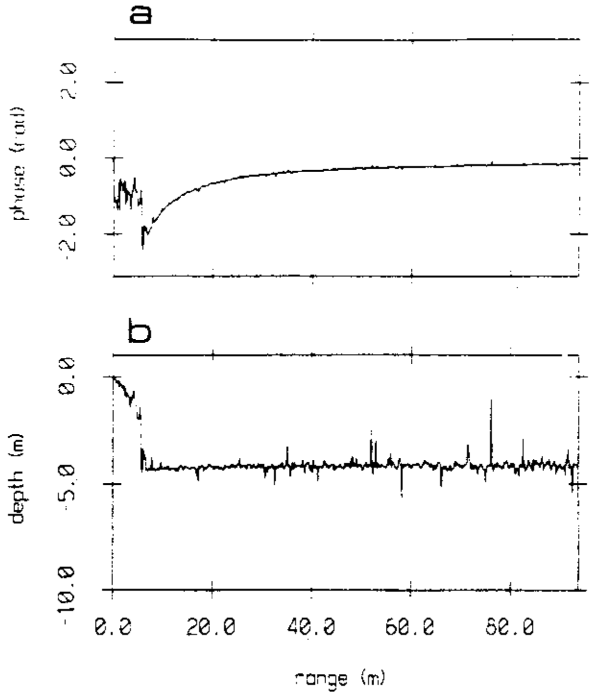

Figure 8. 30 ping average for receiver pair (1,2), bottom and volume reverberation: (a) Phase difference estimate, (b) depth estimate.

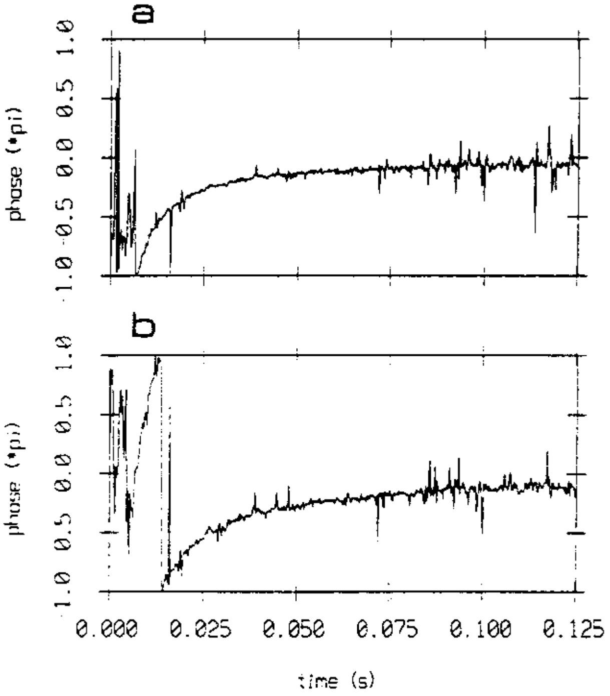

Figure 9. Phase difference time series, bottom and volume reverberation and ambient noise: (a) Receiver pair (1,2), (b) receiver pair (1,3).

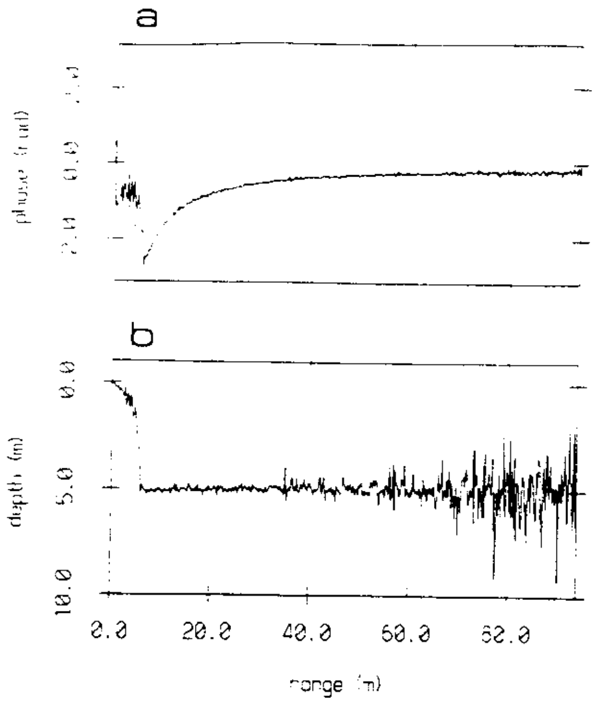

Figure 10. 30 ping average for receiver pair (1,2), bottom and volume reverberation and ambient noise: (a) Phase difference estimate, (b) depth estimate.

Phase bias

It may be observed that all phase estimates produced by averaging are characterized by an obvious underestimation of the true phase when its absolute value approaches π. This is due to a well-known bias effect resulting from an "aliased" phase distribution whereby large positive phase values appear as large negative values and *vice versa*. Therefore, averaging leads to a phase estimate biased towards lower absolute phase values. This is more evident for wide phase distributions. Simulation 4 is a good candidate for a demonstration because it produced the highest phase variance. A phase histogram taken at t=0.027 demonstrates the phase bias mechanism (Figure 11). Various bias-correction procedures have been suggested in the literature (e.g. [6]).

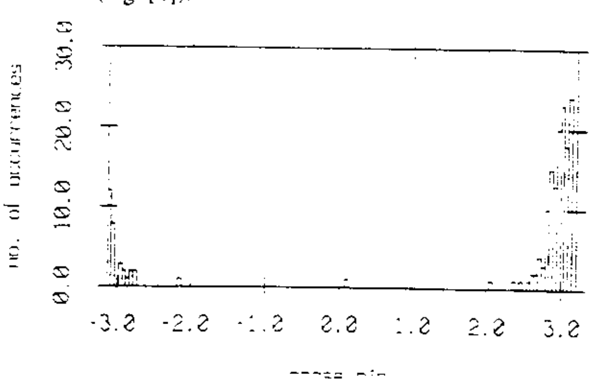

Figure 11. Phase histogram illustrating the origin of the phase bias effect.

SUMMARY

A series of computer simulations was performed revealing certain limiting factors in the performance of bathymetric sidescan systems. Sloping bottom features were shown to lead to reduced reverberation coherence and poor bathymetry for slopes exceeding a range-dependent "critical angle". Volume reverberation was shown to be sufficiently directional to cause a pronounced bias towards lower bathymetric estimates. Incoherent ambient noise will most likely be the limiting form of interference in the far ranges.

These initial simulations have shown REVGEN to be highly effective in simulating the bathymetric sidescan concept. Our intention is to proceed with more complex system configurations, using more realistic beam patterns and simulating other factors such as ray bending, multipath interference and vehicle motion.

ACKNOWLEDGEMENTS

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