THE IMPACTS OF SCENE STABILITY AND ACOUSTIC BACKSCATTER COHERENCE ON AUTOMATED SEABED CHANGE DETECTION

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1 INTRODUCTION

Practical implementation of long-term seabed monitoring for civilian and military activities requires automated tools for detecting temporal seabed changes, such as for detection of new trawling activities or mine-like objects on the seafloor. Automated Change Detection (ACD) identifies relevant changes in a particular area of seabed by comparing a pair of Synthetic Aperture Sonar (SAS) images collected before and after the change. Some amount of time after the baseline SAS image data is collected, the same seafloor scene is resurveyed, producing the repeat-pass image. Predicting the optimal time interval between images, known as the resurvey frequency, is needed for the best implementation of ACD. Presently, there is no standard procedure for determining the resurvey frequency that optimizes ACD performance. This paper discusses recent work on factors affecting seabed stability and impacts on requirements for resurvey frequency and effectiveness of ACD.

The ACD processing chain can be summarized in four steps: (1) collect a pair of baseline and repeat-pass images, (2) co-register/align the images, (3) generate a change map[1,2], and (4) detect changes of interest, along with false alarms. There are multiple techniques for co-registering image pairs; for example, one method applies a large-scale alignment followed by a small-scale co-registration[3,4]. ACD methods applied to multi-temporal SAS imagery can be broadly categorized as incoherent (ICD) or coherent (CCD). ICD techniques process the mean backscatter power of the images, while CCD employs both the amplitude and phase of the backscattered energy. Generally, CCD demonstrates increased sensitivity to small changes, while ICD is more robust over longer time intervals[5,6]. This is because utilizing the phase difference between two complex images (i.e. interferogram) can lead to the detection of a physical disturbance in the scene even when there is negligible change in amplitude, such as a slight disturbance of the seafloor or the introduction of an object that has similar scattering properties to the seabed. Figure 1 shows multi-temporal SAS seafloor imagery with a physical change (likely an animal track traversing one burrow to another) that is apparent only in phase, resulting in it being detectable in the coherent change map[3].

To identify changes of relevance, ACD exploits areas of reduced coherence between the pair of coregistered images. Detecting areas of reduced coherence on the change map implies that the image backgrounds have maintained high coherence throughout the duration of the resurvey frequency. Maintaining temporal seabed coherence depends heavily on the stability of the scene, often determined by the composition of the seafloor that is the image background. The seafloor can be dynamic, and between surveys the scene may undergo drastic changes. Changes in the scene due to changes in background seafloor characteristics, rather than changes of interest, can confound ACD and increase the false alarm rate. Higher scene stability improves ACD processing and results, reducing the number of false alarms and allowing for sensitive interferometric analysis techniques such as CCD.

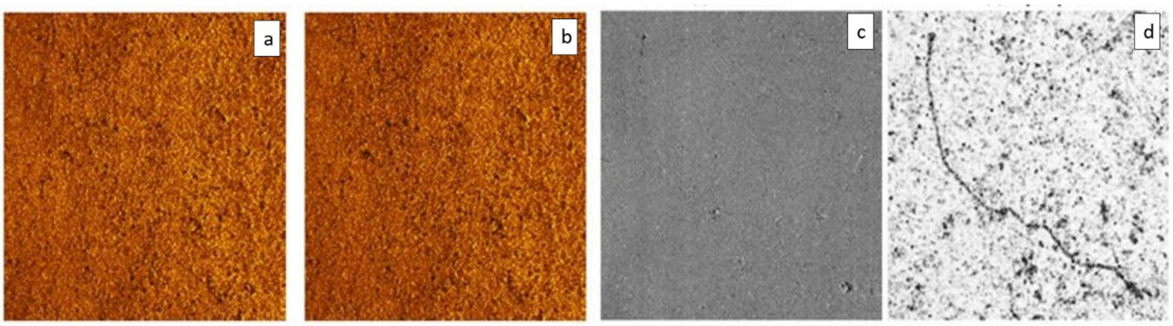


Figure 1: Comparison of Incoherent (ICD) and Coherent (CCD) Change Detection where (a) is the baseline image, (b) is the repeat pass image, (c) is the incoherent change map, and (d) is the coherent change map.

Environmental and anthropogenic factors that affect the seafloor, such as bottom type, weather, bathymetry, hydrology, biota, and dredging, also affect ACD performance. For optimal ACD performance, an appropriate resurvey frequency must be chosen while taking into account the specific scenario, including environment, sensor, and mission. This paper is concerned with laying the groundwork for developing a tool to predict the optimal resurvey frequency by employing environmental dynamics modeling to make scenario-specific predictions, using a sandy seafloor and CCD techniques as an example.

2 RESURVEY FREQUENCY & SCENE STABILITY

Scene stability in ACD refers to how static the seabed, or SAS image background, remains between baseline and repeat pass images. Scene stability can be quantified as the amount of loss of coherence between pixels in a coregistered image pair over the duration of the resurvey interval. The loss of background coherence over time is known as temporal decorrelation and is a cause of deterioration in ACD performance.

Temporal decorrelation can result in a high false alarm rate due to numerous detections of changes in the scene background, which can obscure detection of changes of interest. Increased false alarm rates due to low scene stability can decrease ACD performance to potentially insufficient levels. ACD performance can be measured as the ratio of detected changes of interest to the total of detection opportunities, while the false alarm rate is the proportion of detected changes that are not of interest compared to the total number of detections. Understanding and being able to predict scenario-specific scene stability could inform resurvey frequency and allow prediction of ACD performance in that scenario.

2.1 Relationship between Resurvey Frequency and Scene Stability

Complex interferometric data is sensitive to small physical changes that affect the magnitude, but also the phase of SAS backscattered energy, which means that CCD is more susceptible than ICD to increased false alarm rate caused by low scene stability. This sensitivity to small changes can be a problem in sandy seabeds where ripples form and evolve over time, responding dynamically to environmental conditions such as currents, waves, and bioturbation. A sand ripple field will naturally decorrelate over time at some rate, which we explore in the next section. It follows logically that a shorter resurvey interval would counteract the effect of temporal decorrelation of a dynamic scene. In a practical implementation of ACD, surveys are completed intermittently rather than continuously. An understanding of the decorrelation rate of the scene, combined with sensor, technique (CCD or ICD), and mission parameters, would allow for prediction of ACD performance in that scene for any given resurvey frequency, allowing for selection of a resurvey frequency which optimizes ACD performance.

The processes causing temporal decorrelation can be persistent over a timeframe (e.g. bioturbation, turbulent diffusion, fish pitting) or impulsive, which have an outsized effect in a short duration (e.g. storm events, dredging events, dumping). By combining information on the processes affecting both persistent and impulsive seabed changes, we can better understand the seabed stability of a particular scene or time of year. Table 1 is a non-exhaustive list of processes that affect sandy seabed stability, sediment mobilization, their time scales, and typical seabed characteristics affected.

Table 1: Examples of physical, anthropogenic, and biological processes affecting seabed decorrelation timescales; applicable to both coherent and incoherent change detection.

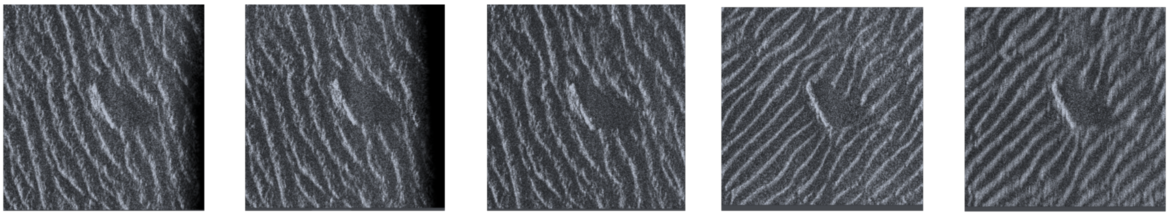
Physical process	**Time scale**	**Effect**
Tidal-generated bottom currents	Impulse, Diurnal	Background decorrelation
Wave-generated bottom currents	Impulse, Episodic	Background decorrelation
Turbulent diffusion	Persistent	Background decorrelation
Anthropogenic process	**Time scale**	**Effect**
Dredging	Impulse, Location-dependent	Seabed reset
Dumping	Impulse, Location-dependent	Increase false alarm
Trolling, Trawling, Anchor dragging	Impulse, Location-dependent	Seabed reset
Biological process	**Time scale**	**Effect**
Bioturbation	Persistent, Seasonal	Background decorrelation , increased false alarm
Fish pitting	Persistent, Seasonal	Background decorrelation , increased false alarm

Persistent processes act on scene stability between impulsive disturbances, so models for scene stability must take both into account. For example, after a storm event completely resets the seabed, bioturbation and turbulent diffusion govern the decorrelation rate until another high-energy event occurs that resets the seabed again. The temporal decorrelation rate is both location- and timescale-dependent, being composed of the combination of more reliable persistent processes and less predictable impulsive disturbances. Accurate decisions on resurvey frequency would require environmental dynamics models that account for these complexities.

3 SEABED DYNAMICS

Seabed composition is a primary factor that sets the rate of temporal decorrelation. Here we take the example of a sandy seabed, leaving consideration of other seafloor types (mud/silt, rock, vegetated) for future work.

Sandy sediment is granular with a mean grain size of diameter between ~0.06 mm (very fine) and 2.0 mm (very coarse)[7]. Ripples can form on sandy seabed, where ripple height, spacing, orientation, and crest shape describe the pattern of the ripple field. If an impulsive event of sufficient energy occurs, the ripple pattern can completely reset. Figure 2 provides an example of ACD data collected in South Florida where ripple reset was observed. The left image is the initial pass over the target of interest. Four repeat passes were taken at multiple resurvey intervals. The sand ripple field maintains a high scene stability within the first 24-hours; however, a complete ripple reset is apparent between June 2 and June 21 (note the orientation of the sand ripples), which coincides with a storm passing through the area. The observed ripple reset is a scene instability resulting from environmentally driven seabed dynamics, and results in a loss of scene coherence that would be sufficiently large to reduce the performance of ACD.



6/1/2022
[Initial Survey]

6/1/2022
[1-Hr Time Interval]

6/2/2022
[24-Hr Time Interval]

6/21/2022
[20-Day Time Interval]

7/11/2022
[39-Day Time Interval]

Figure 2: Cylinder in sandy ripple field before and after a storm occurred in mid-June, showing a complete ripple reset (South Florida).

Persistent processes typically cause the seafloor to change gradually while impulsive events change it rapidly; however, both can occur simultaneously, with the dominant process shifting from one to the other. Time-dependent seafloor boundary layer models can be used to predict the forces imposed on the seafloor sediment by both impulsive (e.g., wave- and current-generated forces) and persistent (e.g., bioturbation) processes[8,9]. The models take inputs of seafloor sediment properties, surface waves, and ocean currents to calculate the hydrodynamic forcing on the seafloor sediment (shear stress) and the critical shear stress required to mobilize the sediment. If the shear stress is above the threshold for sediment incipient motion (i.e., an impulsive process), then time dependent ripple models can predict the changes in ripple geometry (height, length, and orientation). If the shear stress is below the threshold for incipient motion, then the persistent forces are dominant and turbulent diffusion/bioturbation acts to diffuse the ripple amplitude. By examining climatological hydrodynamic data for a particular area and utilizing time-dependent seafloor boundary layer models, the background decorrelation rate can be estimated for the specific area and time period which takes both persistent and impulsive factors into account. While these models can estimate hydrodynamic and biologic processes, anthropogenic events in that area must also be accounted for. If seabed type and various decorrelation-causing processes can be simulated or estimated with high enough fidelity, then an optimal resurvey frequency and the resulting ACD performance could be predicted.

3.1 Observations of Scene Stability and Seabed Dynamics

The effect of the disturbances to the seabed discussed in the previous section are evident in the temporal coherence of the scattered acoustic field which is used in CCD. Temporal coherence was estimated for two sites near Portsmouth, New Hampshire, using several datasets obtained during long time-series experiments. A site off New Castle Island is composed of fine sand with shell material. The site is approximately 10 m deep and is dominated by strong tidal currents up to 2 m/s. A 22 m deep site off Star Island, Isle of Shoals, is composed of coarse sand with shell material and is dominated by wave-induced currents during storm events occurring mostly in the winter months. Biological activity at both sites increases in the spring and summer.

The autonomously recording acoustic system used for these experiments had 38, 70, and 200 kHz transducers with 18° beamwidths positioned to point at a mean grazing angle of 20°. Sonar data was collected every hour from a fixed position for up to 5 months. Example coherence values for 200 kHz for the two sites are shown in Figure 3, with results for two different times of year shown for the Star Island site. The solid lines on these plots are best fit exponentials, the dashed lines are 50% prediction confidence intervals, and color represents the distribution of estimates at each ping time separation value.

The tidal current-dominated New Castle site with data collected in the spring/summer time frame (April-June) displays the longest correlation time of the three examples, with a time of 90 hours or 3.75 days. Correlation time is here defined to be where the exponential fit to the correlation coefficients crosses 1/e[10,11]. Both seasons at Star Island, summer/fall (July-November, with correlation time of 28 hours or 1.17 days) and winter/spring (November-July, with a correlation time 42 hours or 1.75 days), displayed coherence estimates that were shorter than the New Castle spring/summer estimates. This is possibly owing to higher continuous biological activity (summer and fall) and larger sediment movement caused by more exposure to episodic storm-related bottom currents (winter and spring).

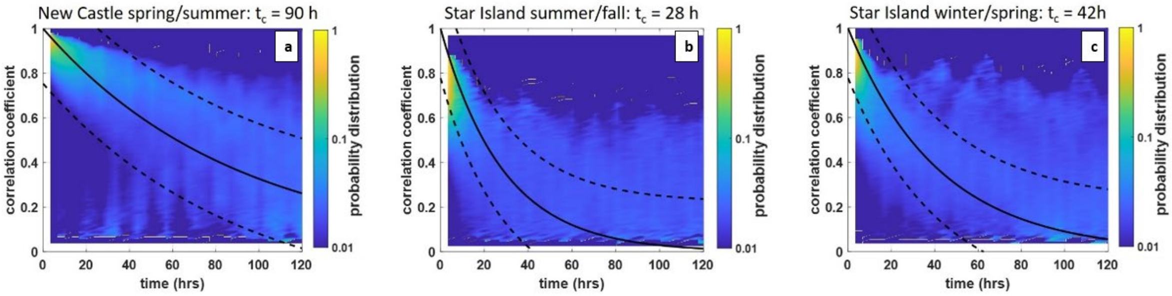


Figure 3: Example coherence measurements for 200 kHz for two sandy sediment sites near Portsmouth, New Hampshire, (a) New Castle, (b & c) Star Island.

Characteristics of the system used to collect SAS seafloor images impact perception of the seabed changes controlled by scene stability. For sediment movement that can be treated as a random diffusive process, data and modelling based on perturbation theory for scattering show that coherence time is inversely related to the square of the sonar frequency[10,11]. For this example, this relationship suggests that lowering the sonar frequency by a factor of five will increase the correlation times at the New Castle site from almost 4 days at 200 kHz to more than 13 weeks at 40 kHz.

Scene stability will influence the resurvey frequency required for CCD operations; however, more research is required to understand the relationship between resurvey frequency and seafloor composition, temporal coherence, and scene stability. Temporal decorrelation rates are thought to be highest for dynamic seabeds such as sand, and lowest for stable substrates such as rock or cemented bacterial mats. In Synthetic Aperture Radar, CCD decorrelation times typically are shorter for landscapes with lush vegetation than for those of arid environments[6]. However, this trend is not definitively established in the SAS-underwater context. For example, it could be hypothesized that a vegetation-covered seabed will have high temporal decorrelation because seagrass blades move easily in the current. The ARISE'12 sea trials employed the HISAS1030 sonar[2] to collect images off the coast of Italy in an area partially covered by *Posidonia oceanica* seagrass (Figure 4). CCD processing was applied to the image pairs and it was found that the *Posidonia* maintained a high level of temporal coherence over the 28 hour survey interval. This demonstrates the requirement for additional investigation into the seabed-dependent resurvey frequency.

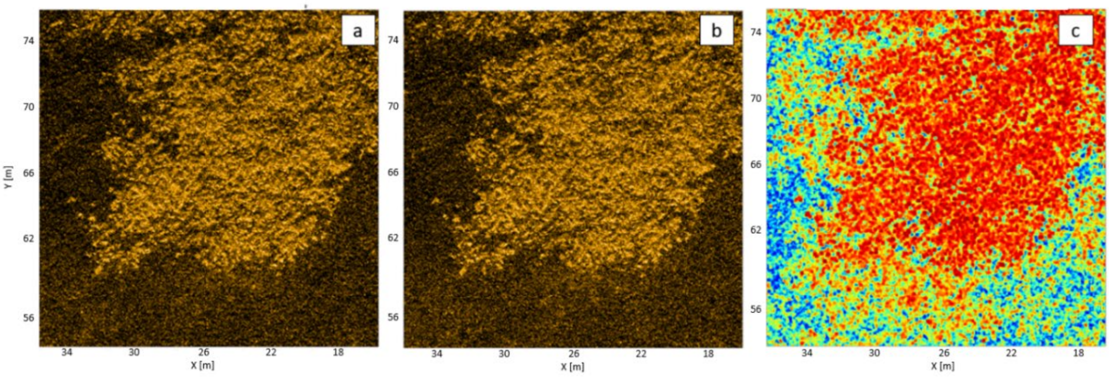


Figure 4: Seabed SAS images from ARISE'12 off the coast of Italy showing the same patch of Posidonia seagrass (yellow) and sediments (dark brow). (a) Reference image, (b) repeat pass, (c) coherent change map with red color indicating high coherence values.

4 DISCUSSION

The impact on ACD performance of using a given resurvey frequency is dependent on the environment, in addition to the sensor, platform, mission, and change detection technique. Presently, there are no standard guidelines for determining the optimal resurvey frequency for ACD. We hypothesize that accurate models of seabed dynamics can inform a location- and time-specific resurvey frequency that could optimize ACD performance. The development of operator tools with associated standard operational guidelines and procedures will facilitate the transition of ACD to a wide variety of military and civilian applications[5,12].

In order to develop guidelines for seabed-specific resurvey frequency, a strong understanding of scene stability as a function of time, and of the resulting impact on acoustic backscatter coherence, is required. Table 1 presents a non-exhaustive list of physical, biological and anthropogenic factors that affect scene stability and resurvey frequency. The processes listed have various time-scales ranging from persistent to impulsive, with seasonal- and location-specific influences, and can occur simultaneously as well as switch which dominates at any given time. The example of repeat pass SAS imagery over sandy sediment in Figure 2 depicts a sandy seabed exemplifying high scene stability for some duration until the scene experienced an impulsive change that reduced seafloor coherence before persistent processes took over once again. The relationship between resurvey frequency, location, and time-specific scene stability is non-trivial.

Accurate seabed dynamics models can inform ACD performance prediction by quantifying scene stability and allowing estimates of temporal decorrelation rate to inform when to resurvey an area. Dynamic seabed models would be especially powerful when the model is location- and time-specific, and validated with observations. Experimental observations of coherence measurements of sandy sediments with shell hash are presented in Figure 3. The experimental results suggest the temporal coherence of sandy seabeds is dependent on site-specific environmental factors and sonar frequency. Future work could use these experimental results to validate the predicted decorrelation rates from dynamic seabed models.

In addition to sandy sediments, muddy/silty, rocky, and vegetated seabeds are commonly seen in SAS imagery. A single SAS image can have a homogenous sediment type across the scene, but often the seabed is heterogeneous. Each seabed type is subject to, and responds differently to, the wide variety of physical and biological processes occurring through the year. Figure 4 shows an example of repeat pass SAS imagery where the seafloor is a mix of sand and *Posidonia* seagrass. It was hypothesized that vegetated seabeds will experience higher rates of decorrelation; however, the results presented in Figure 4 contradict the hypothesis and show that a *Posidonia*-covered seabed can maintain high temporal coherence. Further investigation is required to understand the physical processes and acoustic backscatter conditions in vegetated seabeds and how the resurvey frequency can be predicted in these areas.

Models of seafloor dynamics for each bottom type and season would be needed to develop a complete site-specific ACD performance prediction tool that would assist operators in choosing an optimal resurvey frequency for their application. Better understanding is required of the time- and space-dependent factors affecting decorrelation rate over the wide variety of naturally occurring seabeds before effective tools for ACD performance prediction can be developed.

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