Inference of manganese nodule coverage from Sea Beam acoustic backscattering data

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ABSTRACT
Normal incidence reflectivity from a manganese nodule field was measured with a 12 kHz Sea Beam multibeam echo-sounding system, aboard the R/V Thomas Washington and used to infer nodule coverage. A reflectivity map of the area was produced using the intensity of the specular return from each ping. The patchiness of the nodule coverage is evidenced by definite highs and lows in the reflectivity pattern. Ground truth was provided by near-bottom acoustic measurements and photographs taken with the Deep Tow instrument package of the Marine Physical Laboratory. Agreement between the simple nodule coverage predictions from Sea Beam acoustic data and the bottom photographs taken throughout the area is 98 percent. Although the Sea Beam system is limited in its dynamic range, this paper shows that it can be used very effectively to determine both topography and nodule coverage in potential mining areas.

INTRODUCTION
Economic considerations make the exploitation of ferromanganese nodules in the deep ocean strongly dependent upon extensive assessment of the density of nodule coverage at potential mining sites. Depending upon the method used to survey a site, the cost in ship time and manpower can become prohibitive. The approach described here derives its cost-effectiveness from the use of a Sea Beam echo-sounding system operating at optimum ship speed (10-12 knots). By taking advantage of the narrow-beam and multibeam capabilities of the Sea Beam, I was able to combine detailed topographic mapping with bottom backscattering characteristics to infer nodule coverage. The data presented here were gathered during two cruises in the northeastern tropical Pacific in May and June of 1983. The first cruise (PASCUA leg 5) was a rapid Sea Beam survey of an approximately 20 x 15 mile area southeast of Deep Ocean Mining Environmental Study (DOMES) site C (Figure 1), on an Ocean Mining Associates (OMA) trial mining site. This survey provided the topographic and acoustic reflectivity maps which served as the base of a month-long, fine-scale study of the same site, with the Deep Tow instrument package of the Marine Physical Laboratory of the Scripps Institution of Oceanography (Spiess and Tyce, 1973; Spiess and Lonsdale, 1982). The purpose of the Deep Tow survey (ECHO leg 1) was to assess, using a new multifrequency array, the near-bottom backscattering properties of a manganese nodule field. In addition, an environmental impact study of nodule mining was carried out through an extensive box coring program (Spiess et al., 1984). The choice of the site was motivated by the existence of a good DOMES and OMA data base in the general area. This paper discusses the results of the Sea Beam acoustic study, and uses the Deep Tow data as ground truth.

BACKGROUND
Manganese nodules remote sensing
Most techniques used to prospect for manganese nodules on the deep ocean floor rely on acoustic remote sensing, near-bottom photography and/or television, bottom sampling, or a combination of these methods.
Two general approaches have been taken for acoustic remote sensing of nodules. The first is a single-frequency approach, using high-frequency (> 100 kHz) side-scan sonars on a deep-towed instrument (Spiess, 1980), or using a shipboard subbottom profiler to correlate the thickness of the transparent layer with nodule abundance (Piper et al., 1979; Mizuno and Moritani, 1976). The second is a multifrequency approach [Sumitomo Metal Mining Co. (MFES), Magnuson et al., 1981, 1982; Spiess et al., 1984] which uses the frequency dependence of sea-floor acoustic reflectivity to infer nodule sizes and abundance. Both approaches rely on the observation of a difference in acoustic backscatter between a sedimentary bottom laden with nodules and a bare one.
Near-bottom photography techniques range from the conventional deeply towed camera systems to the unmanned, deep diving, free vehicle Epaulard (Duranton et al., 1980; Galerne, 1983). Ground truth for remote sensing of manganese nodules is obtained through direct sampling of a nodule field. To this end, dredging is used where large amounts of nodules with little or no sediments are sought. On the other hand, box cores...
provide an undisturbed sample of the bottom whenever an assessment of the geologic, biological, or acoustical properties of both the nodules and their underlying sediments is needed.

Normal incidence acoustic reflectivity

There is extensive literature dealing with acoustic properties of the ocean floor at various frequencies and angles of incidence, and with their geologic implications. Tyce (1976) and Parrot et al. (1980) gave good reviews of the literature available.

Due to its multibeam, narrow-beam characteristics, the Sea Beam system allows the measurement of the acoustic backscatter of the sea floor from each individual beam. An angular relationship of acoustic backscattering can then be derived. However, in this paper I take a first look at the data by selecting the beam nearest normal incidence and leave the others for later analysis.

Since the depth of this manganese nodule survey area is large (4,500 m on the average), the radius of curvature of the acoustic wavefronts reaching the bottom is much larger than Sea Beam’s acoustic wavelength (12 cm), and the wavefronts can be considered nearly planar. Therefore, I use this approximation in the following development.

In general, the intensity of a plane acoustic wave is related to the acoustic pressure $P$ by

$$ I = \frac{P^2}{\rho c}, $$

where $\rho$ is the density of the medium and $c$ the propagation velocity in this medium. The product $\rho c$ is called the characteristic acoustic impedance of the medium. The bar indicates that the pressure is averaged over some time (usually the integration time of the instrument) (Urick, 1983). If $I_0$ denotes the intensity of sound at unit distance from the source, the intensity of the normal incidence return $I$ from the bottom at depth $r$ is given by

$$ I = I_0 R^2 e^{-2\alpha r}, $$

where $\alpha$ is the exponential attenuation coefficient and $R$ is the Rayleigh reflection coefficient. Equation (2) assumes that the bottom reflects the sound rather than scatters it. This assumption seems reasonable for a manganese nodule field whose aggregate response was shown theoretically in Magnuson (1983) to be reflective rather than scattered.

For a plane wave normally incident on the boundary between two media of respective impedance $\rho_1 c_1$ and $\rho_2 c_2$, the Rayleigh reflection coefficient is the ratio of the reflected to the incident pressure waves:

$$ R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}. $$

For the purpose of this paper, medium 1 will be water and medium 2 will be sediment or nodules. The fraction on the right side of equation (2) indicates that seawater absorbs some of the energy, causing an exponential loss with distance from the source, and that intensity decreases proportionally to the square of distance due to geometric spreading. This is summarized in the sonar equation for an echo sounder obtained by taking $10 \log_{10}$ of both sides of equation (2):

$$ EL = SL - BL - TL, $$

where

$$ EL = 10 \log_{10} I = \text{echo level}, $$

$$ SL = 10 \log_{10} I_0 = \text{source level}, $$

$$ BL = -20 \log_{10} R = \text{bottom loss}, $$

and

$$ TL = 20 \log_{10} (2r) + 20 \alpha r \log_{10} e = \text{transmission loss}. $$

Equation (4) was used to determine the reflection coefficients of various marine sediments types as a method of classification (Breslau, 1967). Likewise, Hamilton (1970a, b) did extensive work toward predicting in-situ acoustic and elastic properties of marine sediments. Tyce (1976) focused on the determination of the attenuation coefficient in ocean sediments with a 4 kHz near-bottom profiler. His data indicate a large variability in seafloor reflectivity over short horizontal distances due to changes in local bottom roughness and composition. Breaker and Winokur (1967) observed an increase in the magnitude of the echo level fluctuations with distance from the bottom. Considering that most of the acoustic reflection comes from the first Fresnel zone which increases in size with distance from the bottom, they attributed these fluctuations to changes in the reflective characteristics of the bottom over very short distances. Again, these changes are most likely due to variations in bottom substrate and/or bottom roughness. The effect of roughness is to change the phase relationships between the different reflectors within a Fresnel zone. How rough a surface appears depends on the ratio of the root-mean-square (rms) bottom roughness $\sigma$ to the acoustic wavelength $\lambda$ (Clay and Medwin, 1977, chap. 10). Using the vertical component of wavenumber $k$, one can distinguish three cases:

(1) $\lambda \sigma \ll 1$, the surface appears to be smooth and the amplitude of the backscattered return is determined by the reflection coefficient (coherent return);
(2) \( \kappa \sigma > 1 \), the surface appears to be rough and the returns are mostly incoherent;
(3) \( \kappa \sigma \approx 1 \), intermediate range bridging the coherent and incoherent regimes.

Clay and Leong (1973) pointed out that when \( \kappa \sigma \approx 1 \) and when the spatial dimensions of bottom roughness are much smaller than the diameter of the first Fresnel zone, the reflective components add as the sum of squares and the returned mean square signal is proportional to the number of reflectors in the ensonified area. This means that bottom loss depends also on the ensonified area and therefore on the beam width of the measuring system. The diameter of the first Fresnel zone is given by \( d = (2\lambda h)^{1/2} \) where \( \lambda \) is the acoustic wavelength and \( h \) is the distance from the sonar to the reflection plane (Clay and Medwin, 1977, p. 50). For hull-mounted sonars such as Sea Beam, this distance is approximately the water depth. In this survey area, Sea Beam’s 12 cm wavelength yields a diameter of about 33 m for the first Fresnel zone at 4 500 m depth. As shown later, the rms roughness in this manganese nodule area is about 2 cm, so that \( \kappa \sigma \approx 1 \), and the spatial dimensions of roughness (10 cm or less) are much smaller than the dimensions of the first Fresnel zone.

Other investigators have tried to correlate acoustic frequency dependence of bottom reflectivity with bottom type and/or bottom roughness (Mackenzie, 1960; Zhitkovskii et al., 1966). This turns out to be a difficult problem when the acoustic wavelength and/or the bottom are such that subbottom reflections can no longer be ignored. Note that when the bottom is assumed horizontally stratified with plane interfaces between layers, subbottom reflections from thin layers (Clay and Medwin, 1977, chap. 2) yield a closed-form solution. However, in order to perform a first-order analysis, simplifying assumptions considering the ocean bottom as locally homogeneous in depth are made. An ideal ocean bottom can then be defined where, for normal incidence, the dimensions of the bottom irregularities compared to the acoustic wavelength and the impedance mismatch at the water-sediment interface are the main parameters in the determination of bottom reflectivity. Higher reflectivity corresponds to a high impedance contrast between sea water and bottom (generally hard substrate) and a locally smooth relief (dimensions smaller than the acoustic wavelength). As the ratio of the size of the bottom irregularities to the acoustic wavelength increases, the bottom irregularities act as scatterers and the specular component of an echo is lower. Reflectivity is again lower when the impedance contrast is low (soft bottom with impedance similar to that of sea water).

A manganese nodule field consists of a soft bottom (sediments) on which a variable number of nodules lie. Nodule acoustic remote sensing is then possible, provided there is enough impedance contrast between nodules and sediments.

Although no values are presently available for the acoustic impedance of manganese nodules or surface sediments in the survey area, the values given in Hamilton (1970b) for sediments of the Pacific and in Magnuson et al. (1981) for nodules can be used to compute an expected acoustic reflectivity difference between nodules and their underlying sediments. The sediments are mostly pelagic silty clay (Spies et al., 1984) for which Hamilton gave an in-situ reflective coefficient of 0.1316 at normal incidence and the corresponding bottom loss of 17.6 dB. For Pacific nodules, Magnuson gave a range of values for both nodule density and compressional wave speed. I use \( \rho_2 = 1.95 \text{ g/cm}^3, c_2 = 2400 \text{ m/s for a nodule, and from Urick (1983)} \)

\[ \rho_1 = 1.0475 \text{ g/cm}^3, c_1 = 1520 \text{ m/s for seawater at 4 500 m depth.} \]

Substituting these values in equation (3) yields a reflection coefficient \( R = 0.4923 \), which when expressed as the bottom loss term in equation (4) becomes \( BL = 6.2 \text{ dB} \). When the bottom depth is relatively constant, the transmission loss of equation (4) can be assumed constant. Therefore bottom loss is the only variable in equation (4), and the difference in reflectivity between a nodule and the underlying sediment is simply the difference in bottom loss: 11.4 dB.

Hamilton (1970b) also indicated there is little or no dependence of bottom loss with acoustic frequency for sediments where there is no lower layer to reflect sound which interferes with sea-floor reflections. Such is not the case for a nodule field. Studies by Magnuson et al. (1981, 1982) and the Sumitomo Metal Mining Co., where manganese nodules were modeled as spheres on an infinite flat plane, show that the bottom reflectivity of a nodule field can be expected to reach a maximum for a frequency corresponding to

\[ ka = 1, \quad (5) \]

where \( k \) is the acoustic wavenumber and \( a \) is the mean nodule radius. By comparing the results from measurements at sea with the foregoing models, some clues arise as to the validity of the assumptions made. However, before I can discuss these results, I need to characterize the data base and the measuring systems, Sea Beam and Deep Tow, used in this survey.

**SEA BEAM ACOUSTICS**

The Sea Beam system uses a multibeam, narrow-beam echo sounder operating at a frequency of 12.158 kHz with a pulse length of 7 ms and an echo processor to generate, in near real time, contour maps of the ocean floor while the ship is under-
Figure 2 illustrates the Sea Beam transmit/receive geometry. The transmitted beam pattern spans 54 degrees athwartships by $2\frac{1}{4}$ degrees in the fore-aft direction. It is pitch-stabilized to ensure vertical projection. As a result of the Sea Beam beam forming, the receiving beam pattern can be approximated by 16 adjacent rectangles $2\frac{2}{3}$ degrees by 20 degrees. The acoustic energy received at the ship comes from the intersection of the transmit and receive beam patterns, that is 16 "squares" $2\frac{2}{3}$ on a side.

With contour mapping as a goal, the Sea Beam does not preserve all the acoustic information it receives. As a result some valuable information not necessary for depth determination, such as the amplitude and the shape of the echo signal, is lost.

In order to preserve the echo amplitude information, a parallel data acquisition system was built around an LSI 11/23 minicomputer (de Moustier, 1985). This allows digital recording on magnetic tape the 16 Sea Beam detected, nonroll-compensated beams, along with time-varied-gain (TVG) and ship roll information. The TVG is designed to compensate for transmission loss [attenuation and spreading terms in equation (2)] and has already been applied by the Sea Beam system when the data are recorded. Figure 3 shows a typical 16 beam return, not roll-compensated, where the envelopes of the detected acoustic signals are plotted in analog-to-digital (A/D) units versus time after transmission. These units correspond directly to sound pressure levels with TVG applied. In this instance, the sea floor is essentially flat, resulting in the parabola outlined by the 16 returns. The amplitude is highest in the near-specular direction (first arrival in time) and decreases rapidly from the center outward. The early, synchronous returns on the side beams represent side lobe energy from the specular return and are rejected in both depth and return amplitude processing.

The Sea Beam system has not been calibrated; therefore in the following all the measurements are presented as relative.

**DATA**

The data presented here were collected during a 40-hour Sea Beam survey and a subsequent Deep Tow near-bottom investigation. Although the Sea Beam system maps a swath of sea floor three-quarters of the ocean depth wide, a high degree of overlap between swaths (80 percent in places) was used to provide as much redundant acoustic data as possible. Figure 4 shows the topography of the survey area contoured from the Sea Beam data. The contours are at 20 m intervals, implying a relatively flat portion of sea floor with less than 200 m of total relief in 40 km. Aside from two north-south troughs which bottom out at 4 600 m on the edges of the map, the mean depth is 4 300 m.

The general pattern agrees well with the known north-south orientation of sea-floor features, perpendicular to the spreading direction in this part of the Pacific Ocean.

At this depth the Sea Beam system transmits every 8 s. For each transmission, a set of 16 returns (Figure 3) is digitized and recorded on magnetic tape. For a first look at these data, the postprocessing consisted in selecting the highest amplitude in each set. The highest amplitude generally represents the near-specular return, which in the case of a relatively flat bottom, as in this area, comes in first.

This set of peak amplitudes is then low-pass filtered by applying a running mean along the track, averaging over the

![Figure 3. Acoustic signal envelopes of the 16 performed beams at the output of the Sea Beam echo-processor receivers. The x-axis represents time after transmission in seconds. The y-axis represents the amplitude of the signals expressed in A/D units (0-4095) linear scale. Such data are recorded digitally on magnetic tape every transmission cycle, along with time-varied-gain and ship's roll. No roll correction has been applied to the data at this stage.](image-url)
Fig. 4. Contoured map of the survey area from Sea Beam data. The contours are in uncorrected meters. The contour interval is 20 m.
Fig. 5. Ship's track of the Sea Beam survey in the manganese nodule area (PASCUA leg 5). The peak amplitude from each ping (Figure 3) has been selected, low-pass filtered, and plotted along the track in A/D units linear scale (0-4095). Five intervals were chosen on this scale and pattern coded as shown in the key.
size of the vertical beam's footprint: roughly five transmission cycles at 11 knots. The resulting data are plotted and pattern coded along the ship's track on Figure 5. The A/D units linear scale is the same as indicated in Figure 3.

The Deep Tow survey was concentrated in the southern portion of the area where the Sea Beam survey density is greatest. The Sea Beam acoustic data served as a reference for the Deep Tow work during which camera runs, near-bottom multifrequency (4.5, 9, 15, 30, 110, 160 kHz) backscattering measurements, and side-looking sonar data (110 kHz) were collected. As part of a mining environmental impact study, 16 box cores were also taken throughout the Deep Tow survey area. The various elements of the Deep Tow work are summarized in Figure 6 (Spiess et al., 1984).

DISCUSSION

Sea Beam reflectivity data

Inspection of the peak-amplitude data reveals a substantial ping-to-ping variability as well as definite mean amplitude highs and lows along the ship's track. This point is illustrated in Figure 7 where amplitude versus distance along the track is plotted in conjunction with the center beam width profile. The

![Figure 6. Deep Tow track chart showing camera runs, near-bottom multifrequency backscattering measurement runs, box core locations, and navigation transponder positions. Coordinates are in meters east and north of 14°34′N, 125°30′W.](image-url)
amplitude is expressed in relative decibels, with reference to the mean amplitude of the data displayed. The data shown in this figure have been averaged over five transmission cycles for clarity; actual ping-to-ping variability is much greater. Some small correlation with topography can be seen. However, remember that the vertical exaggeration on the depth profile is 18. The slopes are therefore rarely in excess of 2 degrees. On the left side of Figure 7, large fluctuations in amplitude are apparent, and the average value is around -6 dB. Compared with the right side where the average amplitude is +4 dB, the bottom reflectivity has changed significantly from one side to the other.

Following this result, I divided the peak amplitude data set into five intervals on the A/D linear scale (0-4095) and pattern coded each one as shown in Figure 5. The data match, to within 130 A/D units on the average, over all except three track intersections where there are slight offsets. Because normal satellite navigation is simply inadequate for track positioning at the level of Sea Beam’s resolution, one relies upon matching Sea Beam topography at crossings and overlaps for accurate track positioning. However, accurate adjustments are difficult to achieve when the sea floor surveyed exhibits little relief, as in this area.

A histogram of the data distribution is shown in Figure 8. The histogram suggests that the data suffer amplitude clipping at 3000 A/D units, since there are no values beyond this point. This unfortunate characteristic is an artifact of the data acquisition system which was saturating at 7.3 V. This problem has since been corrected. In addition, it was found that the output of the Sea Beam echo processor receivers is limited to 8.5 V instead of the 10 V announced by the manufacturer. As a result, the receivers’ dynamic range is apparently inadequate to accommodate both the low backscatter levels received on the side beams from a smooth bottom and the high amplitude associated with some strong specular returns. For this simplified application, however, the nodule distribution results are not significantly affected, since I arbitrarily chose to start the last A/D interval at 2500 units. Nevertheless, this amplitude clipping does limit resolution for high-amplitude returns and prevents discussion of the abilities of such a sonar to characterize similar nodule fields or other seafloor types. From discussions with the Sea Beam manufacturer, it seems that a first-order improvement to this dynamic range limitation can be achieved by a simple modification of the detection amplifiers. Obtaining the full range needed, however, might require modification of the hydrophone preamplifiers which have been found to saturate occasionally and would also require use of logarithmic detection amplifiers.

Drawn from the data in Figure 5, a contour map of reflectivity in the southern portion of the survey area is presented in Figure 9. It uses the same pattern code as previously described. Two main characteristics stand out on this map: a region of strong reflectivity in the center, bordered to the east and to the west by strips of much lower reflectivity. Some of the low values correspond to the north-south troughs apparent in the bathymetry (Figure 4). However, the low reflectivity extends 3 to 4 km into the flat center portion. Changes in relative reflectivity of 12 dB or more (Figure 7) can therefore be expected as one crosses the leveled ground area in an east-west direction. Although this number is biased in trying to account for the clipping of the high-amplitude return (I added 2 dB to the 4 dB average amplitude shown on the right side of Figure 7), it is reassuring to note that it is close to the expected value computed in the “Background” section (11.4 dB). Since we were surveying a manganese nodule site, I would like to associate the above changes with differences in nodule coverage, with high-amplitude values corresponding to a dense coverage and low values indicating absence of nodules. To do so, however, re-
quires ground truth available only from near-bottom instruments with bottom photographic capabilities. Therefore, this Sea Beam reflectivity work was done in an area intended for Deep Tow coverage.

Deep Tow ground truth

It was a rewarding experience to watch Deep Tow camera runs unveil snapshots of the sea floor which matched the simple predicted bottom pattern. Each camera run (Figure 6) consistently output pictures which agreed with the simple manganese nodule coverage inferences made from the Sea Beam reflectivity data. Three representative pictures are shown on Figure 10. Each picture typifies an amplitude interval. The dense nodule coverage of photo A corresponds to the dot patterned areas on Figure 9 (2 500 A/D units and greater). The intermediate nodule coverage seen in photo B is found in areas with the brick pattern (2 000-2 500 A/D units) and the hatched pattern (2 000-1 500 A/D units). The two remaining patterns (1 500 A/D units or lower) turned out to be bare mud as shown on photo C. Inspection of over 3 000 Deep Tow bottom photographs and classification according to the three types shown (dense, intermediate, and bare) yielded a 98 percent correlation with the simple nodule coverage made from the Sea Beam data.

During a camera run, the towed instrument is flown approximately 10 m above the bottom. This renders pictures which cover about 35 m² of sea floor, thus giving a clue to nodule sizes. From the photographs and from the 1/4 m² box cores (photo D), the average nodule was found to be 4 to 8 cm in diameter, with a flattened and irregular cauliflower-like shape, as opposed to the rounder nodules found in other areas (Heezen and Hollister, 1971; Bischoff and Piper, 1979). The first results from the Deep Tow multifrequency, near-bottom acoustic backscattering measurements (Spiess et al., 1984) also reinforce the belief that Sea Beam is well suited to map out manganese nodule coverage in this prospective mining area. Figure 11 shows the normal-incidence reflectivity difference between a densely nodule-covered patch and a barren one, as measured at the six frequencies of the Deep Tow backscatter system. The optimum frequency for this site appears to be between 15 kHz (16 dB) and 9 kHz (13 dB). The operating frequency of the Sea Beam system (12 kHz) falls exactly halfway between these two frequencies. At 12 kHz equation (5) yields a mean nodule radius of 2 cm (1.6 cm at 15 kHz). Although the nodules of this site are poorly approximated by spheres, the foregoing results indicate that the Sea Beam frequency is near optimum for the area surveyed. However, do not presume that 12 kHz will be optimum for all types of nodules, or that any 12 kHz sonar would provide the same results, since Sea Beam is a roll- and pitch-stabilized system with 2 1/4 degree resolution. As pointed out earlier, this high resolution has a significant effect on observed backscattered levels and associated fluctuations due to the size of the observed area. In comparison, normal echo sounders typically have a beam width between 30 and 60 degrees and a bandwidth wider than Sea Beam's, resulting in a substantially lower signal-to-noise ratio. Both the Deep Tow and the Sea Beam data point to the patchiness of the nodule coverage, some patches being less than a kilometer in extent. It is doubtful whether an unstabilized system which spans an area 2.4 km wide (30-degree beam at 4 500 m) can resolve such patches.

Note that the value obtained for mud-to-nodule reflectivity difference with Sea Beam is lower than those obtained with Deep Tow at 9 and 15 kHz. Even though the frequency dependence of mud-to-nodule reflectivity might not be linear, it is reasonable to expect the value at 12 kHz to be between those at 9 and 15 kHz. To explain this discrepancy, the differences in the geometry of measurement between the two systems should be considered. Indeed, for Sea Beam the area of the first Fresnel zone is approximately 33 m wide at 4 500 m depth, which is almost one order of magnitude larger than the diameter of the first Fresnel zone (4 m at 15 kHz) observed with Deep Tow when the instrument is 80 m off the bottom. However, the Deep Tow acoustic data have been averaged over spatial distances along track commensurate with Sea Beam's normal incident footprint. Moreover, the beam width dependence presumably cancels out when the reflectivity difference between nodule and mud is measured with the same instrument. In the reflective model the geometric argument is then ruled out. To account for the Sea Beam's mud-to-nodule reflectivity difference being lower than those of the two neighboring Deep Tow frequencies (9, 15 kHz), I therefore need to reconsider the reflectivity model. In this manganese nodule area, the local roughness over a 200 m horizontal extent is primarily due to the presence or absence of nodules. From the bottom photographs and core samples, I estimate the rms roughness to be about 2 cm and spatial dimensions of roughness to be 10 cm or less. At 9 and 15 kHz, 80 m off the bottom, the diameter of the first Fresnel zone (5.2 and 4 m, respectively) is then still substantially larger than the spatial dimensions of the bottom roughness and κσ = 0.75 and 1.25, respectively. As mentioned in the "Background" section, κσ = 1 corresponds to the ill-defined boundary between reflection and scattering.

If I now take the difference between the mud-to-nodule reflectivity difference (16 dB) measured at 15 kHz and the computed bottom loss for the mud (17.6 dB), I obtain a bottom loss for nodules of 1.6 dB. In comparison, a smooth layer of chert (a
Fig. 9. Contour map of relative reflectivity drawn from the lower half of Figure 5, where ship track density is greatest. Same pattern code as in Figure 5. The dotted line delimits the Deep Tow survey area shown in Figure 6.
sedimentary rock having an acoustic impedance almost 4 times greater than the estimated impedance of a nodule) has a bottom loss of 3 dB (Tyce et al., 1980). The estimate of the mud bottom loss is perhaps questionable. However, it is reasonable to believe that this value is within 2 dB of the real one. Moreover, the nodules are porous and do not form a continuous slab, but rather are scattered at variable distances from each other. Therefore the bottom loss of such an assemblage is expected to be greater than the 3 dB given for a chert layer. Clearly, a simple reflective model is insufficient to explain the high value found at 15 kHz.

A more realistic result is obtained by considering the nodules as a thin layer separating water from mud. In this case, the reflection coefficient at normal incidence (Clay and Medwin, 1977, chap. 2) is given by

$$ R = \frac{R_1^2 + R_2^2 + 2R_1R_2\cos(\phi)}{1 + (R_1R_2)^2 + 2R_1R_2\cos(\phi)}, \quad \phi = \frac{4\pi f h}{C_{nod}}, $$

where $R_1$ is the water-nodule reflection coefficient [as given by equation (3)], $R_2$ is the nodule-mud reflection coefficient, $f$ is the acoustic frequency, $h$ is the thickness of the thin layer, $C_{nod}$ is the compressional wave speed in nodules. Using $\rho = 1.37$ g/cm$^3$ and $C = 1507$ m/s for mud (Hamilton, 1970b), $h = 4$ cm for the thickness of the thin layer, and the values given in the “Background” section for the other parameters, yields a bottom loss of 5.3 dB at 15 kHz. Also with these values, the reflection coefficient $R$ of equation (6) reaches a maximum at 15 kHz. Therefore, this thin-layer model agrees with the frequency dependence shown in the Deep Tow data (Figure 11), but does not match the mud-to-nodule reflectivity difference measured at 15 kHz, especially since (as mentioned above) the nodules do not form a continuous slab. A scattering model should then be considered for nodules. However, it requires knowledge of the ensonified areas and therefore of the beam patterns of the Deep Tow backscattering assembly. These beam patterns were not available at the time of this writing, precluding this analysis.

Fig. 10. Photographic ground truth: (a) dense nodule coverage representative of the dot patterned areas in Figure 9; (b) intermediate coverage representative of the brick and hatched patterns; (c) bare mud representative of peak amplitude values 1 500 A/D units and lower; (d) 1/4 m$^2$ box core number 358 (Figure 6) giving clues to representative nodule sizes for the area.
Further analysis of the data presented here, on a scattering rather than a reflective basis, and investigation of the angular dependence of acoustic backscattering from the Sea Beam and the Deep Tow data should help explain the processes at work here.

**Further use of Sea Beam's acoustic returns**

Using only the peak amplitude of the specular return of the 16 Sea Beam preformed beams to map out normal incidence bottom reflectivity is a nice first-order application. It yields good results over this particular manganese nodule field. Clearly, more can be expected from the Sea Beam acoustic data. Work is currently in progress to model the angular dependence of Sea Beam acoustic backscatter over various types of sea floor and to relate the data to the geologic characteristics of the bottom (Patterson, 1967). Following work done by Clay and Leong (1973) and recently by Stanton (1984) the variations in the shape of the echo envelope can also be used to predict bottom roughness. According to Stanton, his statistical analysis works best for amplitudes of sea floor roughness less than a quarter of the acoustic wavelength.

Since the Sea Beam acoustic wavelength is about 12 cm and since I estimated the local rms bottom roughness to be about 2 cm, the data from this manganese nodule area qualify for such a statistical analysis which could prove useful for discrimination between various bottom substrates with similar reflectivity patterns.

**CONCLUSIONS**

In a recent monograph on polymetallic nodules (Rapport de l'Académie des Sciences, Paris, 1984) the Sea Beam system was deemed an essential tool for any large-scale nodule prospection since detailed knowledge of the bathymetry is a prerequisite to nodule mining.

The data presented here bring a new dimension to the Sea Beam multibeam echo-sounding system. In addition to contour mapping, I have shown that it is possible to detect changes in reflectivity along the track by using the amplitude of the near-specular acoustic return. This works particularly well over a manganese nodule field with little relief, since nodules and mud provide a definite acoustic contrast (11 dB or more). Although a scattering model would seem more appropriate than the simple reflective one used here, the normal-incidence backscattering data gathered with the Deep Tow multifrequency acoustic array confirm that high reflectivity contrast between nodules and mud should be expected at Sea Beam operating frequency (12 kHz). This frequency seems to be near optimum for this manganese nodule site. Bottom photographs taken throughout the site agree surprisingly well with the simple nodule coverage prediction made from Sea Beam acoustic data.

In spite of dynamic range limitations evidenced in my data, I believe that nodule coverage assessment can be performed very effectively with a Sea Beam system while contour mapping the topography of a prospective mining site. In essence, areas where amplitude saturation occurred correspond to areas of denser nodule coverage with strong reflectivity. Photographic ground truth can be obtained with an unmanned, deep-diving free vehicle, with towed vehicle camera and sonar systems, or even with conventional bottom cameras.

More extensive processing of Sea Beam's detected echoes is in progress with the intent of assessing whether the backscattered returns separated by Sea Beam's high angular resolution can be correlated with seafloor geologic characteristics. This includes identification of the reflectivity and roughness characteristics of different bottom types: sediments, rocks, rock outcrops, manganese nodules, etc. Initial results have been very encouraging, as suggested both in this paper and in ongoing work on various types of sea floor.

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