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SEAFLOOR ROUGHNESS, SEDIMENT GRAIN SIZE, AND TEMPORAL STABILITY

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Abstract: *Measurement of seafloor microtopography is rapidly approaching the status as a standardized element of geoacoustic characterization of the sea floor. With the advent of underwater stereo cameras and, recently, multiple-megapixel digital cameras adapted for underwater use, more investigators are measuring seafloor roughness at high resolution for applications to high-frequency acoustic modeling. An assessment of the methodologies used to characterize seafloor roughness, the parameterizations of the characterization of seafloor roughness, and the predictability of seafloor roughness seems appropriate at this time.*

Use of the roughness power spectrum to characterize seafloor roughness has a wide applicability for acoustic modelers. Currently, the slope and intercept of the regression line through the roughness power spectrum are used to parameterize seafloor roughness for acoustic modeling. Recent availability of digital roughness height datasets allows computation of two-dimensional roughness power spectra at sub-cm resolution. Ideally, these 2-D spectra would make the estimation of 2-D roughness parameters from 1-D roughness parameters unnecessary. Although much seafloor microtopography has been characterized concomitantly with sediment grain size, empirical prediction of roughness from grain size remains problematic. The inherent problem in relating seafloor roughness parameters to grain size is that the sediment-water interface is dynamic. Although seafloor microtopography may be thought to evolve predictably through cycles driven by hydrodynamic and biological processes, the rates of these processes and the resultant bedforms are highly variable. Another aspect of seafloor roughness that needs to be *addressed is the character of its power spectrum over several orders of magnitude of spatial dimensions.*

Keywords: *roughness, sediments, grain size, power spectrum, photogrammetry*

1. INTRODUCTION

Measurement of seafloor roughness has been an essential task in characterizing parameters controlling bottom backscattering and penetration for a number of high-frequency acoustic experiments [1-7]. Current or wind-wave-generated ripples, as well as biogenic features such as mounds, pits, and trails, may be relevant to modeling high-frequency scattering because acoustic scattering from the seafloor surface is determined by the size of the feature in relation to the acoustic wavelength. In order to measure the seafloor features that may control interface scattering, a number of methods have been employed. Simple profiles of the sea floor have been generated by divers' tracings on Mylar, megahertz-frequency acoustic transducers, laser-line scanners, and a conductivity probe [7-10]. When the optical quality of the water permits it, underwater stereo photogrammetry is an accurate method of determining the seafloor microtopography [8, 11, 12]. Assuming there is sufficient spatial coordinate control and camera separation for the image pairs, height profiles can be generated with sub-millimeter horizontal and vertical resolution from photography conducted almost a meter from the sea floor [7].

The 1-dimensional (1-D) profiles produced from traces, soundings, or interface imagery are high-frequency deterministic representations of relatively small areas (on the order of 0.2 m^2 for close-range stereo photographs) of the seafloor that are used to model the acoustic scattering from areas defined by the acoustic "footprint". Depending on the distance from the high-frequency acoustic source used, the "footprint" from which scattering is measured could be twice the photographed area for 40 kHz. Because the profiles need to be representative of the entire photographed area, multiple profiles are measured with the objective of attaining a stable statistical model of the roughness variability.

Furthermore, seafloor roughness is a dynamic property: the interface morphology evolves over time and is subject to physical and biological processes acting on the sediments. The nature and the magnitude of the effects of the processes modifying the sediments depend on the sediment type. That is, muddy, cohesive sediment will have a different response to a given bed stress as well as have a different bioturbating fauna than a sandy sediment [13]. The ability to predict the variability of seafloor microtopography would greatly benefit acoustic modeling. Thus, at the very least, a stochastic model of seafloor roughness must be defined in terms of sediment grain size, time, and space.

2. STATISTICAL ANALYSIS OF SEAFLOOR ROUGHNESS

Relative height measurements, *e.g.*, 1-D profile data, can be used to estimate the dispersion of seafloor feature height calculated as the *rms* roughness. This statistic is simply the standard deviation of the relative height measurements and it has applicability to scattering models [14]. The *rms* roughness statistic, however, does not provide any information on the size and spacing of seafloor roughness features.

The seafloor roughness power spectrum, estimated from the same 1-D relative height measurements is a characterization of the variance of the size and periodicity of the seafloor height fluctuations as a function of the spatial frequency [15]. For simplicity, the roughness power spectrum can be parameterized using a power law by the slope and the intercept (value of spectrum at a spatial frequency of 10^0) of the linear regression line through the points of the periodogram estimate in log-log space. The parameters of slope and intercept of the roughness power spectrum are often used by acoustic modelers to predict bottom backscattering [3, 4, 16, 17]. In fact, the parameters γ_2 and w_2 used in the perturbation model of Jackson (3) are actually the slope and intercept, respectively, of the two-dimensional (2-D) roughness power spectrum, which are estimated from the 1-D power-law values. Whereas in principle it is possible to determine the 2-D roughness spectrum (and its slope and intercept) from a digital elevation model (DEM) of the stereo overlap area, the impracticality of digitizing the area at high-resolution with conventional analog methods encourages estimation of the 2-D slope and intercept rather than the straightforward determination from the DEM.

The introduction of the digital camera to underwater applications, however, permits the use of digital image processing software to achieve DEMs from digital images [6, 18]. The digital cameras available to date have either a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) for collection of optical images. CMOS chips require less power than CCD chips, making a larger size for collection of images practical for battery-powered cameras. Typically, CCD chips have a smaller image-collecting area than 35-mm film, thus introducing a magnification factor into the image resolution. The trade-off on the larger size of the CMOS chip is the higher noise, though recent advances in semiconductor technology have significantly reduced image noise in situations where there is abundant light. Image resolution is determined chiefly by the size of the light-sensing chip, usually indicated by the total number of pixels making up the image stored by the camera. For instance, a digital camera collecting an image defined by dimensions of 2160 × 1440 pixels provides a 3-megapixel image. Currently, image size from commercially available digital cameras ranges up to 15 megapixels. Resolution of seafloor features depends on the distance between the image sensor and the sea floor. For a camera altitude from the sea floor allowing a 110-×-70-cm area, a 3-megapixel image would resolve a 1-mm-sized feature with about 2 pixels in either length or width dimensions. A 13.5-megapixel image of the same seafloor area would resolve a 0.5-mm feature with the minimum number of pixels. Of primary importance to the obtaining of usable images underwater is the optical quality of the water. The presence of fine, light-scattering particles or larger suspended material in the water may thwart digital photogrammetry by degrading resolution or introducing an unacceptable amount of visual noise for image processing. Provided there is sufficient water clarity, image resolution, adequate computing speed, and memory to accommodate processing large data arrays, generation of 2-D roughness spectra from DEMs are possible.

An example of a 2-D roughness spectrum estimated from a DEM that was generated from digital stereo photographs of a bioturbated medium sand sediment is displayed in Figure 1. The roughness spectrum is essentially isotropic, *i.e.*, the spectrum has a central peak without any pronounced directionality in 2-D spectral spatial frequency space. In contrast, the spectrum estimated from a DEM generated from a rippled sand bottom exhibits an anisotropic spectrum with obvious directionality (Fig. 2). The photograph in Figure 2 displays a rippled sediment surface. The 2-D roughness spectrum corresponding to the DEM created from this sediment surface indicates prominent peaks at the 1.9-cm spatial periodicity (± 52.6 m^{-1} spatial frequency) of the grooves.

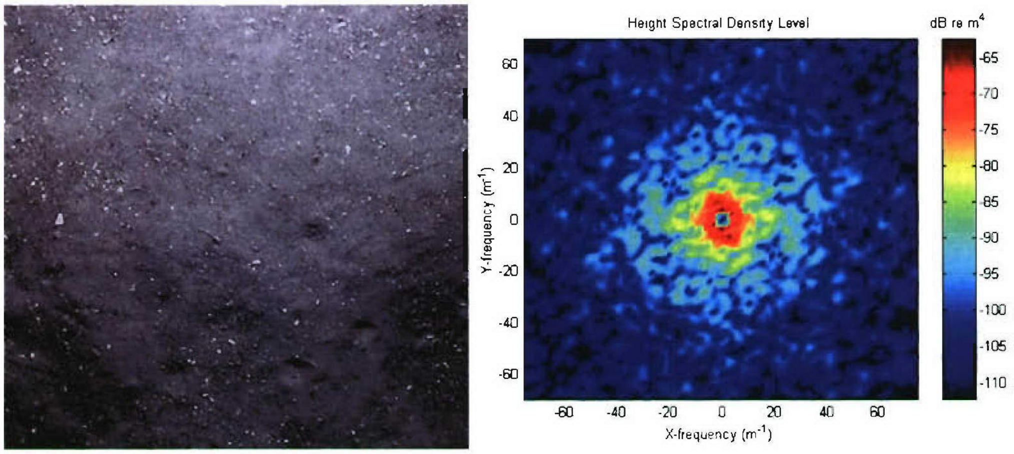

Fig. 1: One image from a stereo photograph pair of a bioturbated medium sand sediment and the isotropic 2-D roughness spectrum estimated from the DEM.

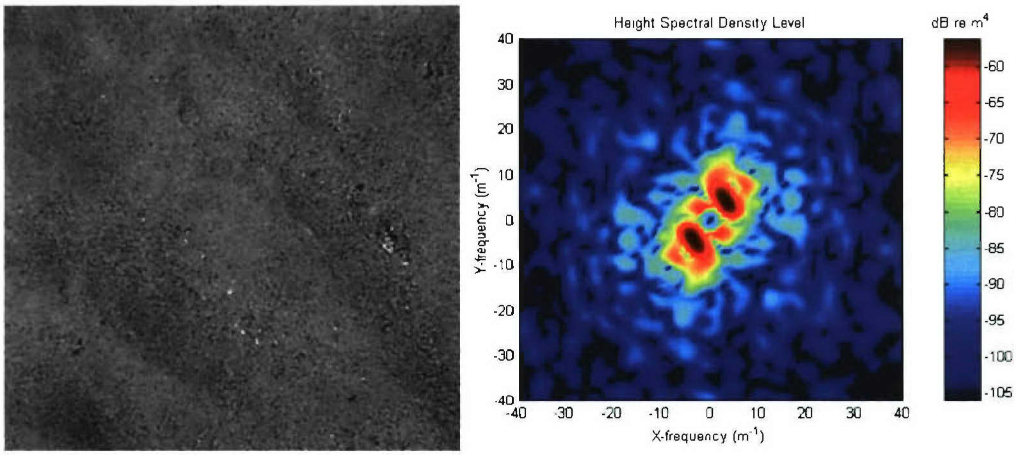

Fig. 2: One image from a stereo photograph pair of an artificially grooved sediment surface and the anisotropic 2-D roughness spectrum estimated from the DEM.

In order to statistically characterize the anisotropic 2-D roughness spectrum, however, one of two approaches must be used. Either isotropy can be assumed and a regression fit is made to the radially averaged 2-D roughness spectrum [6], or "slices" can be made at azimuthal orientations corresponding to the roughness features such as perpendicular and parallel to the ripple crests or parallel to the acoustic ensonification azimuth [18]. Each "slice" through the 2-D roughness spectrum is a 1-D representation of the 2-D roughness spectrum in a particular orientation, but it is not the same as the 1-D roughness spectrum estimated from 1-D profiles. The regression intercept of the "slice" through the 2-D roughness spectrum has units of length to the fourth power and represents the parameter w_2 in the perturbation model of Jackson [3]; whereas the regression intercept (w_1) of the 1-D roughness spectrum has units of length cubed and w_2 must be estimated from w_1. The regression slope of the "slice" represents the spectral exponent γ of the isotropic power-law roughness spectrum, $W(K) = w_2(h_0 K)^{-\gamma}$, with K representing the 2-D roughness vector and h_0 is a 1-cm reference length [3].

3. RELATIONSHIP OF ROUGHNESS STATISTICS TO SEDIMENT TYPE

Although sediment type is assumed to control morphology of bedforms, evidence of a relationship between seafloor roughness and sediment grain size has never been systematically developed. When seafloor roughness as represented by *rms* roughness is plotted as a function of mean grain size, the result is a scattering of points across the range of sediment types (Fig. 3). The figure shows a general decrease in relative height variation as the sediment grains become finer, which may be related to the ability of waves and currents to mobilize sediment and build bedforms in cohesionless *versus* cohesive sediments. There are more measurements in sands, and consequently there is clustering of data from coarser grain sizes. The measurements from muds, however, are certainly underrepresented. Thus, the relationship of *rms* roughness with grain size as presented here is incomplete.

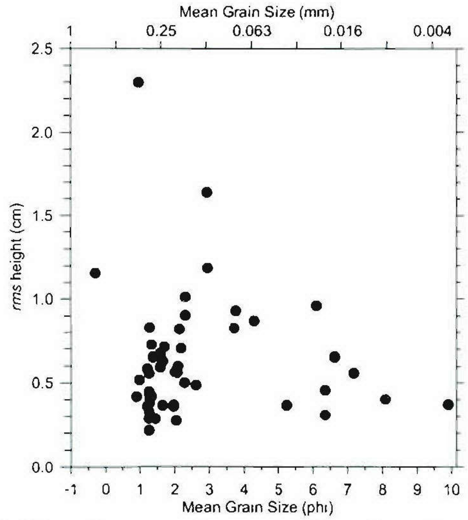

Fig. 3: Plot of rms *roughness as a function of mean grain size. Units of grain size (ϕ) are equal to* $-\log_2$*(dia. in mm).*

An attempt to construct regressions on grain size was made using values of 2-D roughness spectral exponent and strength measured in acoustic experiments and calculated from 1-D values of spectrum slope and intercept. These data were collected from 42 sites where grain size as well as seafloor roughness were measured [6, 19, 20]. As displayed in Fig. 4, the plots indicate that there is not a unique empirical relationship between roughness spectrum exponent and grain size or between roughness spectrum spectral strength and grain size. However, the measurements of spectral exponent and strength appear to cluster according to sediment type, with separate trends for sands and muds. The dashed lines in Fig. 4 are not regression fits but a delineation of trends for the different sediment types. Measurements from sites that include roughness features such as storm ripples and biogenic mounds and pits are distributed throughout the data and do not align, as do the trends delineated in Fig. 4. Again, because of a relative dearth of measurements from fine-grained sites these relationships are less than conclusive about the effect of sediment type on roughness spectra.

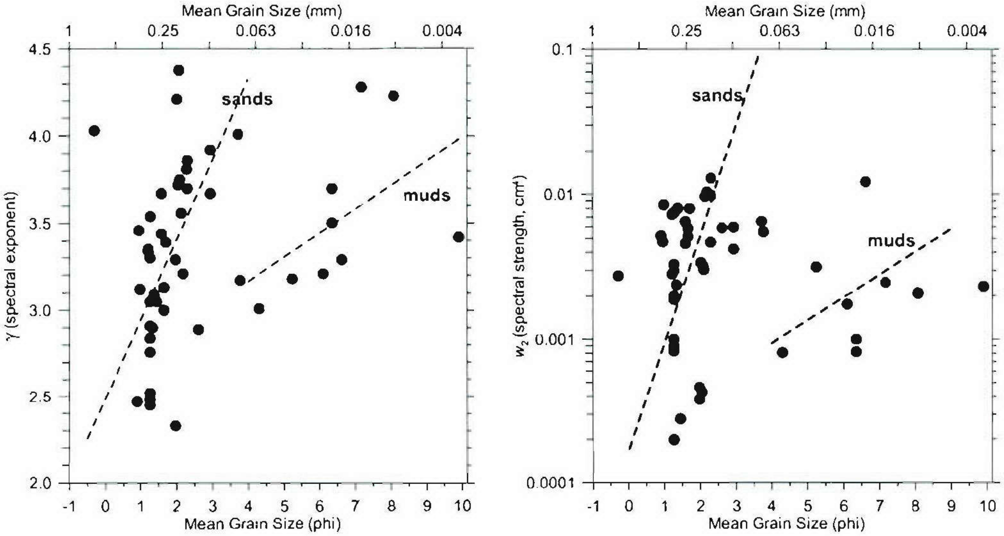

Fig. 4: Plots of 2-D seafloor roughness spectral exponent (γ) and spectral strength (w_2) as a function of mean grain size. Units of grain size (phi) are equal to $-log_2$(dia. in mm).

4. TEMPORAL VARIABILITY AND SPATIAL SCALE OF ROUGHNESS

Briggs et al. [7] demonstrated how sand ripples degrading over the period of a month could change the values of statistical parameters describing the roughness power spectra. Changes in ripple morphology from sharp-crested, relatively steep ripples freshly generated during a storm event to subtly undulating ripples appear to affect the values of slope and intercept of the 1-D roughness spectra. Diver observations indicate that mobile benthic fauna incrementally smooth the ripples, reducing their height, sharpness, and steepness. The rate at which this transformation occurs is related to the type and numerical density of the fauna. For instance, movement of sand dollars across the sediment surface vastly accelerates the degradation of ripples. A significant effect may be ascribed to the community of smaller infauna such as polychaete worms, crustaceans, and microscopic nematode worms. The cumulative effect of these burrowing fauna on moving grains is significant due to their great abundance and intense activity near the sediment-water interface where they reside. Fishes that feed on the sea floor can also greatly degrade ripples, and their feeding effects can be magnified by their attraction to submerged equipment or moored ships [21]. Feeding activity by most benthic fauna tends to roughen the interface on a fine scale and degrade roughness at larger scales. Thus, the overall effect of bioturbation is to decrease the low-spatial-frequency roughness by collapsing ripples and increase the high-spatial-frequency roughness by creating fine structure. These changes have the effect of lessening the power spectral steepness (slope) and raising the spectral strength (intercept). Besides the smoothing of the ripples, bioturbation decreases the anisotropic nature of storm-generated microtopography and creates a more isotropic roughness. Because of the continuous cycle of the generation of ripples by storm waves and currents and the degradation of the anisotropic roughness by bioturbation, seafloor roughness can be seen as a dynamic feature. Consequently, any measurement of seafloor roughness characterizes only an instant in time.

Although small-scale (<1 m) seafloor roughness is a function of hydrodynamic and biological processes, there is a question of whether the processes that control larger-scale

(10^0-10^4 m) seafloor roughness would result in roughness spectra with slopes and strengths dissimilar to those from small-scale roughness. An indication that seafloor roughness spectra may be self-similar over seven orders of magnitude is shown in Fig. 5. Spectra generated from multibeam bathymetry have spectral slopes of -1.74 (NWSE) and -2.72 (NESW), which are similar to spectral slopes of -2.53 (decayed ripples) and -3.16 (fresh ripples) derived from photogrammetry collected from the same area and time. These spectra have overlapping ranges for w_1, also, indicating that there is a consistent distribution of spectral "energy" over diverse scales of roughness. Comparisons of bathymetry and microtopography for consistency of spectral slope have been made before in deeper water [15, 22] with similar results, but more data of this type are needed to confirm this accordance among spectra spanning several spatial scales and different environments.

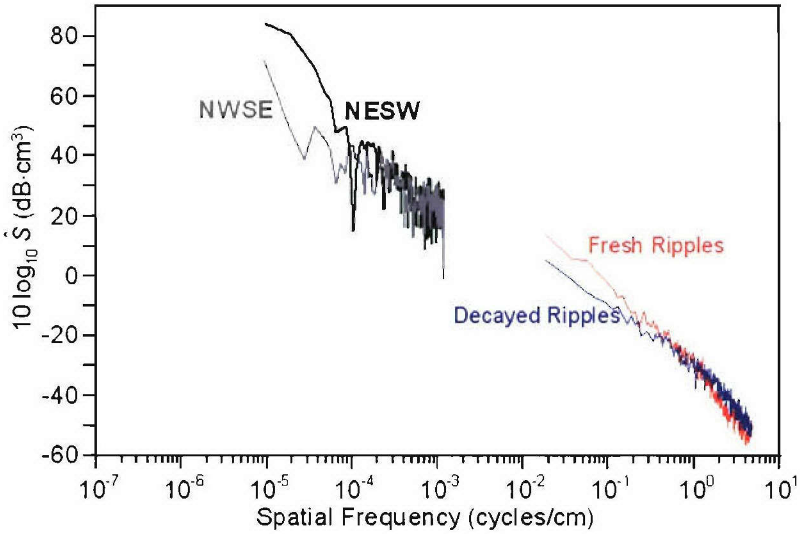

Fig. 5: 1-D roughness power spectra from multibeam bathymetry (NWSE, NESW) and close-range photogrammetry (Fresh and Decayed Ripples) measured during SAX99.

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