Seabed Texture and Evolution Studies

applying and advancing procedural methods for sonar characterization and simulation in dynamic ocean environments

Cumulative Final Report

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LONG-TERM GOALS

The littoral seafloor is a dynamic environment; hydrodynamic and biologic forces continuously modify the seabed relief. For example, sandy environments are often particularly active, with storm and tidal forces organizing sediment into orbital ripples while bottom-feeding and bottom-dwelling organisms rework the seafloor (i.e. bioturbation), destroying this structure and returning it to random equilibrium. Understanding and predicting the temporal evolution of the seafloor is vital for a variety of oceanographic (e.g. hydrodynamic flow in the presence of sand ripples) and acoustic (e.g. synthetic aperture sonar-based detection) techniques.

The importance of this work lies in the ability to link measurable environmental properties to biologic and hydrodynamic mechanisms that modify the seabed, with an emphasis on the representation of the seabed in synthetic sonar imagery. While complete understanding of all associated processes is not feasible, it is expected that this work will elucidate several key aspects and precipitate a tangible improvement in both our understanding of, and modeling and simulation of, the dynamic seabed environment.

OBJECTIVES

Recent work has demonstrated the ability to identify a model for a bioturbative event, predict the seafloor roughness spectra that might be generated by a series of these events, couple to a hydrodynamic model, and then stochastically simulate sonar imagery [Johnson & Jackson 2015; Penko, Johnson, & Calantoni 2015].

The philosophy of this approach is often referred to as Procedural Texture or Procedural Generation, and is extensively utilized for computer-generated imagery (CGI). These techniques employ an understanding of the science underlying the phenomenon being modeled. For example, [Fréchot 2007] combines an understanding of atmospheric dynamics and hydrodynamics to estimate ocean surface wave spectra and subsequently generate realistic realizations from input wind magnitude and direction. Similarly, a CGI artist may incorporate a geophysical model for a fractal terrain, employ watershed and erosion models to fill valleys with sediment and create streams, include vegetation models for lichen at high altitudes and trees at lower altitudes, and mimic solar illumination and shadowing to produce a realistic "rendering" of a mountain scene.

Work conducted under this program includes extensions of grants N00014-1-1-0539 and N00014-13-0019 – Coherence Studies for Synthetic Aperture Sonar, and was conducted in close coordination with BOA N00014-15-G-0001/0003 – Simulation, Data, and Analysis in Support of Automatic Target Recognition.

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14. ABSTRACT
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The importance of this work lies in the ability to link measurable environmental properties to biologic and hydrodynamic mechanisms that modify the seabed, with an emphasis on the representation of the seabed in synthetic sonar imagery. While complete understanding of all associated processes is not feasible, it is expected that this work will elucidate several key aspects and precipitate a tangible improvement in both our understanding of, and modeling and simulation of, the dynamic seabed environment.

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This combination of discrete events or phenomena, coupled together in a physically valid manner, is the basis of procedural methods, with the accuracy and realism only limited by our understanding of, and ability to model, the science involved. Therefore, while the results of this previous work are promising, to improve understanding and realism, there are several outstanding questions to be addressed pertaining to understanding of environmental impacts of seabed texture and its evolution. Of specific interest for this work is our ability to quantify these impacts with useful parameters, and our ability to incorporate this information with procedural methods into synthetic data generation for the benefit of researchers studying a variety of topics, from assessment of environmental impacts, to those working to predict SAS-based ATR performance.

APPROACH

The program as a whole consists of a variety of components, including analysis of *in-situ* data, and advancement of *in-silico* methods. The unifying focus for this study is the formation and evolution of seabed texture, drawing upon both novel techniques developed under this program, as well as application of established techniques (e.g. procedural methods employed for computer graphics and animation). The topics outlined below serve as guidance for both formal and informal collaborations and discussions with a variety of ONR-funded researchers, and leverage experience, models, and simulations developed under previous and current research programs. The program of study can be categorized by three distinct, yet interrelated, topics:

Topic 1: Quantify Bioturbative and Hydrodynamic Diffusion
Topic 2: Biologically-Inspired Procedural Methods
Topic 3: Simulation Methods and Synthetic Data

Concisely the broad objectives are to:

1. elucidate the role of bioturbation and hydrodynamic flow in horizontal diffusion,
2. advance procedural methods for modeling bioturbation, and
3. apply this improved understanding to synthetic data generation.

WORK COMPLETED

A principal objective of this program was to advance sonar simulation of realistic seabed texture and its evolution leveraging procedural methods. A secondary, but critical, objective was the generation of representative acoustic time series suitable for synthetic aperture sonar (SAS) beamforming. The combination of these two objectives permits validation of texture generation with procedural methods by way of close comparison to collected SAS imagery.

Another objective of the program was to investigate the availability and content of biologic databases. For the inverse problem, these data may be used to help identify features that might be found in SAS imagery. For the forward problem, these data may be used to improve realistic textures by mimicking flora and fauna that might be found in a particular region of interest. An example of this linking is shown in Figure 1 were large pits were observed in collected imagery, and investigation of a biologic database support a hypothesis these may be caused by sting rays known to be present in the region. As these biologic (as well as bathymetry and sediment type) databases cannot possible capture seabed texture and evolution on the space and time scales for simulated sonar imagery, consideration was given to best practices for incorporation of incomplete and disparate information to produce meaningful “content” for simulated data, again leveraging procedural methods.

Figure 1: SAS imagery from the ONR TREX experiment showing a suspected sting ray pit (left), example of burrowing stingray (middle), and *Dasyatidae* (stingray family) distribution along CONUS (right). Images courtesy of ONR, Wikipedia, and Ocean Biogeographic Information System respectively.

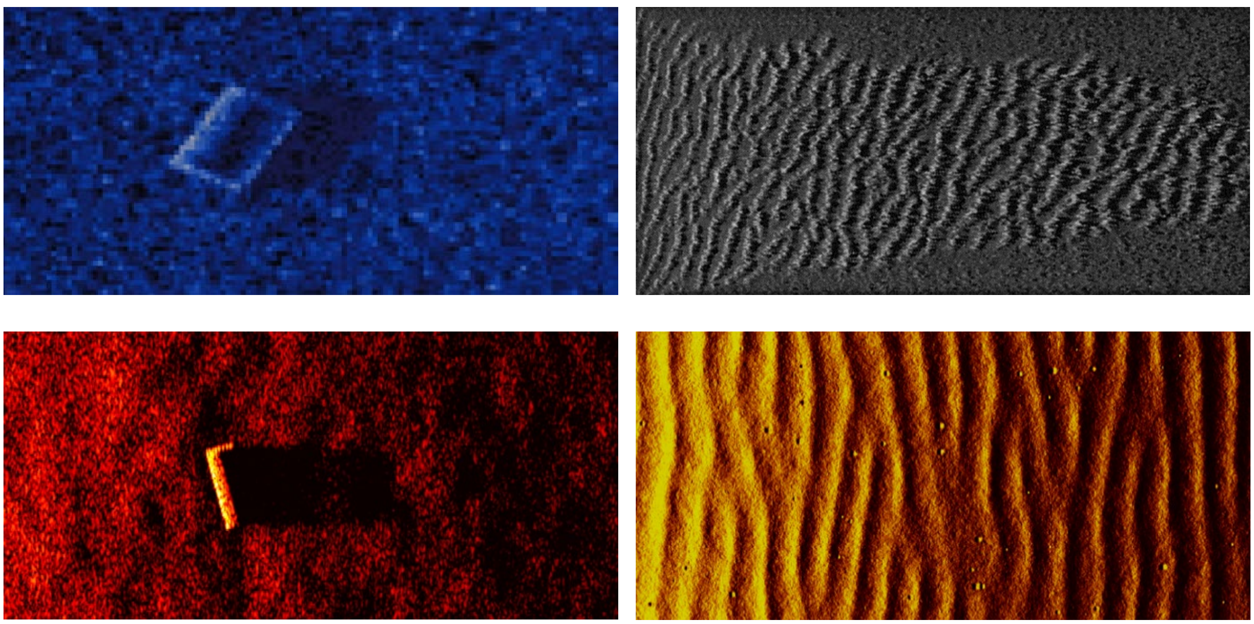

Figure 2: Example simulated imagery with approaches by Sammelman (upper left), Bell (upper right), Hunter (lower left), and this work (lower right).

RESULTS

A texture that is generated by an algorithm or model implemented in a computer, rather than being composed by hand by an artist, is typically referred to as a "procedural" texture, with genesis often attributed to the work of Ken Perlin for the 1982 movie Tron. In the nearly four decades since, Procedural Texture has become a mainstay of computer-generated imagery (CGI), and is the principal tenet of this project. Interesting, Judith Bell mentioned "procedurally defined objects" in her 1997 paper on side-scan simulation [Bell & Linnett 1997]. However in the nearly 24 years since, backgrounds for side-scan and SAS time-series simulations in the published literature have been relatively benign, with flat or power-law textures [Bell & Linnett 1997; Sammelmann et al. 1994; Hunter 2006] (Figure 2; upper right, upper left, lower left respectively). This fact severely limits the utility of simulated data to classification performance only, and only valid for comparably benign environments; while full assessment of sonar, automated detection algorithms, and broader autonomy cannot be tested with the current tools and practices. However, combining the appropriate seabed texture and evolution models, with basis in (or at least drawing inspiration from) the relevant physics and biologics, we expect to significantly improve the utility of simulated data (Figure 2; lower right).

Myriad classes of techniques for procedural generation of textures have been described in the computer graphics literature, and many have been summarized by Hendrix [Hendrikx et al. 2013] (Figure 3). In previous and current work we have leveraged techniques from the classes of Pseudo-Random Number Generators (e.g. ambient noise), Image Filtering (e.g. coherent-imaging speckle), Spatial Algorithms (e.g. ripple texture, shape bioturbative fish pits), and Complex Systems (e.g. path of bioturbative fish pits). Not all major or minor classes depicted in Figure 3 directly apply to seabed texture and evolution simulation, whether because of the mechanisms employed or the lack of available input parameters to initialize and/or bound their utilization. However, this list serves as inspiration for best practices and implementation techniques to consider as environmental parameterizations improve and phenomenological models are developed.

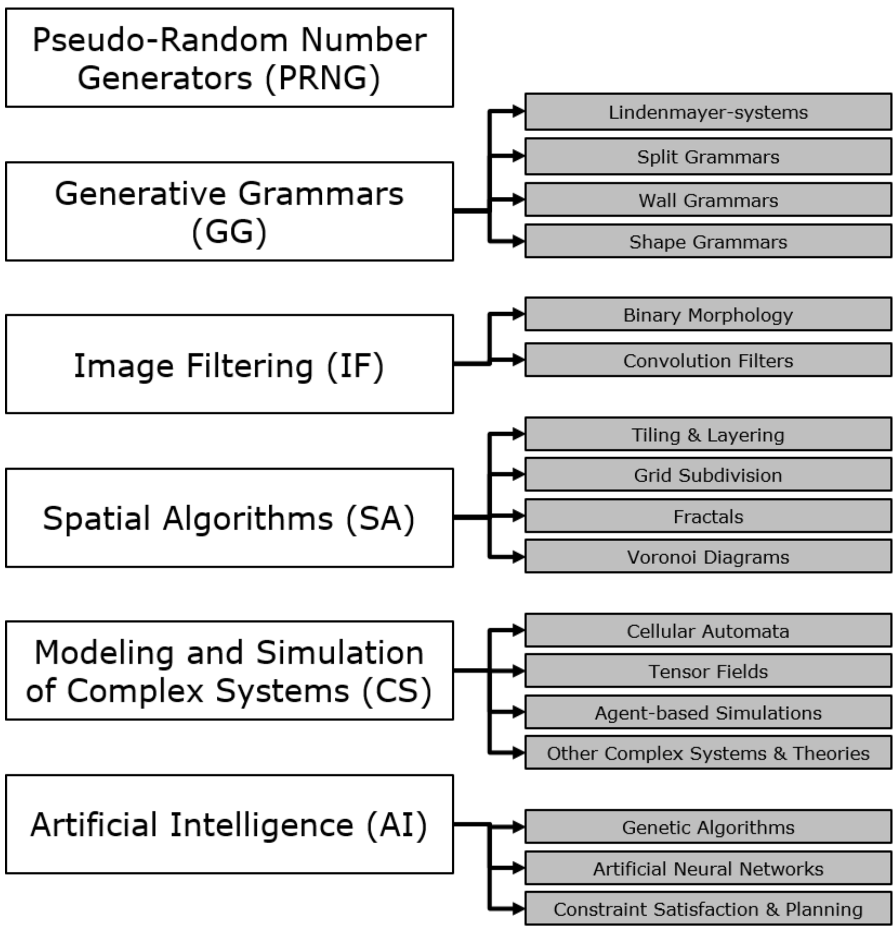

Figure 3: Hierarchy of Procedural Texture methods ranked from least (top) to most (bottom) complex by [Hendrikx et al. 2013].

Building upon Procedural Texture, Procedural Content Generation (PCG), particularly for games (PCG-G), is a rapidly advancing field (n.b. while one may only consider gaming for entertainment purposes, the role of “serious” games, for example to train human operators, also heavily relies on PCG-G). PCG is essentially taking a step back from the specific texture generation (or content currently being presented to a single user), and employing the concept of an overarching “story” or game theme (Figure 4). This concept may somewhat assuage the lack of available input parameters, as well as ensure that representative content is being generated.

In the early 1990's development for a particular game was typically done by 5-6 people; but by the early 2000's development required hundreds of people. Demand for quantity and quality of content is significantly outpacing development. In 2009, 68% of American households reported playing computer or video games, with the average player age of 35 having 12 years of experience playing games [Hendrikx et al. 2013]. World of Warcraft (WoW), with 2 regions the size of Manhattan or ~120km2 of playable area, had an estimated initial budget of $20-120M during 4 years of development, with an additional $200M in the 5 years following the 2004 release. Blizzard, makers of WoW, *already* had 2 previous, similar, very successful, games to leverage: Warcraft and Starcraft. In 2012 Blizzard laid off 600 of its 5000 employees after ramping down from initial WoW production. This model of high-quality, multi-agent content can serve as a benchmark of what is possible, but with the high financial and labor cost begs the question – what frameworks and methods exist that can be leveraged for underwater modeling and simulation purposes? Two constructs from the PCG community will be disused here as examples of what may be possible.

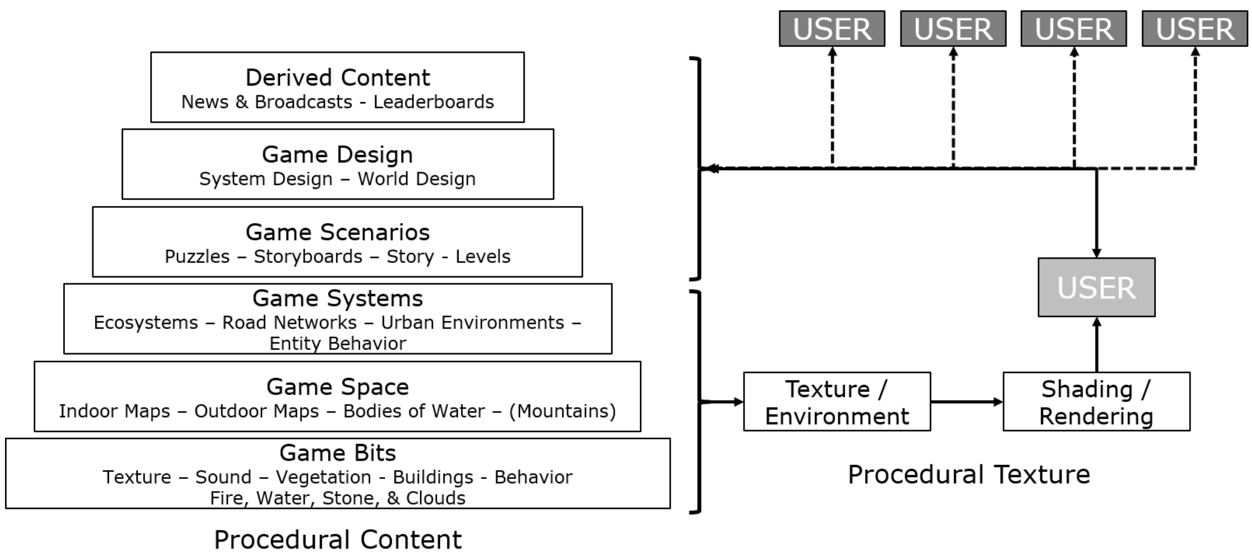

Figure 4: Hierarchy of Procedural Content Generation components described by [Ebert et al. 2003, Hendrikx et al. 2013] and compiled here. Previous work has focused on Procedural Texture for a single "user," which was expanded for re-visitation of an evolving scene. Adaptation of the larger concept of Content Generation would permit content generators to more easily and realistically vary the synthetic environment for single and multiple "users."

The first construct presented here is that of biomes. R.H. Whittaker proposed a habitat classification scheme based on only two parameters: average annual temperature and annual precipitation [Whittaker 1975]. For example, the tropical rainforest biome is characterized by high values of both parameters, while the tundra biome is characterized by low values of both parameters (Figure 5, left). Minecraft, the best-selling video game of all time (as of fall 2021) [https://en.wikipedia.org/wiki/List_of_best-selling_video_games], employs an approximation of biomes to aid realism by self-similarity within regions (Figure 5, right) [www.minecraft101.net/biomes.html]. A player should expect content to be within the theme of the region (e.g. tundra content within tundra regions, and rainforest content within rainforest regions). This construct of biomes aligns nicely with work being conducted to survey benthic habitats, and could be used to augment self-consistent simulations. For example, Mareano is an initiative to classify Norway's benthic habitats [www.mareano.no]. A user can access these geo-referenced maps of classified habitats (e.g. hard bottom coral garden, soft bottom sponge aggregations), and can even view photographs taken of benthic flora and fauna (Figure 6). This sort of information, whether actual or mimicked via procedural generation techniques (because of a lack of relevant parametrizations), could be very useful for generating the types of heterogeneous scenes encountered by underwater imaging systems such as side-scan and SAS.

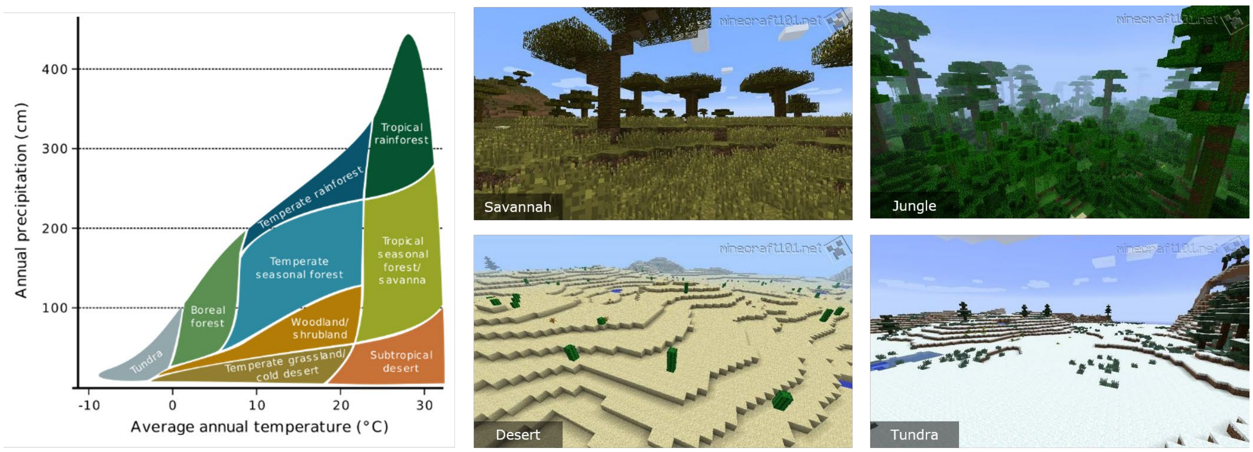

Figure 5: Two-feature biome classification by Whittaker (left), and four examples of biome-inspired gaming scenes (right four panels) from MineCraft. The biome construct ensures realistic themes across game terrain and content (e.g. ground cover, flora, fauna, etc.).

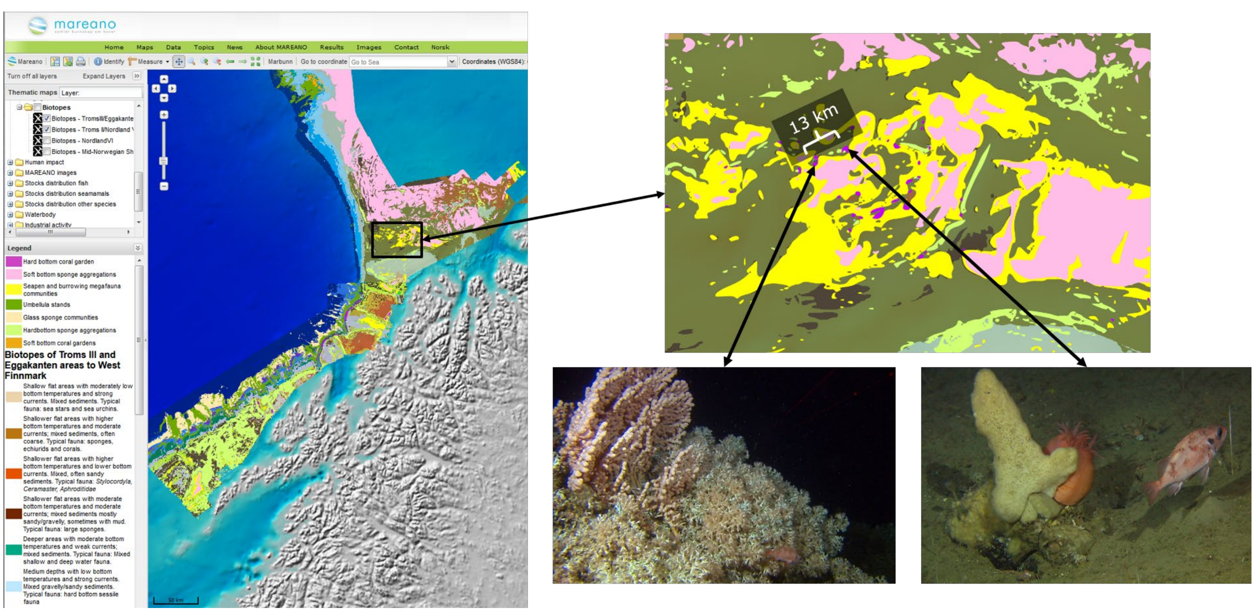

Figure 6: Example of benthic habitats from the Mareano database of the Norwegian coast. Such database information could potentially be used to seed biome descriptors for Procedural Content Generation methods.

A second construct presented here is that of Declarative Generation, or semantic texture mapping. In this construct, an instructor or other expert designs a map of texture classes manually, while the texture realizations generated procedurally. Smelick demonstrated the efficacy of this approach to generate "geo-typical" terrain for a serious gaming application. This approach was adopted for work here to increase the heterogeneity of wavenumber and spatial-domain texture synthesis [Smelik et al. 2009;

Smelik et al. 2010] (Figure 7). The left panels of Figures 8 & 9 depict two examples of a 3-component sematic map which was generated in a basic computer drawing tool. Parameters specific to each texture class were prescribed and texture realizations generated procedurally. In these examples a power-law roughness component, rippled-sand component, and a bioturbative component with the bioturbative component modifying the rippled-sand component are shown in the center panels of Figures 8 & 9. The individual components were then combined to produce a height map, shown as the right panels of Figures 8 & 9. These height maps were then input along with sonar parameters typical for an imaging SAS system to produce element-level time series with The Point-based Sonar Scattering Model (PoSSM) [Brown, Johnson, & Olson 2017; Johnson & Brown 2018], and the result was processed with synthetic aperture techniques to form a representative SAS imagery. Within the simulation, the sonar was prescribed to travel at several different paths relative to the seafloor which resulted in aspect-dependent imagery. The heterogeneous nature of the seafloor texture is evident in Figures 10 & 11, significantly increasing the realism of the simulated data.

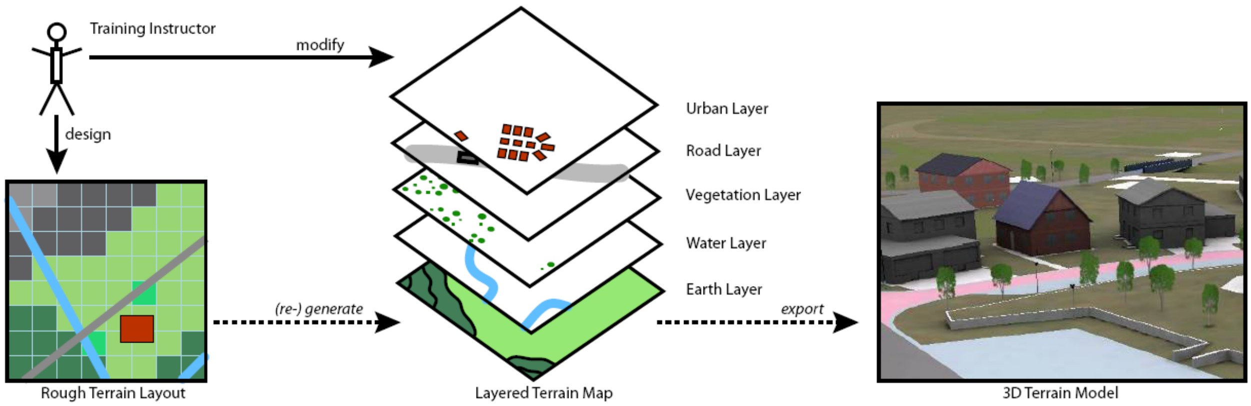

Figure 7: Example of Declarative Generation of multiple textures to represent a heterogeneous scene [Smelik et al. 2009; Smelik et al. 2010].

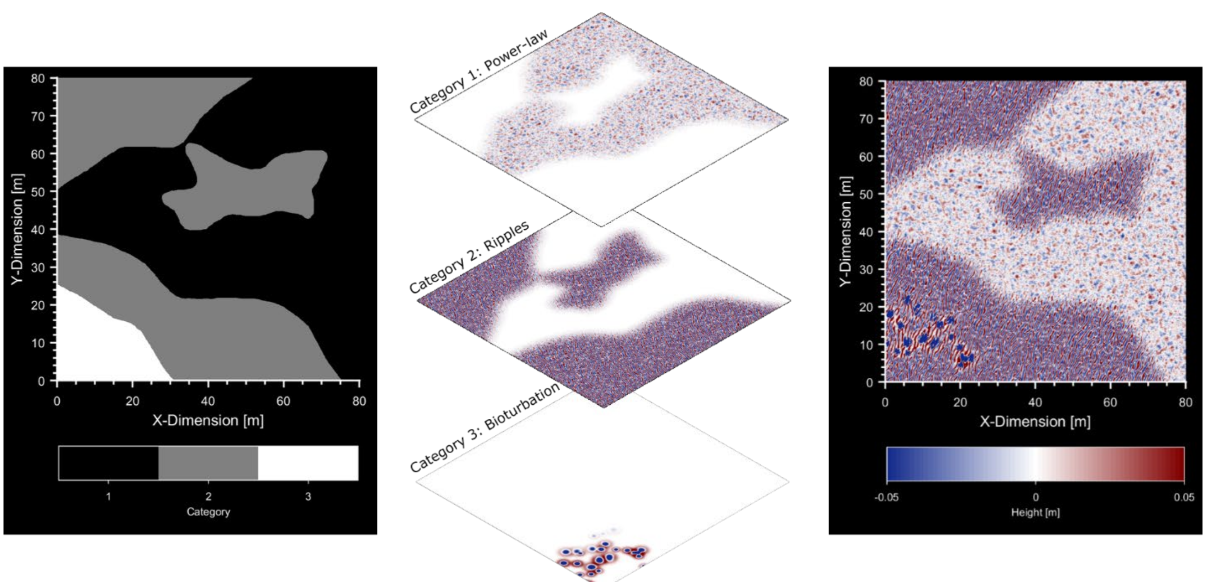

Figure 8: Application of Declarative Generation of multiple textures to represent a heterogeneous underwater scene.

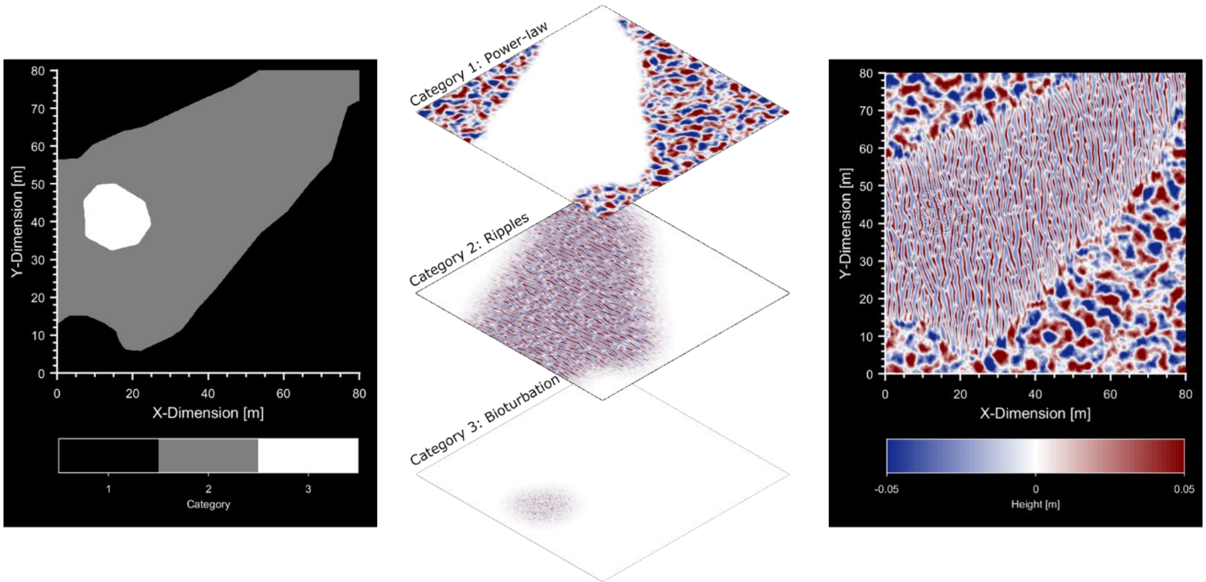

Figure 9: Another example of Declarative Generation of multiple textures to represent a heterogeneous underwater scene.

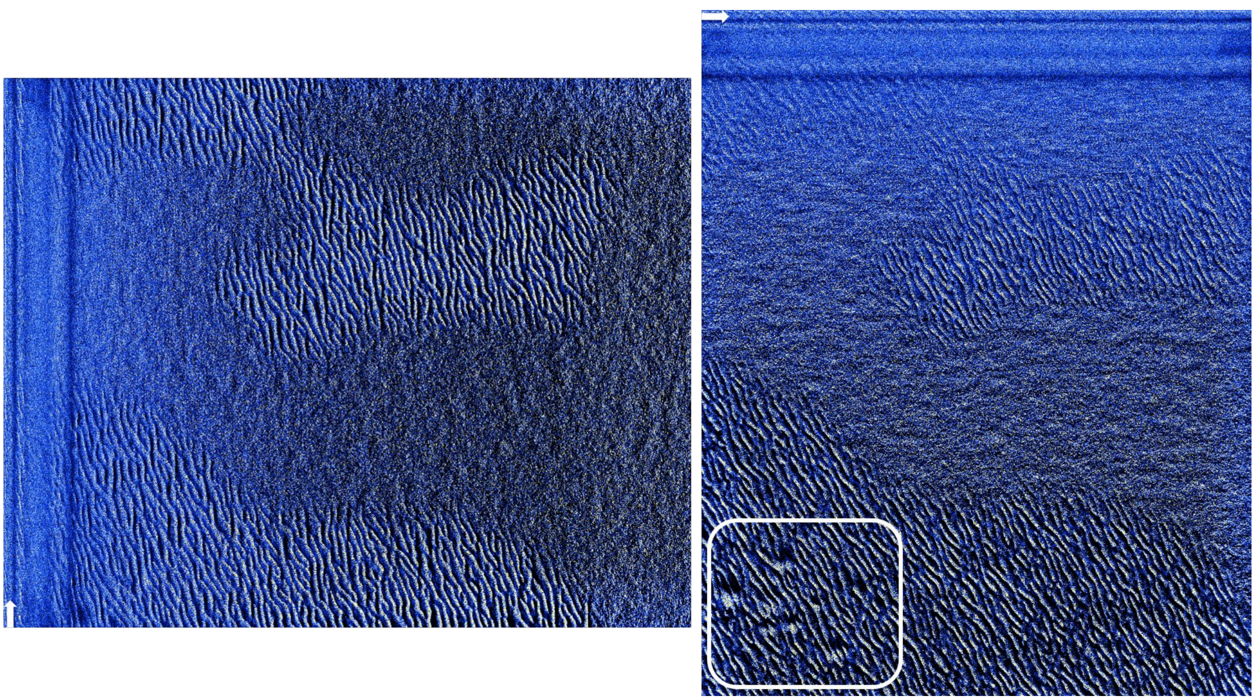

Figure 10: Simulated imagery from SAS-beamformed time-series PoSSM data collected along orthogonal tracks with the texture of Figure 8. White arrow depicts sonar path. Note the large bioturbative fish pits at long range (on the bottom left side of the right image) are visible owing to the lower grazing angle geometry of this collection when compared to the left image.

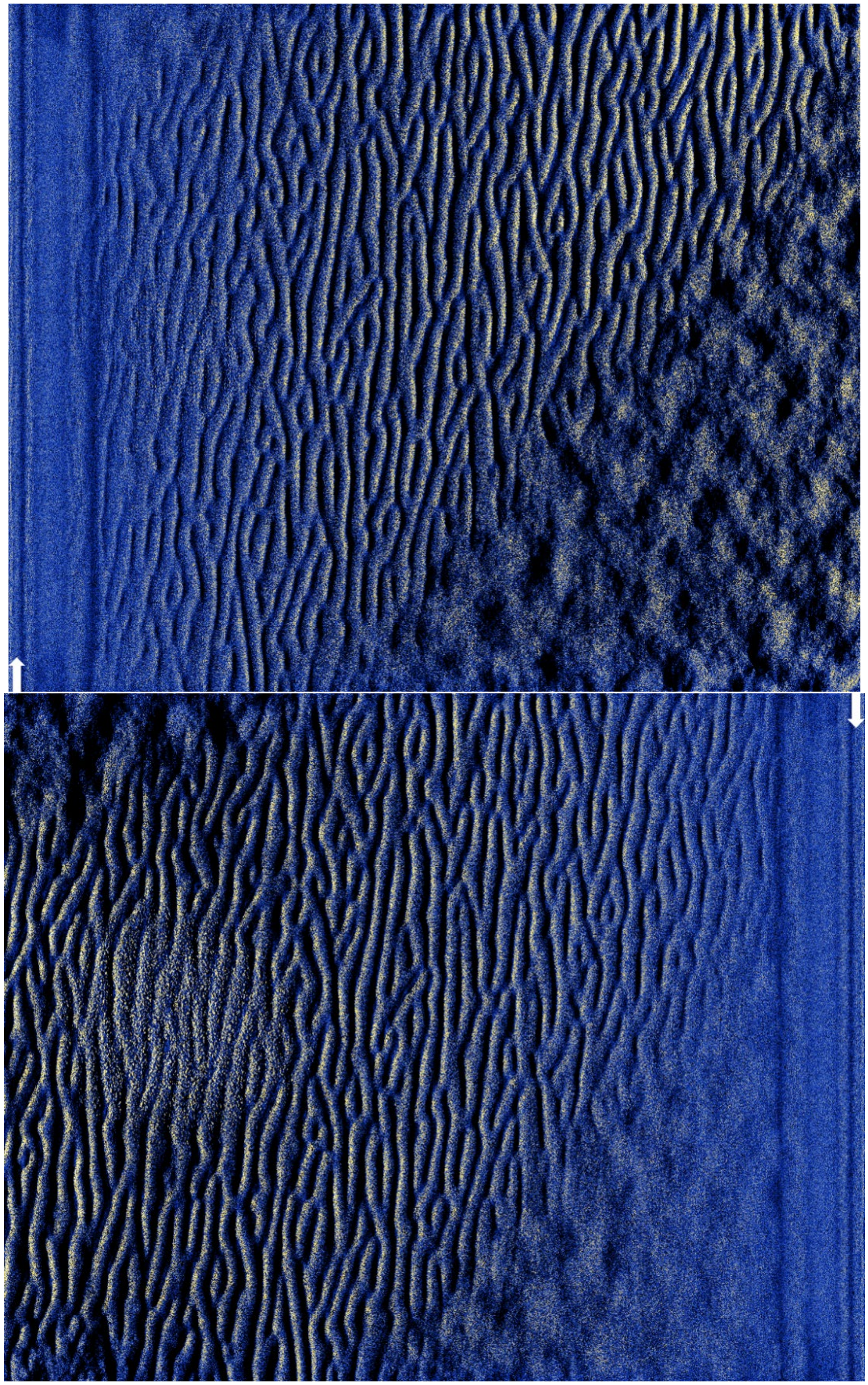

Figure 11: Simulated imagery from SAS-beamformed time-series PoSSM data with the texture of Figure 9. White arrow depicts sonar path. Note the small bioturbative fish pits at long range (on the left side of the bottom image) are visible owing to the lower grazing angle geometry of this collection when compared to the same location in the top image.

A combination of both procedural and declarative content generation was employed for the simulation of discrete objects. Figure 12 shows a pair of procedurally-generated rocks [Saksala 2016, Tan 2016] along with a procedurally-generated cylinder. These objects were then combined with seabed texture as described above to combine both multiple textures and objects into a single height map (Figure 13), "rendered" with PoSSM, and beamformed with synthetic aperture techniques to produce the simulated imagery of Figures 14-16. For these examples, the discrete objects were just placed into the background textures with no interaction with the background. However we know from reviewing photographs and SAS imagery that the presence of an object impacts the local hydrodynamics causing effects such as scour and ripple bifurcation, and combining textures and objects from disparate models and techniques remains a consideration for future investigations.

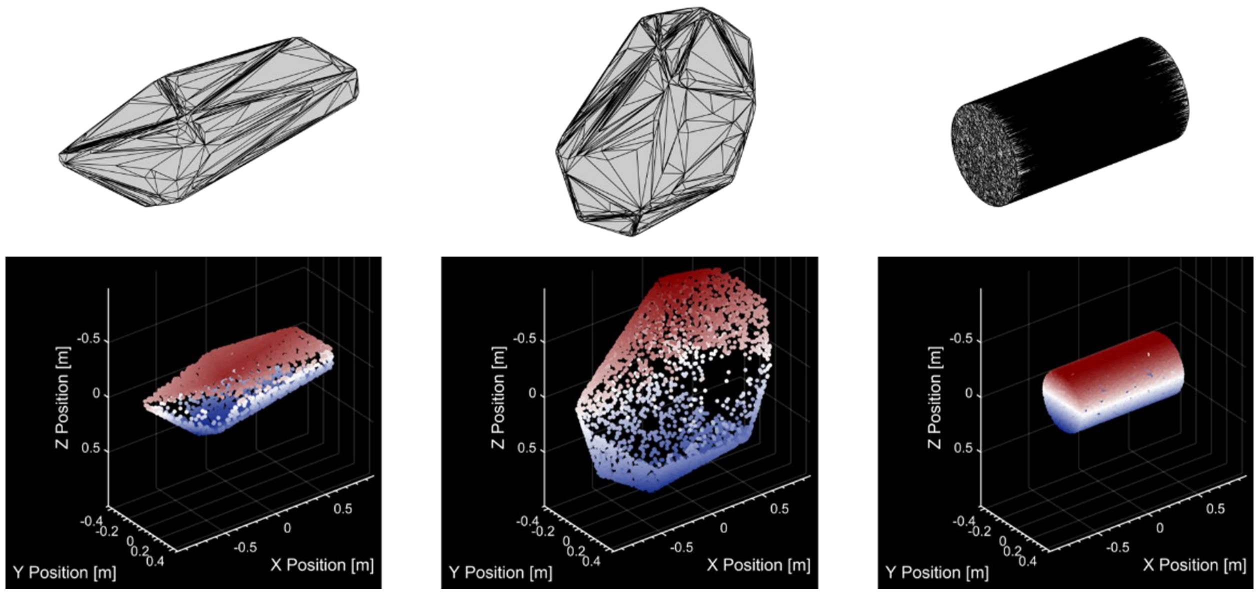

Figure 12: Two examples of procedurally-generated rocks (left, middle) [Saksala 2016; Tan 2016] and a procedurally-generated cylinder (right). The bottom row shows the computation locations for acoustic models in the Point-based Sonar Scattering Model (PoSSM).

RELATED PROJECTS

The following SERDP project has contributed to the development of the PoSSM simulation leveraged for a portion of this work:

- Sediment Volume Search Sonar (SERDP), The Pennsylvania State University Applied Research Laboratory (PSU-ARL), Dr. Daniel Brown, W912HQ-16-C-0006.

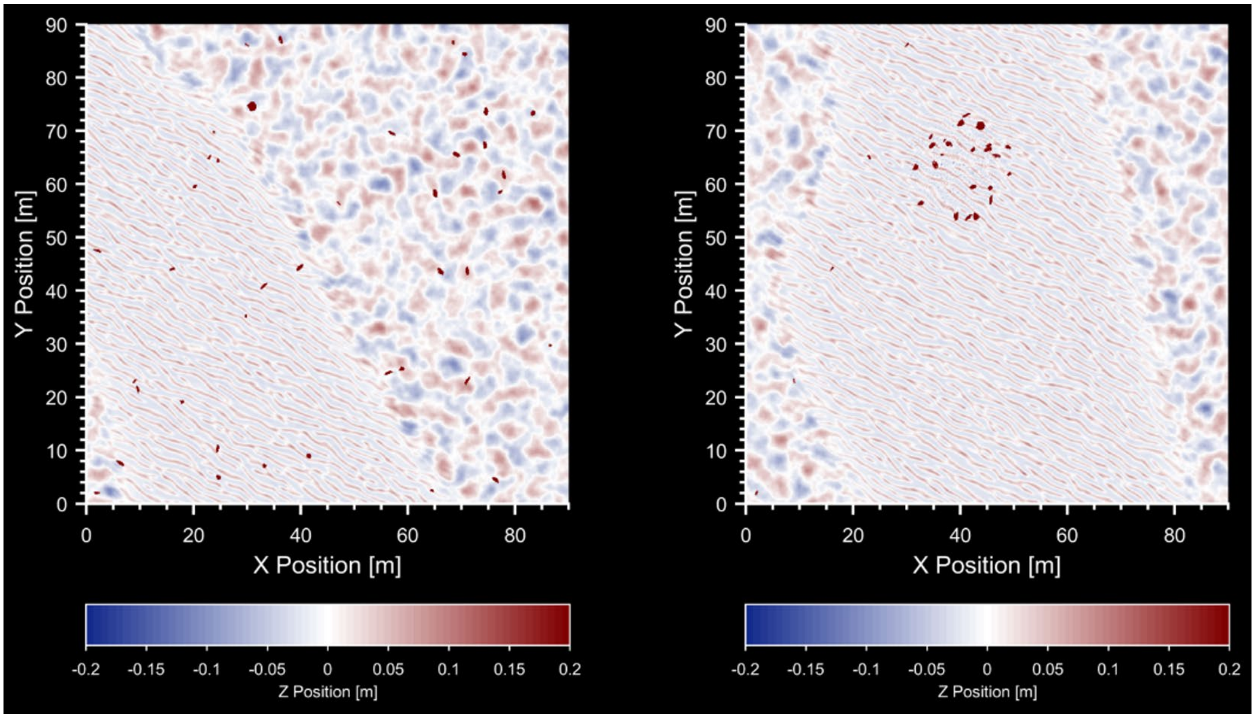

Figure 13: Two examples of procedurally-generated textures using multiple textures using semantic maps, wavenumber domain methods, and discrete objects.

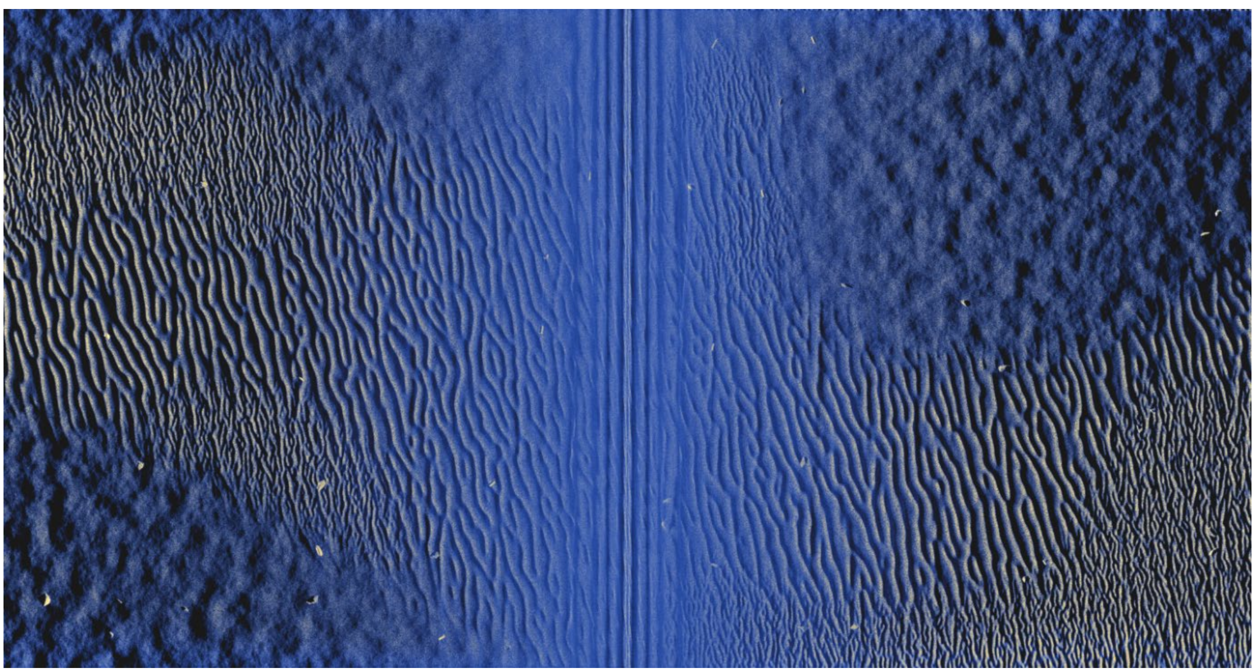

Figure 14: An example of simulated imagery produced after synthetic aperture image formation was applied to the time-series output of PoSSM for procedurally-generated textures. Note the acoustic models capture system effects such as beam-pattern nulls, and other acoustic effects such as range-dependent image contrast owing to the backscattering properties of the seabed.

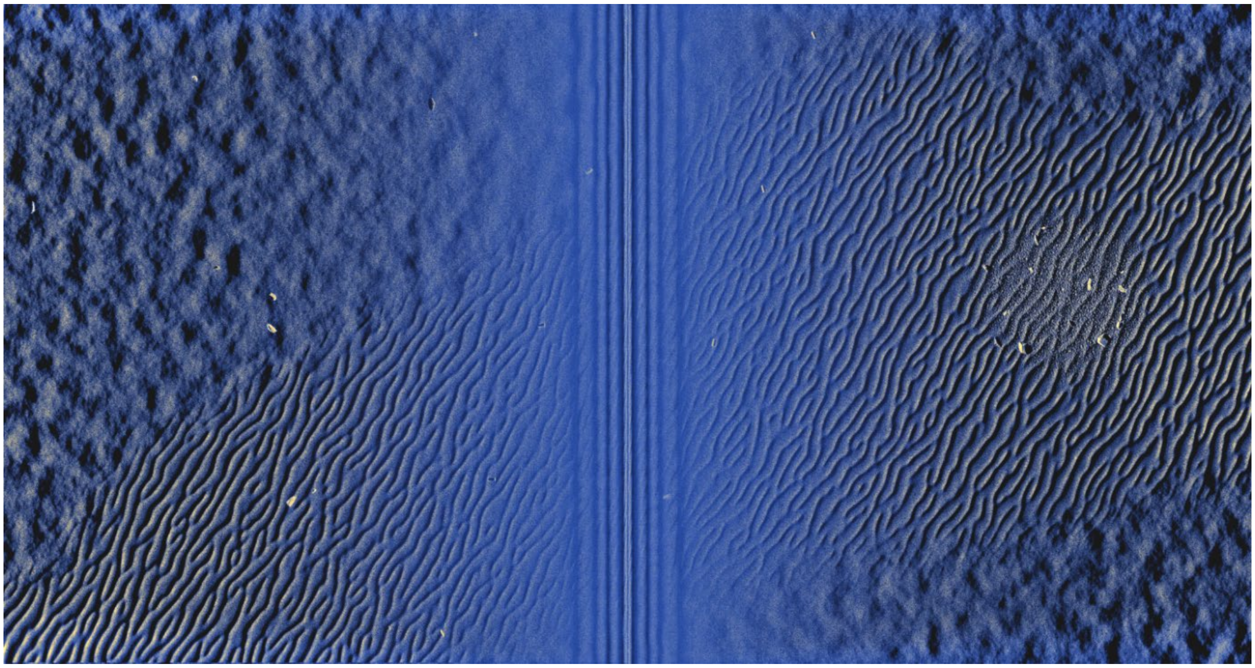

Figure 15: Another example as described in Figure 14.

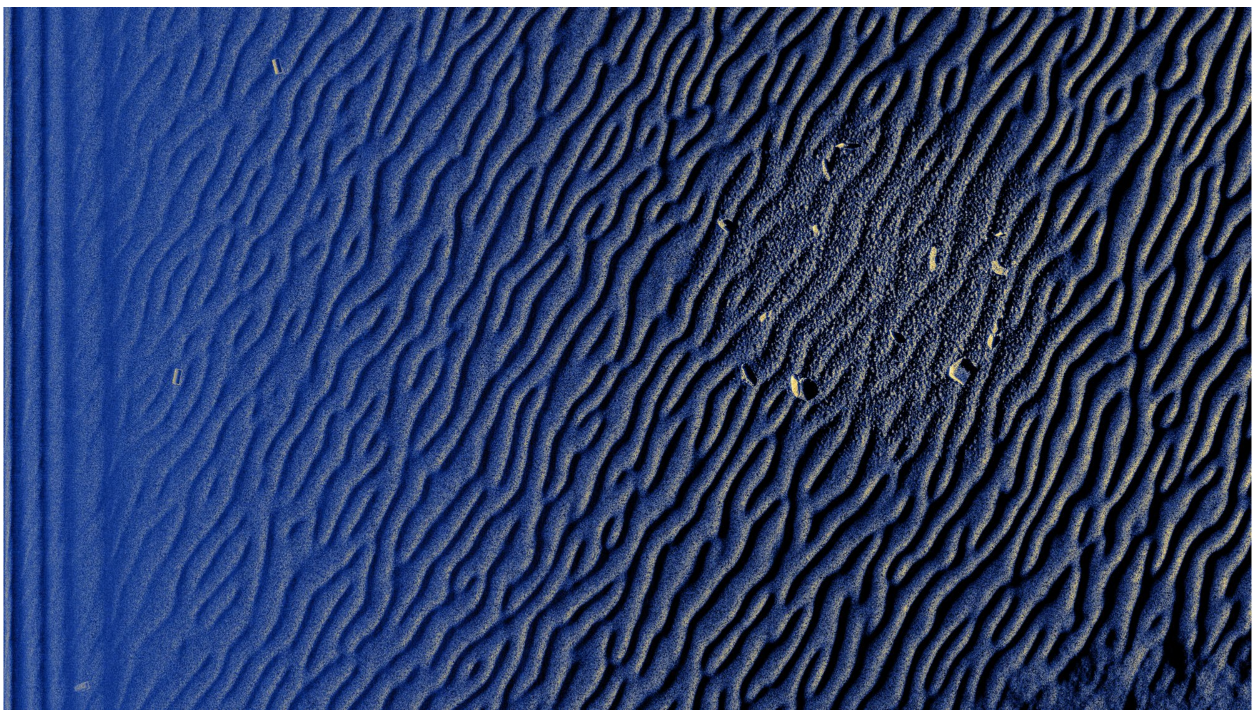

Figure 16: Close up of the starboard image from Figure 15.

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