Methods for artifact identification and reduction in acoustic backscatter mosaicking

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Modern multibeam sonars provide high resolution measurements of acoustic backscatter that were unthinkable just a few decades ago. However, many aspects of the data acquisition can heavily impact these measurements, reducing the data quality in the output mosaic and any attempt of seafloor characterization. This work first describes techniques to identify the presence of artifacts (e.g., bubble wash-down), then explores possible scenarios for how to reduce the lack of knowledge in such areas. Finally, it outlines an approach for how to retain the information from the processing steps used in an attempt to increase output reproducibility and reusability.

Introduction

Sonar data are routinely processed to produce seabed acoustic backscatter mosaics which, coupled with bathymetric models, may be used to estimate the spatial distribution of seafloor type and composition. Although subjective, human visual interpretation of sidescan sonar data has proven to be usable for delineation of seafloor regions in case of sharp demarcations, but the approach is far less effective for areas of high heterogeneity or in the case of gradual variations in seabed characteristics. Backscatter data from multibeam sonars has been recognized as a better means to segment the seafloor into regions with similar acoustic properties, i.e., acoustic themes [1]. After that, it is possible to attempt to determine a relationship between the seafloor acoustic properties of each theme and the surficial characteristics of the seabed.

Two common obstacles in the creation of a backscatter mosaic from multibeam data are the conversion of raw data samples (since they usually represent some kind of relative magnitude) into backscatter strength values, and the removal of the angular response (i.e., the way that the backscatter strength values change with the angle of incidence). A failure in tackling the first obstacle produces a mosaic that cannot be confidently compared to adjacent mosaics, while a partial success in the removal of the backscatter angular dependency generates a mosaic with across-track angular variations in the component survey lines even on homogeneous seafloor areas (together with artifacts in the overlapping areas among different survey lines). An accurate removal of this angular response is only achievable by knowing *a priori* the seafloor type, but this represents a dilemma given the task for which a mosaic is usually built. The typical practical approach is to remove the angular response by calculating angle varying gain (AVG) corrections using one of the available empirical techniques [2-4], and normalizing at a selected angle (or angular range) the amplitudes across the swath. The large variability in the output resulting from adopting different techniques for the removal of

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the angular response and the inherent subjectivity of their parameterization clearly highlight how the values presented in a mosaic provide an ambiguous and weak representation of the seabed acoustic response. As such, the pixel values of a mosaic on their own are not a robust method for seafloor characterization.

Numerous studies have shown the potential of using the backscatter angular response curves (ARCs) for remote estimation of surficial seabed properties such as grain size and acoustic impedance [5-7]. Along with mosaic processing, the analysis of ARCs assumes accurate measurements of backscatter strength and across-swath homogeneity, which might be difficult to guarantee in practice. This assumption is invalidated to varying degrees by the lack of homogeneity of the seabed area insonified by the sonar swath. Furthermore, when compared with a mosaic, the analysis of ARCs alone is characterized by a much lower spatial resolution. This suggests that the two methods (mosaicking and ARC analysis) should be used in combination. Promising results have been obtained following this intuition, by first segmenting high-resolution mosaics and calculating average angular response curves for each segmented area, then using those curves to build a more accurate mosaic before performing a better seafloor characterization based on the inversion of a formal mathematical model that links backscatter observations to seabed properties [1, 8].

However, many aspects of the data acquisition can heavily impact the backscatter measurements. With the specific aim of detection of backscatter artifacts, this work explores the ability to combine seafloor information with WCI data as a potential quality control tool [9]. Most WCI applications only started to be implemented in the late 1990's, lagging behind seafloor-based applications. The main reason for that disparity is usually identified as the heavy data storage requirements associated with WCI data, coupled with the lack of support for WCI digital data logging in past (and even modern) multibeam sonars [10]. By providing a three-dimensional acoustic representation of the water mass between the transducer and the seafloor, WCI may help to better understand issues in the survey configuration, variations in the ocean environment, and even to obtain early warnings of future failures of sonar components. An outcome of this work is that WCI data should be routinely collected not just by the fisheries community for biomass quantification or for military uses [11-14], but their interpretation should be incorporated in the quality control of the hydrographic data processing stream.

We here focus on methods for the identification and reduction of artifacts affecting backscatter measurements collected with multibeam sonars with the aim of improving the quality of the final output. For seafloor characterization, these kinds of artifacts increase the risk of erroneous boundary identification between acoustic facies. Although such risk can never be totally removed, it can be decreased by modeling the expected types of artifacts and by acting on their identification in the early phases of the data processing workflow. For instance, the identification of ping-oriented artifacts is facilitated by working at a survey line level, and the presence of overlapping areas between survey lines can be used to improve confidence in the resulting characterization. The simple removal of the corrupted pings and ping sectors from the output mosaic usually provides a boost in its general visual quality and eases human interpretation. However, we also attempt several exploratory reconstructions of the removed areas.

Finally, we describe an approach for how to retain the information in the processing steps used in an attempt to increase output's reproducibility and reusability. The approach detaches the artifact detection and reduction steps from the following product-oriented steps (i.e., the backscatter mosaicker and the ARC analyzer). A main advantage of this solution is that the outputs from the reduction step are valid data files that can be then imported into the user's favorite application. By adopting the original native format in the 'intermediate' step, we avoid the intrinsic semantic limitations of generic data formats and, at the same time, minimize the additional requirements in data storage.

Background and Methods

Testing data set

In order to test the described methods, we used acoustic sonar data acquired with a Kongsberg EM122 [15], a 12-kHz multibeam echosounder that is gondola mounted on the *MV Fugro Supporter*, during normal survey operations conducted during a 32-day Extended Continental Shelf-related bathymetry cruise to the Northern Mariana Islands Continental Shelf [16].

The sonar arrays were mounted in a Mills-cross configuration nominally providing a one-degree beam width in transmission and two-degree beam in reception (the actual beam widths vary as a function of sector frequency and steering angle.) The system produces 576 beams per ping in dual swath mode giving 864 soundings per ping in High Density (HD) mode, and a maximum coverage sector of 150 degrees. The HD mode provides more bottom detection solutions than physical beams, but such an approach cannot be used for the WCI where only 576 radial channels are recorded. The digital numbers registered in the sonar records are not exactly normalized values of backscatter strength, so it is necessary to correct them by applying both radiometric and geometric corrections based on the processing task considered [17].

During the data acquisition, the presence of corrupted pings was noticed and correlated to rough sea states. It was also evident how this effect was worsened in a cone of vessel routes going towards the main sea direction [16].

Artifact detection

The presence of bubbles in the uppermost part of the water column represents a common issue that impacts the array faces of hull-mounted multibeam sonars. If not properly managed, those intensity drops will most likely become darker stripes in the output mosaic, and they will contribute to bias the outcomes of any attempt at seafloor characterization by inverting backscatter models. In fact, the high impedance contrast between air and water heavily attenuates both the outgoing energy and the returning echo intensity [9]. This effect may not significantly reduce the quality of the bathymetric solutions (bottom detection algorithms use gates and are usually robust with respect to fluctuations in the background noise level), but delivers sudden drops in the received intensity. As such, tracking the statistics of the backscatter samples ("snippets") stored in the Kongsberg data provides a natural candidate for an algorithm that wants to identify possible corrupted pings.

Several sonar manufacturers provide some kind of quality factor values that are usually focused on evaluating the performance of the bottom detection. In the specific case of the Kongsberg EM122, two kinds of quality factor data are available: a figure proportional to the ratio of the standard deviation of the range detection and the detected range; and the recently-added calculation based on [18, 19]. Given that exploratory evaluation of the data showed correlation between quality factors and the corrupted pings, they have been added to the list of artifact proxies together with the beam validity (provided as part of the “Detection info” field in the Kongsberg XYZ datagram) [19].

The effects caused by bubbles tend to have a vaguely periodic nature with periodicity close to that of the attitude (in particular the pitch). However, this characteristic is difficult to correlate with corrupted pings in the case of a deep water survey given that the timing between the transmission of the acoustic impulse and its return is on the order of several seconds. Although not currently used in this work, the attitude time series is a candidate proxy for future developments.

The bubble-related phenomenon usually happens in the sonar’s near field, but the part of the WCI time series actually showing the issue may potentially be at any time between transmission and the maximum two-way travel time due to internal multiple bounces from within the bubble layer [9]. (The localization of the phenomenon in the near field does not represent an issue with focused sonars.)

The bubble wash-down effect is only one of the many possible sources of sudden and wide intensity fluctuations in the water column [20-22]. WCI data are generated by a variable mixture of different processes heavily influenced by environmental spatial variability. In fact, a multibeam sonar simultaneously collects, as a function of angle, both boundary (sea surface and seafloor) and volume (e.g., biologic scatterers, near-surface bubbles) backscatter and reverberation. We used data at ranges shorter that the distance of closest approach to the seafloor; but, since hydrographic multibeam sonars are primarily adapted to extracting echoes about the bottom, seafloor related echoes may contaminate the water column imagery. This makes the collected imagery much harder to interpret than for data coming from sonars specifically designed to collect water column data [9]. However, the high directionality (specifically, in reception) of hydrographic multibeam sonars provides the advantage of being able to discriminate among multiple echoes occurring at the same time, but from different angles.

It is also worth noting that the WCI intensities are mapped to the angle of the principal response axis for each beam (also known as the beam boresite). As such, it is possible that the resulting intensity merges contributions from other directions as a function of the beam-specific sidelobe suppression [9]. In multi-sector multibeam sonars, such as the Kongsberg EM122, this effect is reduced since the insonified area is broken into multiple parts. The transmit beam patterns for the outer sectors are then designed to have local minimum close to vertical incidence, heavily reducing the near-specular return. Since all the sectors are fired within a few milliseconds of each other, a full swath is almost simultaneously obtained (Figure 1, lower pane).

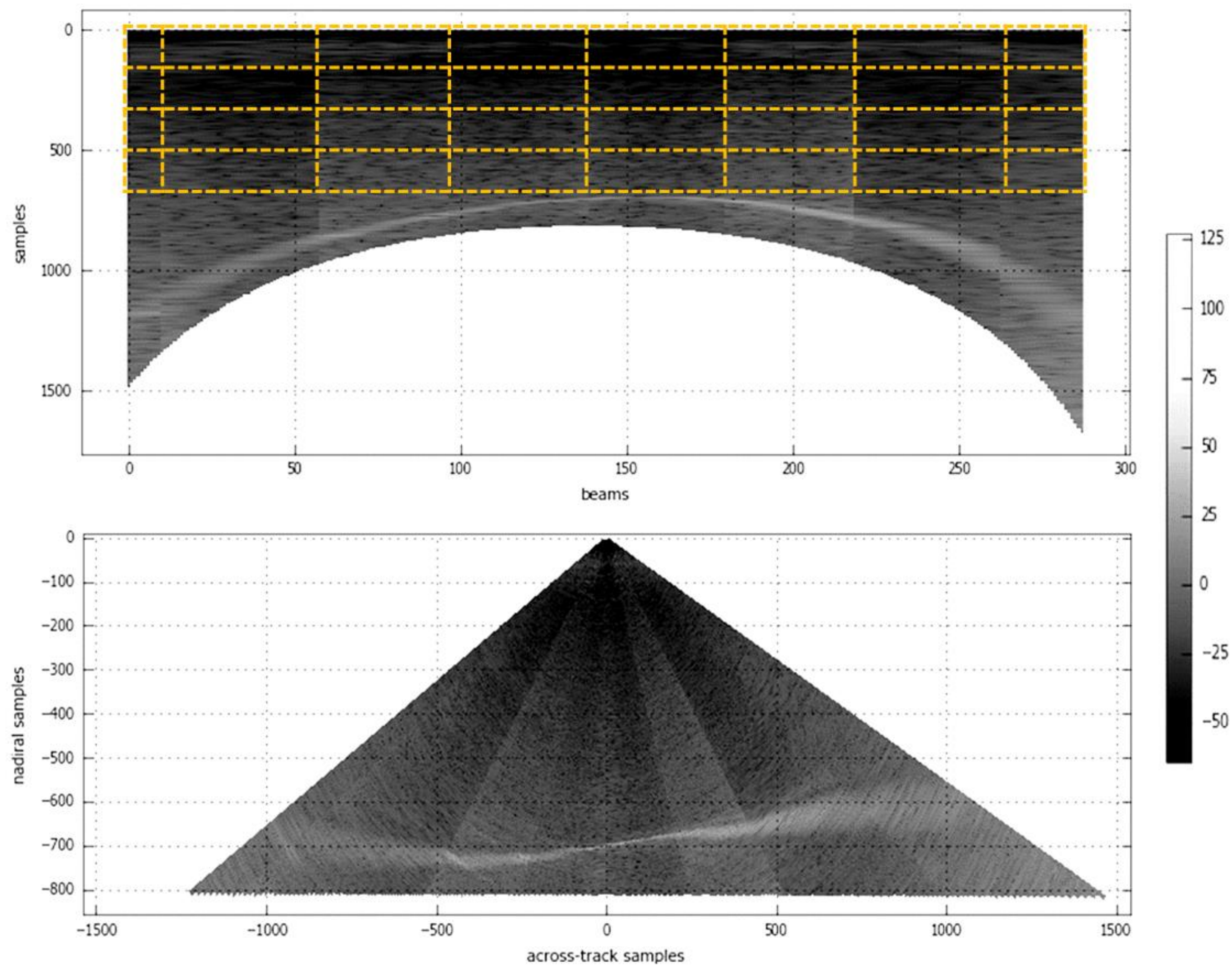

Figure 1 – Time-angle space representation (upper pane) and corresponding Cartesian representation (lower pane) of the WCI data for a given ping. On the upper pane, the section boundaries (in orange) for eight-sector transmission mode and four bands are overlaid. For this latter, ray tracing and along-track distortion should be taken in account for a more accurate visualization.

In this work, the WCI data have been analyzed in the time-angle space that is the multibeam sonar's native way of hearing the external world (Figure 1, upper pane). In fact, a conventional beamformer creates a series of preformed beams to listen along specific (sonar- or vertically-referenced) angles. As a direct consequence, this two-dimensional space displays a flat seafloor as a parabola. A simple transformation from polar to Cartesian coordinates provides a more intuitive two-dimensional representation of the insonified area under the vessel (Figure 1, lower pane).

We attempt to identify and interpret the spatial patterns of echoes in the water column to detect the presence of artifacts in the output mosaic. This is done by splitting the swath into sections, each of them presenting a vote as to the ping validity. Given that the Kongsberg EM122 is a multi-sector sonar, the vertical (angular) limits of the sections were set according to the active sectors. (Using this method with a single-sector insonification would require a different criterion). For horizontal (temporal) limits, different numbers of equidistant bands were empirically tested. Thus, for the case of an eight-sector transmission mode and four bands, a total of 24 sections are monitored (Figure 1, upper pane).

For all the selected proxies, several potential statistics have been evaluated in an exploratory fashion. Based on the current preliminary outcomes, the median and the median absolute deviation (MAD) of the average for both the snippets and the WCI data have been selected. For the WCI's 24 sections, a ping is flagged as corrupted if the majority of sections in a band vote for invalidity.

Artifact reduction

The simple removal of the affected pings and ping sectors from the output mosaic provides a boost in its general visual quality and eases human interpretation. In addition, the removal is clearly the recommended solution in case of ARC analysis both in the patch-based approach (where a number of successive pings are averaged to reduce the signal noise) and the theme-based approach (where the ARC is computed over a segmented mosaic area assumed to be the same acoustic facies).

However, given that a preliminary mosaic is often processed with an image-processing clustering algorithm to define the theme areas, we also explored several reconstruction techniques for the removed pings, ranging from a naïve interpolation at the mosaic level to more sophisticated approaches like [23] and [4] among others. We found that a randomized selection from the snippets belonging to valid beam/ping pairs in the surrounding area of the flagged beams represents a good balance between quality of outcomes and processing efficiency.

HUDDL-generated code was used to read and write native data formats [24-26].

Processing workflow

Current applications processing acoustic backscatter data tend to behave like a 'black box' where the user can only interact by providing raw data inputs and changing a limited set of parameters along the processing workflow. The simplicity in using such applications is surely an advantage since they make those technologies available to a large number of users. However, this simplicity turns into a challenge when it comes time to merge the outputs (i.e., a mosaic image and/or a set of spatial features representing the estimated seafloor characteristics) from different vendors or even from different users using the same application but different settings since all the parameters and processing choices are not currently retained along with the created outputs.

This work proposes a different approach to track down the processing pipeline applied to create acoustic backscatter mosaic and other backscatter-related products (e.g., seafloor characterization). In place of having a monolithic 'black box' that is often quite challenging to properly describe in the metadata, we propose the adoption of a mechanism to fix (or reduce) the presence of artifacts by creating:

- A corrected intermediate file in the same binary format as the input.
- A "difference" binary file with just the imagery datagrams that have been corrected.
- A text file describing the applied post-processing step.

Once the data have been corrected, the resulting files can be ingested by the user's application of choice (Figure 2). This approach should increase user confidence in the validity of the resulting mosaics as well as providing better results in seafloor characterization. The description and difference files, if retained, provide a mechanism to track the applied processing steps, and may ease the integration of output coming from different sources.

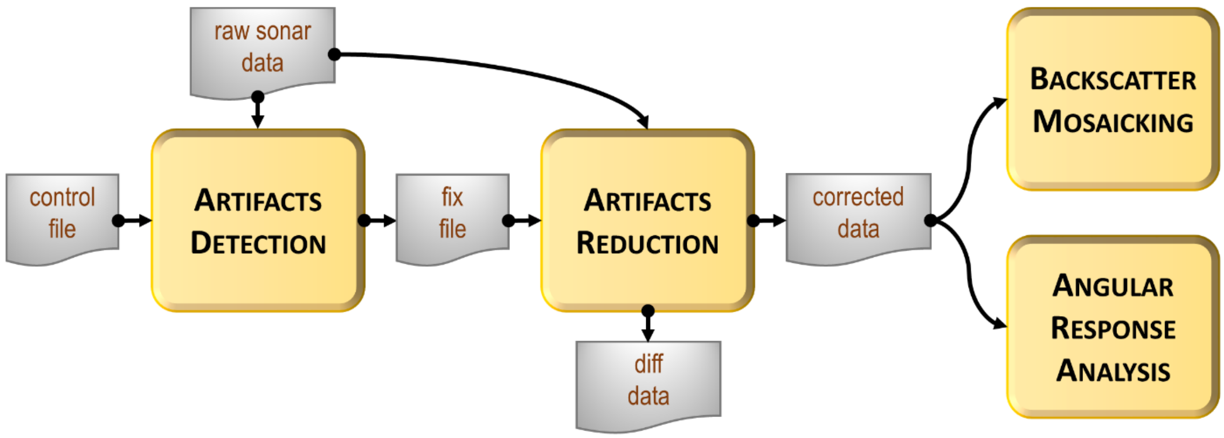

Figure 2 – Visual representation of the adopted processing workflow. The raw sonar data are ingested by a set of artifacts detection algorithms, together with a control file that provides a mechanism to the user to force the flagging or the exclusion from the evaluation of specific pings or ping ranges. The results of the detection step are stored in a 'fix' file containing guidance to the artifacts reduction step. This reduction step produces valid corrected data in the native input format together with a binary file containing just the original ping data. Once created, the corrected data can be ingested by any application supporting the native format, fully detaching the data correction phase from the product generation.

Results

The artifact detection algorithms currently use windowed statistics to track the presence of anomalies in the selected proxies. Examples of section-based tracking applied to real WCI data are presented in Figure 3, for a survey line with a route that was observed to minimize the bubble washdown, and in Figure 4, for data collected in the same area but in the opposite direction. By visual comparison, it is possible to see that the median and the MAD values provides a good tracking mechanism to capture the 'natural' variability in the water column and, at the same time, they are sufficiently robust in highlighting the intensity anomalies.

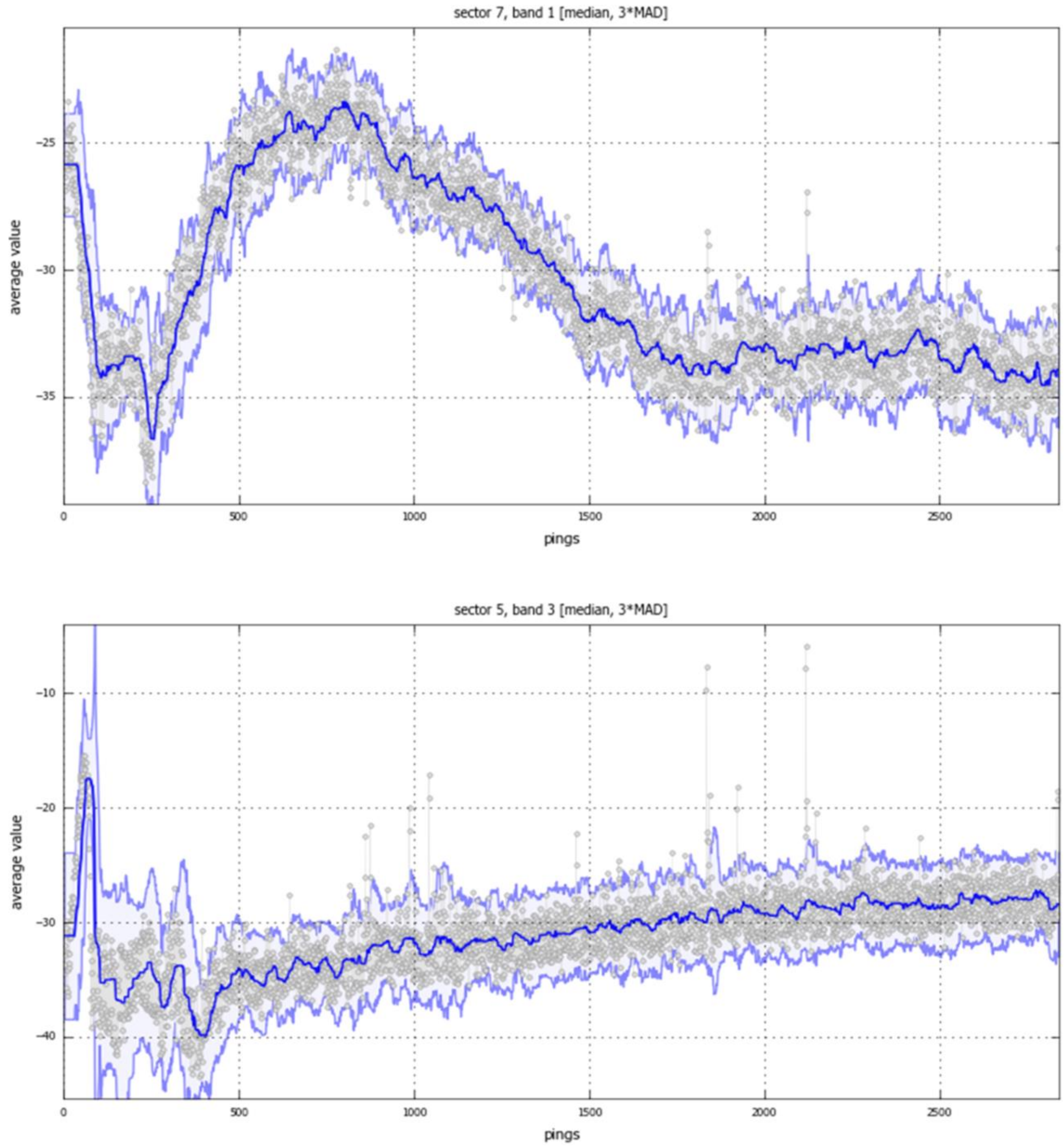

Figure 3 – Plots showing for 2 specific sections (sector 7 band 1 and sector 5 band 3, respectively) the tracking of median (dark blue) and MAD (light blue) of the average intensity value for a survey line (#480) with a route that was observed to minimize the bubble washdown. The grey circles represent individual pings.

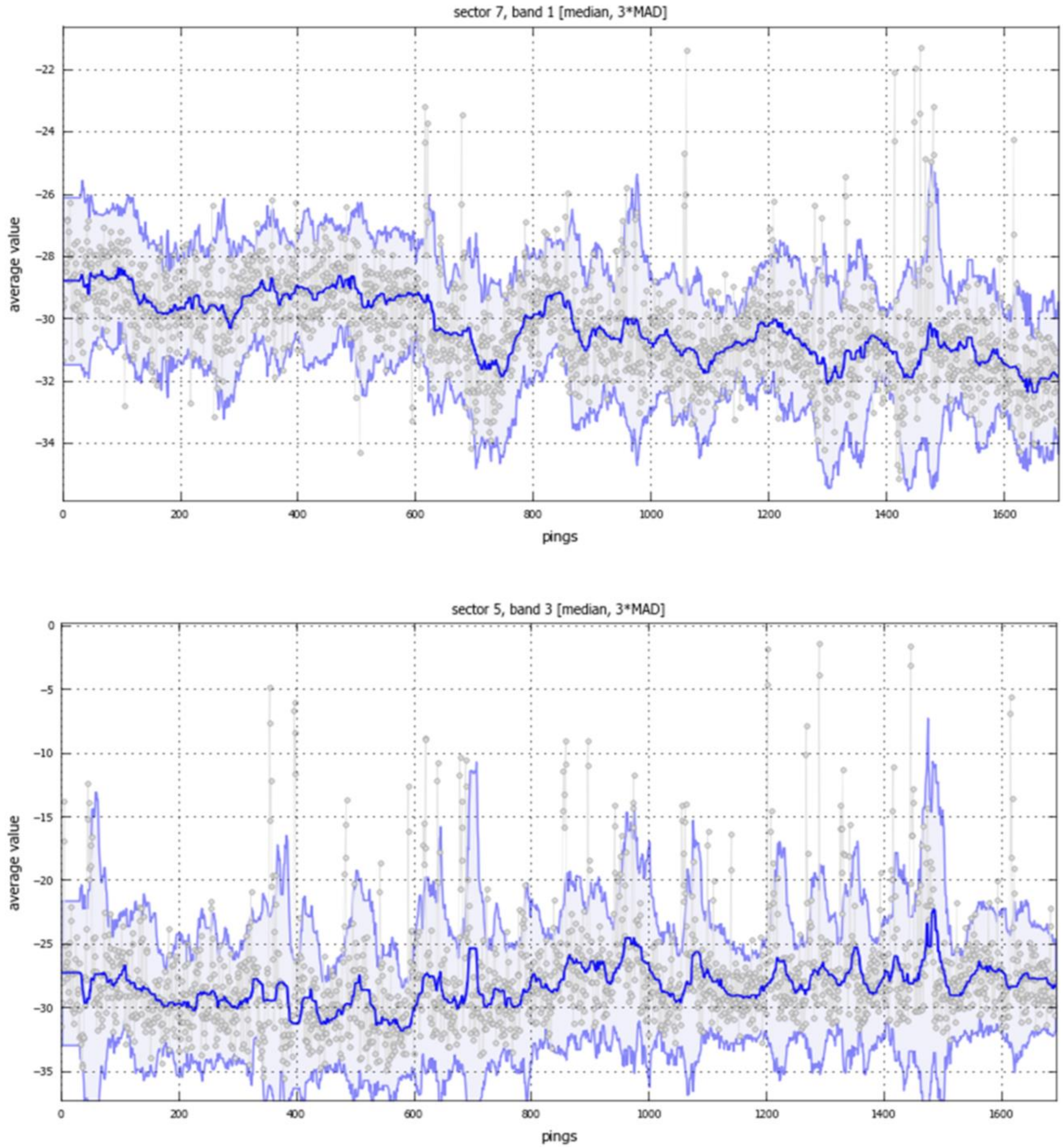

Figure 4 – Plots showing for 2 specific sections (sector 7 band 1 and sector 5 band 3, respectively) the tracking of median (dark blue) and MAD (light blue) of the average intensity value for a survey line (#491) with a route that was observed to be heavily affected by the bubble washdown . The grey circles represent individual pings.

A ping is not flagged when just a section presents an anomaly, but only when an anomalous areas is shown through multiple individual algorithm voters. The number of sections for band that triggers the flagging of a ping is a parameter that can be used to increase or reduce its sensitivity (The results shown use the intermediate value of four band sections for this parameter). An example of a series of successive pings flagged as corrupted is presented in the upper panes of Figure 5. When only a few sections are triggered, the evaluated ping is not flagged (bottom-left and bottom-middle panels in

Figure 5). However, there might be situations (like the bottom-right panel) that are more ambiguous, and human intervention may be required (or the addition of supplementary checks to evaluate whether adjacent pings are going to be flagged).

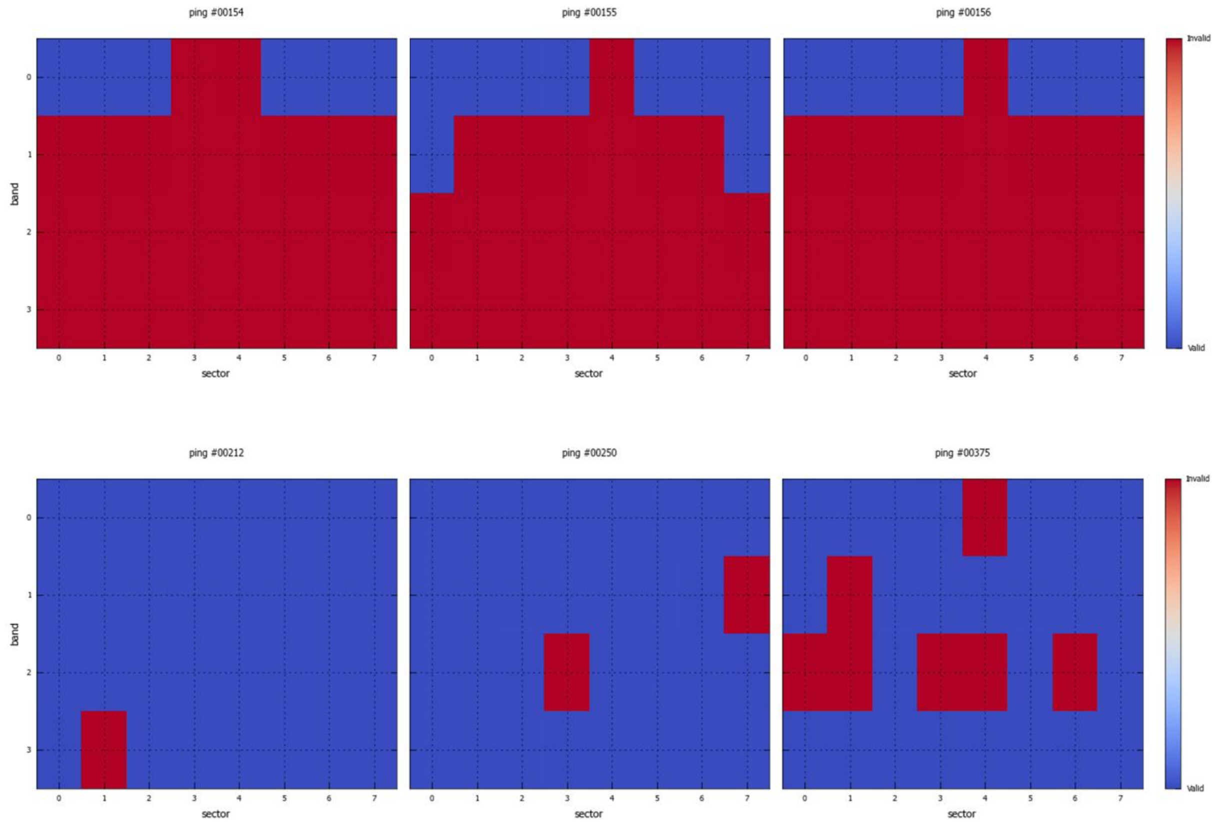

Figure 5 – Each plot show a frame representing 24 sections composed by the combination of eight sectors and four range bands. The upper panels show an examples with three successive pings flagged as corrupted by the WCI tracking algorithm. The lower panels show selected ping where just one section (left plot), two sections (middle plot), or sparse sections (right plot) voting for invalid ping.

Figure 6 compares the output mosaics with and without corrections using a commercial implementation of the Geocoder algorithm [2]. The upper pane shows the mosaic obtained using the original survey data for the two survey lines previously identified in this work. The upper line is the one heavy affected by the bubble washdown, and a number of darker stripes are present in the output. The middle pane of Figure 6 shows the resulting mosaic using the corrected files where the flagged pings were just removed. Finally, the lower pane is based on corrected files where the snippets in the flagged ping have been populated by randomized selection of values from valid surrounding beams.

In order to better evaluate the improvements of the randomized selection in the output mosaic, Figure 7 presents a side-by-side comparison over an area characterized by a high number of flagged pings. In the left pane, the pings were just removed, and the gap filling is simply left to the commercial application. In the right pane, the snippets in the flagged pings were populated with the proposed technique. This latter provides a more ‘natural’ textural distribution, although additional improvements seem to be required to fully eliminate the across-track stripes.

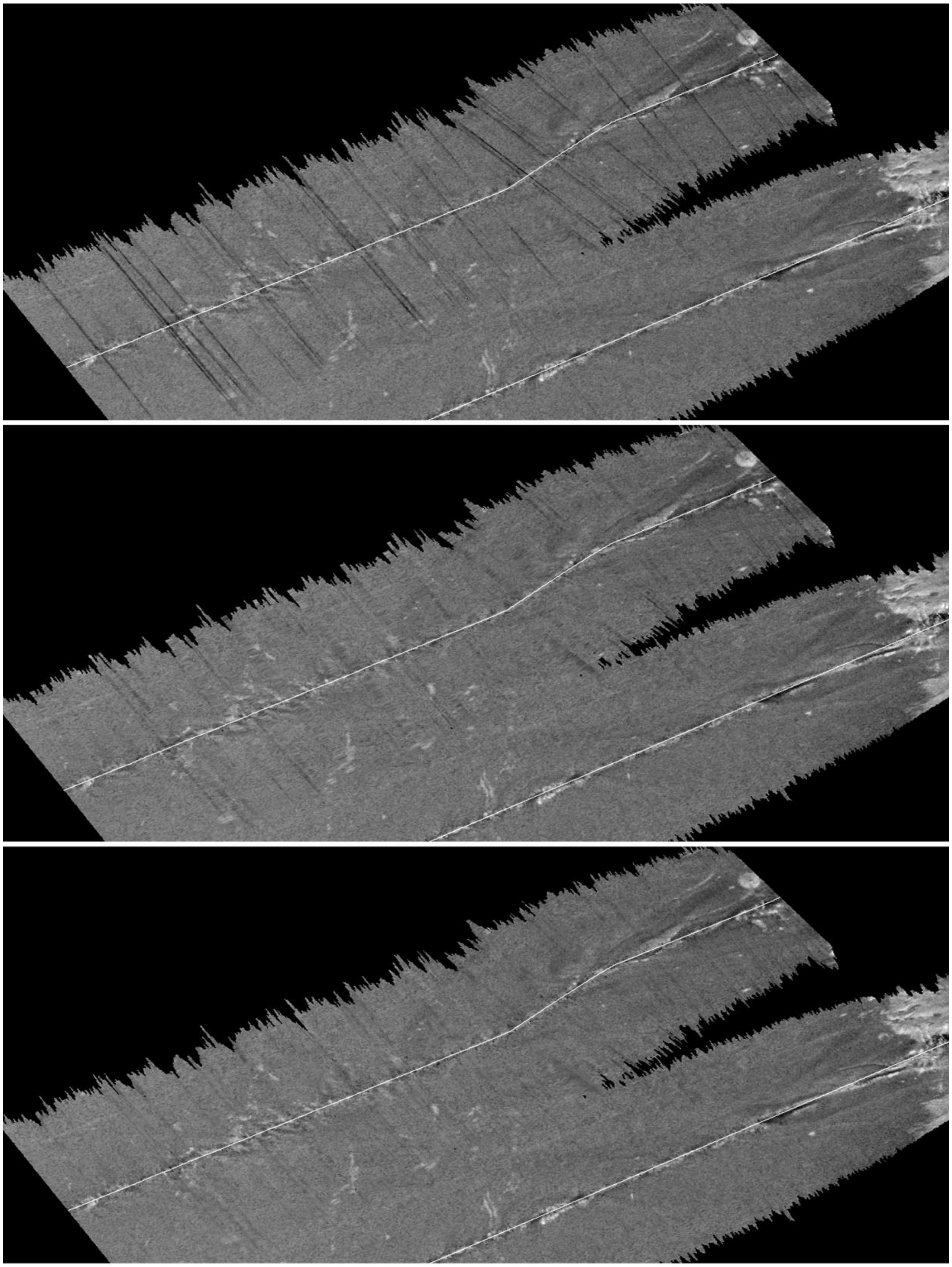

Figure 6 – Comparison of output mosaics from a commercial implementation of the Geocoder algorithm: the upper pane shows the mosaic obtained using the original survey data for two survey lines; the middle pane, using the created intermediate files by just removing the flagged pings; and the lower pane after randomized selection of valid surrounding beam snippets.

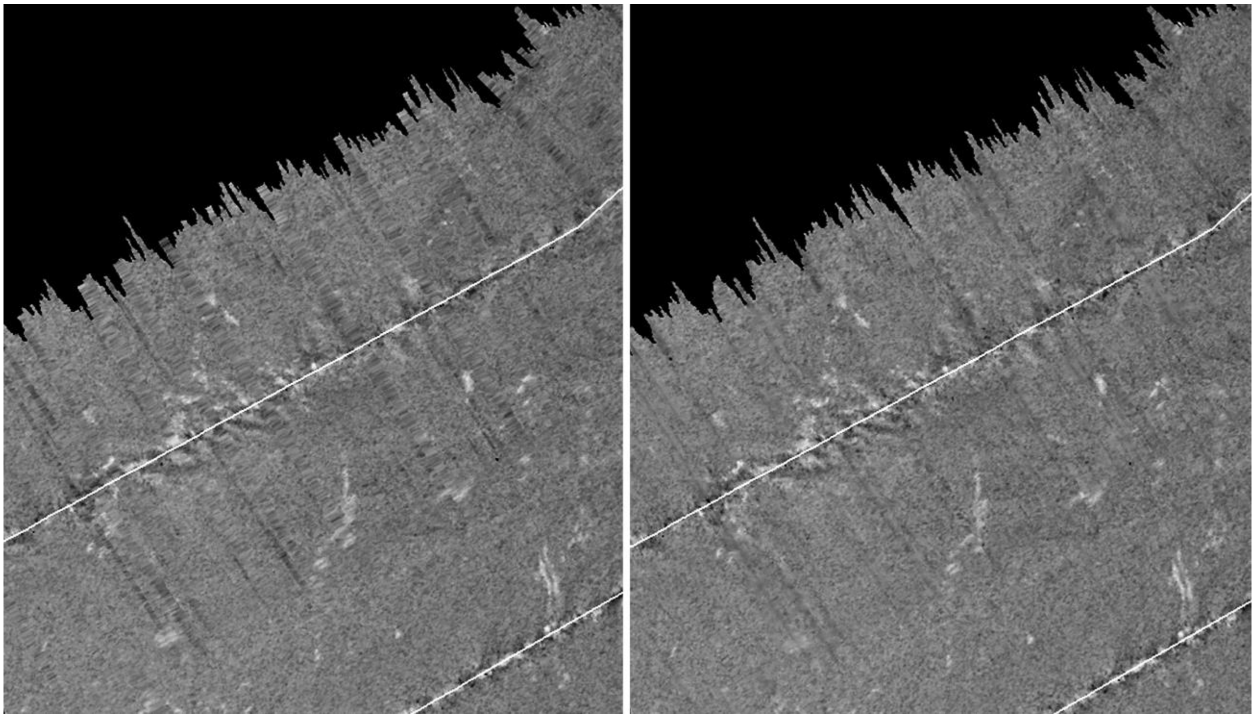

Figure 7 – Side-by-side comparison for a mosaic area characterized by a high number of flagged pings. On the left pane, the pings were just removed, and the gap filling is simply left to the commercial application. On the right pane, the snippets in the flagged pings were populated with the technique described in this work.

Conclusions

The methods described here illustrate some of the advantages of an integrated approach to quality control for the data collected by modern multibeam sonars. The intent to improve common backscatter-based products: mosaics and seafloor characterization. In addition to provide promising results in the detection of pings affected by the bubble washdown, the described WCI-based tracking has potential to be extended to other kinds of intensity fluctuations that affect the quality of the resulting seafloor backscatter. However, additional exploratory work is required to verify the robustness of the observed results, as well as their portability to different environments.

Information from the snippets and the bathymetry complement the WCI data with estimates of the seafloor intensity and indications of the quality of the bottom tracking. The combination of these three type of measurements contributes to improve both the detection of corrupted pings and assessment of different levels of confidence for their use in seafloor characterization. Limitations of this approach remain apparent, particularly when considering the variability that phenomena like the bubble washdown can exhibit (with the resulting observations coming after a possible combination of a number of them). It is also not a trivial task to remove possible biases in the detection of the corrupted pings. To cite only a few of the major concerns: the multibeam sonar must be properly calibrated and the acoustic scattering properties of the water column should be known and consistent across all incidence angles as the multibeam frequencies.

Modern multibeam sonar technology allows WCI data collection that permits three-dimensional water mass monitoring at high spatial resolution. Although the large volume of WCI data generated by these systems presents challenges for analysis and storage, automated approach to WCI data interpretation should become part of the future hydrographic data processing workflow.

From a more general perspective on the processing workflow, this work proposes to split the backscatter data process in two main parts. The identification of issues in the data (and their eventual removal or mitigation) as a preliminary step to the creation of a mosaic and/or to seafloor characterization. A possible future step is to have the processing information collected together within the resulting mosaic. Following an approach similar to the metadata present in the Open Navigation Surface (BAG) format, a list of the input files (with their cryptographic hashes if file verification is a concern) and the processing corrections applied to each of them could be stored with the mosaic to properly document the steps followed during the creation. This would be a significant step towards the repeatability of product creation. There is currently a lack of open data formats that provides a mechanism to store this kind of information in the file metadata in a ‘standard’ way. The definition of a metadata template is a requirement to make the created products portable across different applications. As such, an initiative similar to the one that created the BAG format might be required.

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