QUANTIFYING THE NEGATIVE IMPACT OF BREAKING INTERNAL WAVES ON INTERFEROMETRIC SYNTHETIC APERTURE SONAR

Roy E. Hansen Norwegian Defence Research Establishment (FFI), Kjeller, Norway
Anthony P. Lyons University of New Hampshire (UNH), Durham, NH, USA
Daniel A. Cook Georgia Tech Research Institute (GTRI), Atlanta, GA, USA
Torstein O. Sæbø Norwegian Defence Research Establishment (FFI), Kjeller, Norway

1 INTRODUCTION

Breaking internal waves and boluses can cause refractive effects that have negative impact on seabed imaging and mapping with interferometric synthetic aperture sonar (SAS). The refractive effect causes grouping of the acoustic rays (i.e., focusing) which results in a locally varying distribution of scattered intensity in the SAS images. In addition, ray refraction effects also cause errors in interferometrically estimated bathymetry. These artificial effects manifest themselves as features in the data products, sometimes difficult to separate from real features on the seabed. The potential problems caused by these effects are multiple: incorrect estimate of the seabed texture and seabed bathymetry; failure of detecting targets of interest due to the refractive shadowing; problems in change detection operations; and increased image complexity and thereby poorer target detection and classification.

In October 2012, the Autonomous Reactive Intelligence Sea Experiment (ARISE) ’12 trials were conducted, and in October 2013, the Multinational AutoNomy Experiment (MANEX)’13 trials were conducted, both onboard the NATO research vessel Alliance, hosted by Centre for Maritime Research and Experimentation (CMRE) outside Elba Island, Italy. The Norwegian Defence Research Establishment (FFI) participated with their HUGIN autonomous underwater vehicle (AUV) carrying a HISAS 1030 interferometric synthetic aperture sonar (SAS) (see Fig. 1). Oceanographic conditions at the time of the experiments were dominated by strong thermoclines at 30 - 40 m depth. Strong internal wave and bolus effects were observed in imagery and bathymetry collected, especially as part of change detection data collections in the trials.

Figure 1: NATO research vessel Alliance carrying the HUGIN AUV in the MANEX’13 trials.

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In this work, we quantify errors caused by refractive effects, both in the SAS images and in the interferometry products, by investigating data from repeated passes. We measure the deviation in backscatter intensity and seabed depth from interferometry. We have found that these effects produce local changes in the intensity of more than 10 dB, local changes in the seabed depth estimate of more than 1 m, and complete loss of interferometric coherence. Finally, we suggest simple means to predict and mitigate the negative impact of breaking internal waves on AUV-based interferometric SAS.

2 DESCRIPTION OF THE PHENOMENON

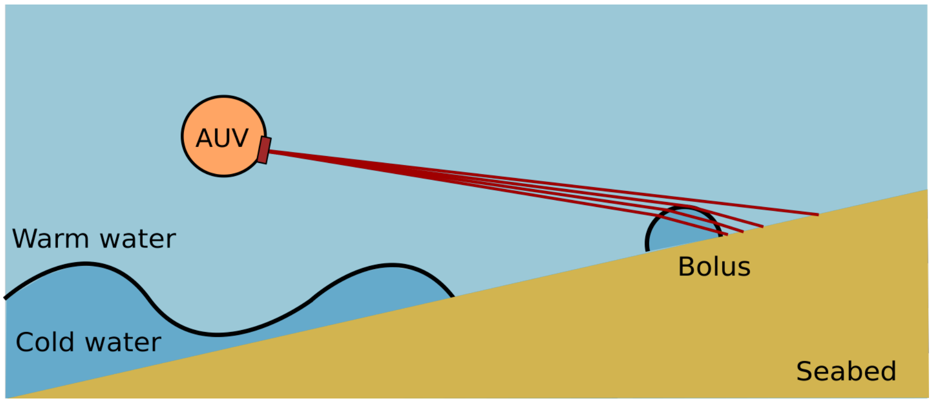

Figure 2: Vertical overview of the geometry.

Internal waves in the ocean are subsurface gravity waves typically horizontally propagating in vertical stratifications.[1]. They are naturally occuring everywhere where there are vertical stratification and driving forces, and they may produce strong signatures near continental shelfs and straits[2]. Internal waves typically are large scale waves compared to surface gravity waves. They may cause significant effects for ocean acoustics[3].Shoaling internal waves may break, producing slow moving features that creep along the seabed towards shore, sometimes referred to as internal wave *boluses*[4,5]. When a sidelooking sonar, sidescan or SAS, is used from a platform where certain conditions are fulfilled, these internal wave features may cause an effect for the acoustic system. This is illustrated in Fig. 2.

The internal wave boluses observed with SAS was first recognized by the authors in Lyons et al.[6], and further studied in Lyons et al.[7], Cook et al.[8], Hansen et al.[9], Hansen et al.[10], Pate et al.[11]. Conducting a directed search for the phenomenon resulted in the conclusion that there are observations from different places and with different sensor technologies[12]. A similar refractive effect has also been observed in airborne synthetic aperture radar (SAR) where it was described as a *moving hill* phenomena[13].

With reference to Fig. 3, these internal wave features (referred to as *boluses*) have the following essential behaviour and affect interferometric SAS in the following manner:

1. The bolus is a confined body of water which results from the breaking of an internal wave. The body contains water of different (higher) density and potentially different sound speed (see Fig. 2).
2. The bolus creeps along the seabed fairly slowly - on the order of 10’s of cm/s to cm/s.
3. The bolus size and speed decreases as the wave is moving towards shore.
4. Sidelooking sonar, SAS or sidescan sonar, is only affected by the refractive effect

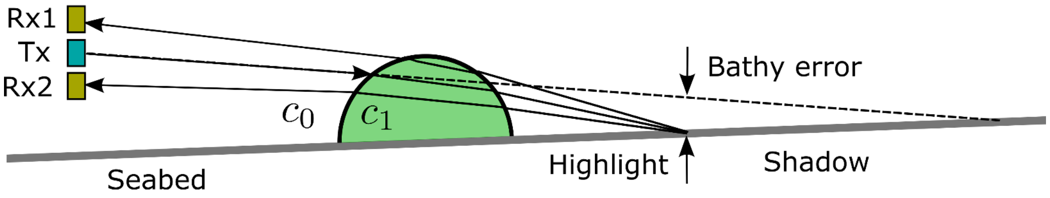

Figure 3: The refractive effect caused by an internal wave bolus.

caused by the bolus. The bolus it self is essentially invisible due to the sidelooking geometry, where backscatter from the seabed produces a competing echo at all ranges. This is in contradiction to e.g. observations in Bourgault et al.[5], where the wave itself is seen by sonar in a downwards looking geometry.

5. The refractive effect of a bolus may cause focusing of acoustic energy in certain regions, and loss of acoustic energy in certain regions. This may appear similar to the highlight and shadow caused by small bathymetric changes.
6. The ray refraction through the bolus causes potential depth errors in the bathymetry estimated by interferometry. These apparent bathymetric changes fit well the corresponding backscattered signal observed, as if there were an actual seabed feature[9].
7. The sonar horizontal look direction must be normal to the internal wave bolus front for maximum refractive effect.
8. The bolus is moving slowly such that there is little difference in the refractive effects when comparing sidescan sonar (real aperture) vs SAS where the integration time may be up to 30 seconds.
9. The bolus always follows the seabed topography and moves upwards towards shallower water.
10. The bolus is in general not a perfect lens with a focal point. The interface between the outer water and the inner water may be perturbed such that some of the lens effect is reduced[11].
11. The refractive effect caused by the bolus is typically more severe for horizontal acoustic propagation (rays close to parallel with the seabed). At grazing incidence, the bolus causes largest refractive effects. This is similar to refractive effects on sonar in general.
12. The water trapped inside the bolus contains heavier water which is colder and/or more saline. If the main difference is temperature, the sound speed is lower inside the bolus, and rays are refracting downwards (the acoustic lens is focusing the energy). These are the only boluses we have studied.
13. The boluses are elevated water objects causing horizontal angle dependence in the refractive effects, similar to acoustic shadow. This horizontal angle dependence may be used to detect and characterize the internal waves[10].
14. In straight line synthetic apeture data collections, there is a link between data collection time (slow time) and horizontal observation angle. The bolus is moving, and the refractive effect caused by the bolus is angle dependent. This may cause ambiguities or misinterpretations when observing data in multi-aspect mode.

3 QUANTIFICATION OF THE EFFECTS

In order to quantify the effects of internal wave boluses, we consider two different scenes in the MANEX'13 dataset. SAS data were collected from both scenes multiple times, as part of a change detection data acquisition. The upper part of Fig. 4 shows a SAS image

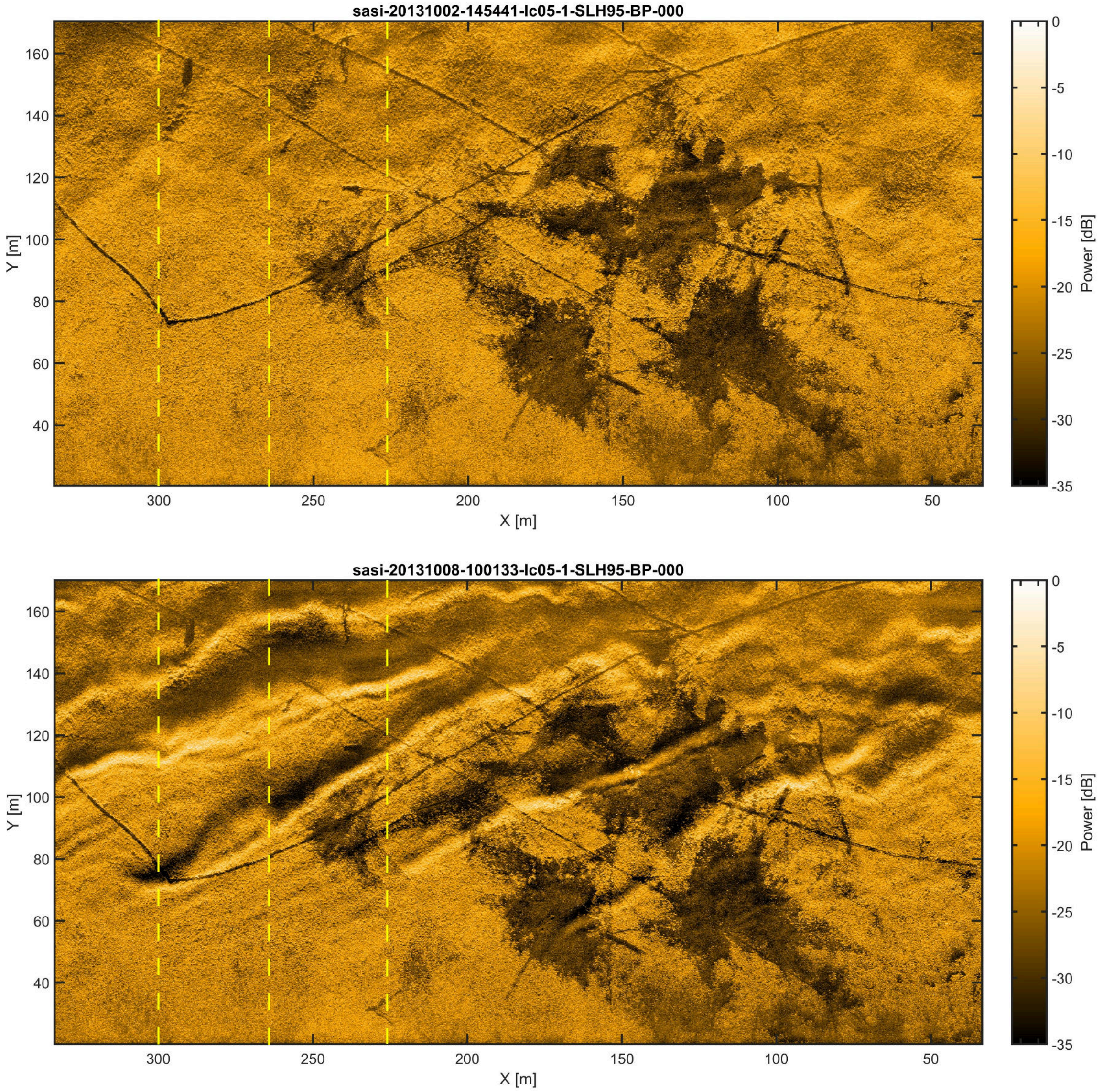

Figure 4: SAS images from repeated passes. Upper: 20131002. Lower: 20131008. Increasing sonar range (cross-track) is towards shallower waters (towards land). Data adaptive time-varying gain (TVG) is applied.

collected at October 2, 2013. The scene contains mostly posidonia (sea grass) as the brighter part, and darker patches of sand (or lack of posidonia). The thin darker lines are man-made dragmarks through the seagrass. This image contains little refractive effects. The lower image, collected October 8, 2013 from the same scene contains massive refractive effects. The images are 300 x 150 m, and the image resolution is 6 x 3 cm. The depth in the scene varies from 37 m at near range to 26 m at far range. The vehicle depth is approximately 22 m. The synthetic aperture length is approximately 30 m at 100 m range, equivalent to 15 seconds of integration time.

We have also studied data from the same scene from October 1 and October 12 (not shown here). These data show essentially the same as the data from October 2, with fairly little refractive effects. We have selected three different x-locations where the internal wave effects are strong, indicated with yellow dashed lines in Fig. 4. Fig. 5 shows a comparison of the backscatter level, the estimated seabed depth from interferometry, and the single pass

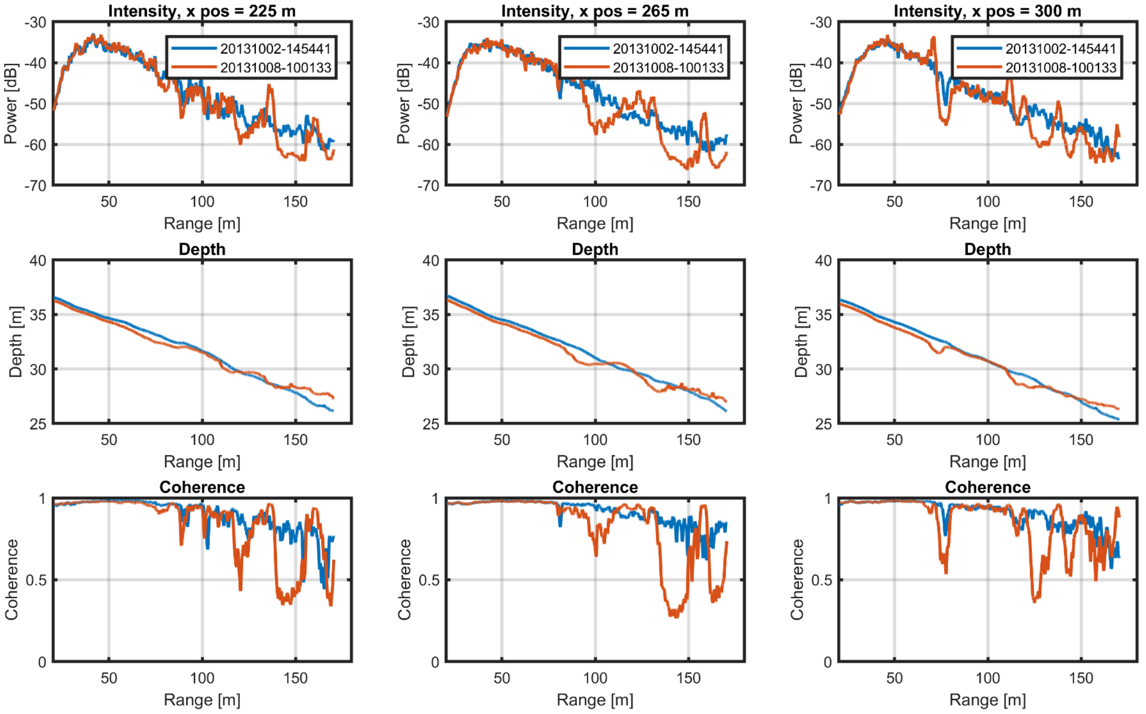

Figure 5: Slices along different x-positions in the images shown in Fig. 4. The results are averaged ± 1 m along-track, and boxcar averaged along y.

interferometric coherence. We see that the contaminated October 8 run deviates ± 10 dB in backscatter level compared to the reference run. The depth error caused by refraction from the boluses is larger than -1 m. We also see that there is almost complete loss of interferometric coherence in the contaminated pass. We see that the largest refractive effects are close to maximum range (as expected, see section 2).

An interesting question is why the refractive effect of internal waves are strong one day, and not three other days for this particular scene. It may be related to the driving force of the large scale internal waves entering the shelf at the island (e.g. the tidal waves). It may also be local variations in space and time. Investigation of sidescan data from these passes and the following parallel lines, shows that there are variations in the internal wave effects both in space, time, and strength.

Fig. 6 shows another image pair, one without strong image corruption, and one with a pronounced feature caused by the refractive effect from an internal wave bolus. The imaging scene is 400 x 100 m. We see a distinct highlight/shadow structure caused by the refractive effect. Investigation of the reflectivity shows around ± 10 dB difference in intensity, and almost complete loss of coherence in the shadow caused by the refractive effect from the bolus. The sonar look direction is away from shore in this case, as opposed to Fig. 4, where the sonar look direction is towards shore. The seabed depth increases from 45 to 48 m with increasing range. The average vehicle depth was 25 m.

In position $[x, y] = [163, -132]\,\mathrm{m}$ we see a small object (a rock maybe) that is present in both passes. The object is misplaced approximately 3 m along-track between passes, due to vehicle navigation errors. Data driven coregistration is not applied.

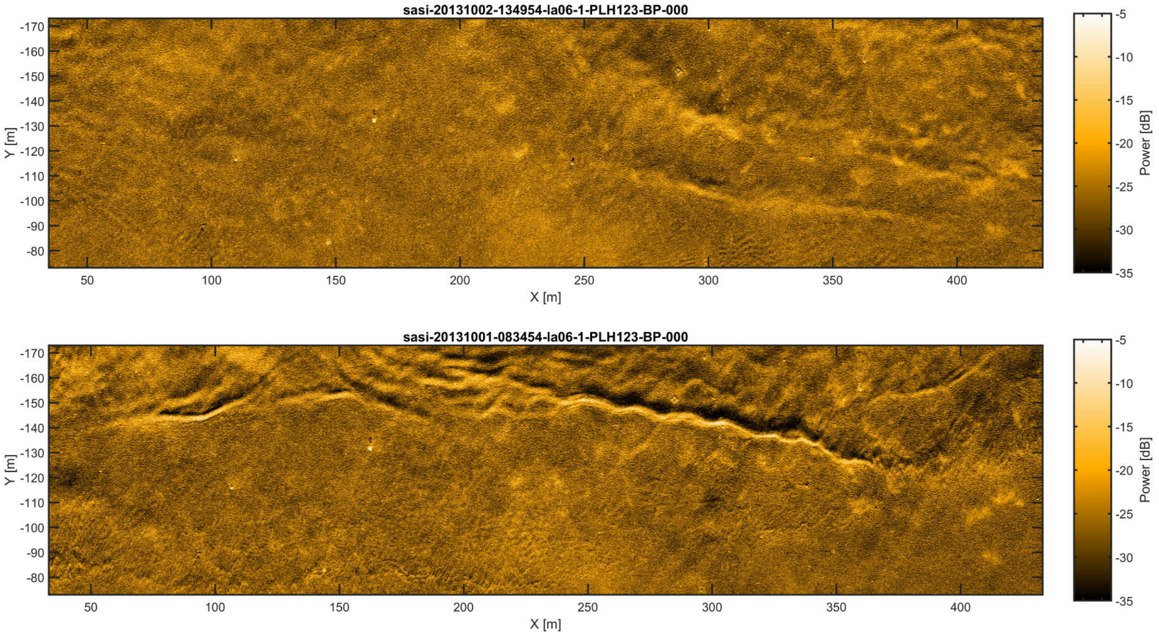

Figure 6: SAS images from repeated passes. Upper: 20131002. Lower: 20131001. Increasing range (negative Y) is towards deeper waters (from land).

4 SUGGESTED MITIGATION TECHNIQUES

Sidelooking sonar data, SAS or sidescan sonar, cannot easily be corrected for the refractive effect caused by internal waves. The refractive effects may be detected in some cases in SAS[10], but to our knowledge not easily removed from data already collected. We therefore suggest that the environmental parameters available should be monitored during the data acquisition, potentially autonomously. And that the collected sonar data is inspected accordingly. This can be done in the following manner.

1. Collect depth profiles with a CTD regularly and inspect if density changes with depth are present. This is a requirement for internal waves to exist. The profiling can either be done with the vehicle (autonomously) or by a ship (e.g. the host ship).
2. Make sure that the profiling is taken place both in the imaging scene and at larger depth than the imaging scene. Boluses are small features creeping along the seabed towards shallower waters caused by breaking internal waves potentially at larger depth.
3. If conditions are met for internal waves and/or boluses to be present, run selected repeated passes with larger than minutes time differences and observe for changes that may be caused by refractive effects from internal waves and/or boluses.
4. If the internal wave activities is expected to be linked to tidal driving forces, collect data through a tidal cycle.
5. If repeated passes cannot be run and a SAS system has been applied, investigate the data collected for horizontal angular behaviour consistent with refractive effects caused by internal waves / boluses[10].

A potentially effective mitigation technique is to change orientation of the data acquisition (especially the horizontal sonar look direction). Consider the data collection from October 23, 2012, illustrated in Fig. 7. This day, we ran multiple sets of lines with corresponding cross-lines (indicated by the yellow lines). Fig. 8 shows SAS images of four different passes of a scene containing a pipeline. The yellow arrow indicates the sonar look direction. The

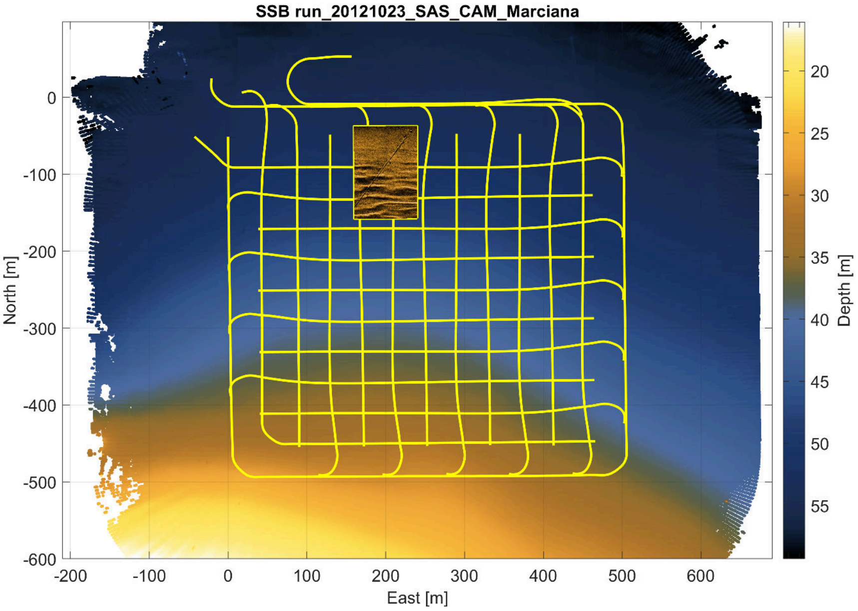

Figure 7: Seabed depth estimated with sidescan bathymetry with indication of the images shown in Fig. 8. Data collected October 23, 2012 during the ARISE'12 trials.

images are aligned such that upwards is towards shore (southwards), opposite to Fig. 7. The internal waves and boluses move towards shore, and an imaging geometry with a sonar look direction normal to the internal wave fronts will cause conditions that are more susceptible to refractive effects from the internal waves. The rightmost image in Fig. 8 is a sonar image collected in a north-south track, where the sonar look direction is westbound, parallel with the internal wave fronts. We see no refractive effect in this image.

5 SUMMARY

Refractive effects caused by internal waves may cause artifacts in SAS imagery and interferometry processing. In this work, we have described the essential behaviour of breaking internal waves known as *boluses*, and how these affect interferometric SAS. We have quantified the problems caused by the refractive effects from the boluses through investigation of real data collected by an interferometric SAS carried by a HUGIN AUV. Finally, we have suggested simple means to flag the potential of such features causing harm to the data, and potential ways to mitigate the effects during data colletion.

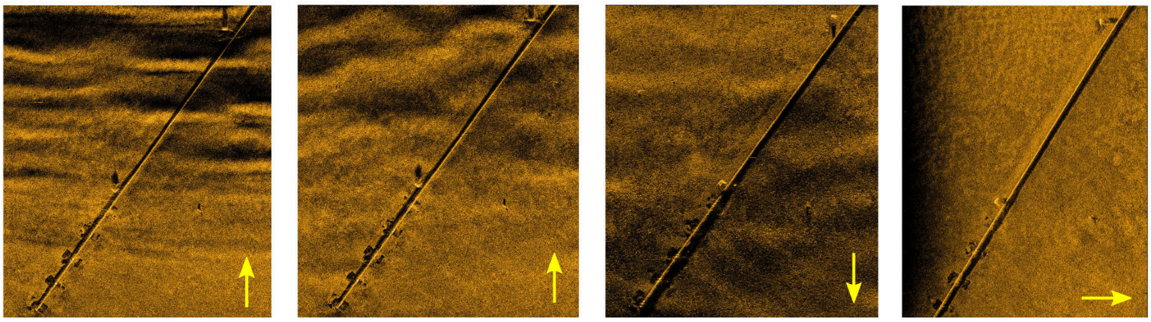

Figure 8: 80 x 70 m size SAS images from a scene containing a pipeline taken in different look direction (see Fig. 7). Left and center left: towards shore. Center right: Away from shore. Right: parallel with shore. The yellow arrow indicates the sonar look direction.

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