LARGE SCALE SIDE-SCAN SONAR MOSAICS

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Large Scale Mosaics of side scan sonar data are a practical visualisation tool for Rapid Environmental Assessment and Mine Counter Measures. The quality of these is dependant on the quality of the underlying navigation solution. The Ocean Systems Laboratory in Heriot-Watt University has developed a system that can fuse the navigation estimates from a standard navigation suite with observations extracted from the side-scan data. This system works by smoothing the output from a Concurrent Mapping and Localisation (CML) algorithm. The chosen CML algorithm is the stochastic map. The stochastic map is an augmented state Kalman filter that can be easily incorporated into a Rauch-Tung-Striebel smoother. This practical tool provides accurate and smooth navigation solutions that can be used to create Large Scale Mosaics. The Large Scales Mosaics are produced using different resolutions. SeeByte's SeeTrack can be used as a visualisation tool. SeeTrack can then compute which resolution is best for optimal visualisation.

1 Introduction

Rapid Environmental Assessment and Mine Counter Measures have been positively influenced by the introduction of *Autonomous Underwater Vehicles (AUVs)*. These vehicles provide a platform that is able to acquire large volumes of high quality sonar and video data. The *Ocean Systems Laboratory (OSL)* in *Heriot-Watt University (HWU)* and SeeByte Ltd., the spin-out company commercialising OSL research, have a long track record working with AUV data products. One of the outcomes of this work is SeeTrack [1], initially developed in the OSL and now commercialised by SeeByte Ltd. SeeTrack offers a user friendly *Geographic Information System (GIS)* that enables the visualisation and processing of the AUV data products. This tool allows the operator to superimpose different layers of geo-referenced data.

Until recently side-scan data has been geo-referenced to create mosaics. These would then be displayed as layers in SeeTrack or other GIS. With this strategy errors in the navigation solution produce discrepancies between mosaics created from different data sets. Certain objects can appear in different positions, although they have not moved. When producing *Large Scale Mosaics (LSMs)* the information corresponding to the same world region needs to be properly registered. The OSL has understood this challenge and produced a system that uses the side-scan data to aid the registration process. This system is a stochastic map [2] that can incorporate measurements from the side-scan sonar data. The stochastic map is nothing more then an augmented state Kalman filter, where the new states represent observable landmarks in the workspace. In this case the landmarks are extracted from the side-scan data. This system has already been successfully implemented to create high quality visual mosaics [3]. This work showed how the stochastic map can be adapted to implement a Rauch-Tung-Striebel Fixed-Interval smoother to further improve the accuracy of the navigation solution.

This paper shows how the new system has been extended to create LSMs. Section 2 examines the CML architecture, the RTS smoother and how these can be used to produce high quality LSMs. The mosaics are visualised in SeeTrack, this tool is re-examined in section 3. Section 4 illustrates results obtained with data products obtained during the BP'02 experiment organised by the SACLANT Undersea Research Centre. The final section summarises the contributions of the paper and details some of the work that is now been carried out by the OSL in HWU to further improve the system.

2 Concurrent Mapping & Localisation Using Side-scan Sonar

This section examines the process implemented by the OSL to produce high quality LSMs using side-scan navigation data. A simple diagram of the system can be seen in figure 1. The system takes the AUV navigation data and landmarks, manually extracted from the side-scan images, and uses them to produce a new navigation solution using the stochastic map architecture. This new solution is further improved by implementing a RTS smoother. The OSL has produced a version of the RTS filter capable of accepting the CML output. The new navigation solution is then used to geo-reference the side-scan data and create LSMs. The LSMs can then be displayed by SeeTrack as a new layer.

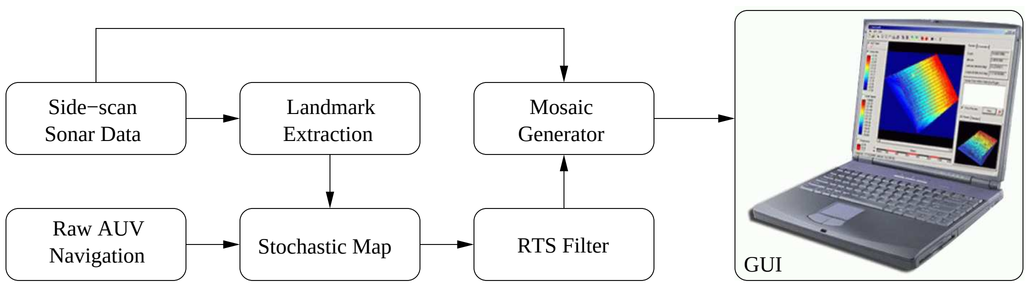

Figure 1. Overview of the System

The system was develop as a desire to extend the CML capabilities of the OSL from forward-looking sonar [4] to also include side-scan sonar. The CML architecture developed was based on the stochastic map and it was largely unchanged. It is examined in the next section.

The RTS smoother has been found to produce smoother and more accurate estimates and it's briefly examined in section 2.3.

The process by which the LSMs are generated is explored in section 2.4.

2.1 The Stochastic Map

The stochastic map [2] is an EKF [5,6] with extra states. These new states estimate the positions of landmarks in the world. This method allows to estimate and maintain the vehicle-to-vehicle, landmark-to-vehicle and landmark-to-landmark correlations. It is a mature technique with well documented advantages [7]. This section summarises the key differences between the stochastic map and the EKF. For a more detailed description of the OSL implementation the interested reader should consult [3].

The state vector of the stochastic map looks like this:

$$\mathbf{x}(k) = \left[\mathbf{x_v}(k)\ \mathbf{x_1}(k)\ \mathbf{x_2}(k)\ \ldots\ \mathbf{x_n}(k)\right]^T \tag{1}$$

where $\mathbf{x_v}(k)$ is the vehicle state vector and $\mathbf{x_i}(k)$ are the landmark vectors for each landmark i. The associated covariance holds the vehicle and landmarks covariances and correlation terms.

The stochastic map's prediction and correction equations are exactly the same to those of an EKF, the interested reader should refer to [5,6] for these.

The difference is that when a new landmark is observed it is placed in the world given the vehicle's own estimate of its position and an observation model. The new state estimate is appended to the state vector of the stochastic map. The covariance and correlation terms for the new landmark can be found from,

$$\begin{aligned}\mathbf{P_{n+1\,n+1}}(k) &= \mathbf{L_{x_v}}\mathbf{P_{v\,v}}(k){\mathbf{L_{x_v}}}^T + \mathbf{L_{z_{new}}}\mathbf{R}(k){\mathbf{L_{z_{new}}}}^T \\ \mathbf{P_{n+1\,v}}(k) &= {\mathbf{P_{v\,n+1}}}^T(k) = \mathbf{L_{x_v}}\mathbf{P_{v\,v}}(k)\end{aligned} \tag{2}$$

where $\mathbf{P_{v\,v}}(k)$ is the vehicle state covariance, $\mathbf{P_{n+1\,n+1}}(k)$ is the covariance of the new landmark and $\mathbf{P_{n+1\,v}}(k)$ is the correlation term between the landmark and the vehicle. Also, $\mathbf{L_v}(k)$ and $\mathbf{L_z}(k)$ are the Jacobians of the function that estimates the landmark's position in the world with respect to the robot vehicle state $\hat{\mathbf{x}}_\mathbf{v}$, evaluated at $\hat{\mathbf{x}}_\mathbf{v}(k)$, and to the new observation $\mathbf{z_{new}}$, evaluated at $\mathbf{z_{new}}$ and $\mathbf{R}(k)$ is the measurement error covariance.

2.2 Extracting Landmarks from the Side-scan Data

The landmark extraction and data association process chosen for this implementation must be manually done by an operator. The operator is required to pin-point landmarks in the sonar data, see figure 2, and match them to landmarks that have been previously extracted. The state vector and covariance of the stochastic map will be augmented to accommodate each new observed landmark. If stored landmarks are re-observed the stochastic map will be corrected.

2.3 The Rauch-Tung-Striebel Filter

The output from the stochastic map produces an optimal estimate of the the vehicle trajectory given all the observations from time 0 to time t. This trajectory is not best suited to produce side-scan sonar mosaics. Each landmark observation or acoustic baseline update

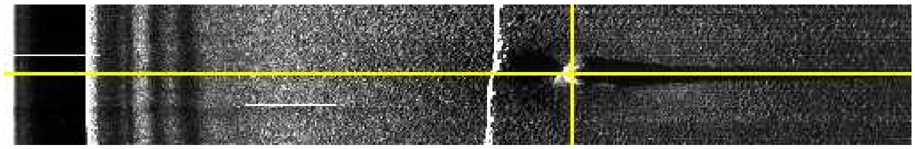

Figure 2. Manual Extraction of Landmarks

produces a *jerk* in the trajectory. A smoother on the other hand is a non-real-data processing tool that also uses the measurements from time t to time T, where $0 \leq t \leq T$. The outcome of a smoother is a more accurate trajectory with no apparent jerks. A smoother that takes all Kalman filter predictions and corrections to produce the smoothed signal is the *Rauch-Tung-Striebel (RTS)* filter [8]. The OSL has shown that the RTS can be readily adapted to handle the stochastic map output [3]. The output from the combined CML-RTS solution can be used to produce high quality mosaics.

2.4 Generating Mosaics

The process by which the mosaics are generated is simple. The data is slant-range corrected and compensated for the AUV pitch and yaw. The sonar beams are assumed to be straight lines (for simple and fast processing). The world is divided into cells of a predefined resolution. The highest resolution is a function of the sonar's range resolution. For each range sample in a sonar beam the algorithm finds its appropriate position in the world grid. Cells in the world with more than one observation assigned to them will average the returns. This can result in the loss of information if the navigation of the vehicle is poor.

The LSMs thus require that the navigation solution be as accurate as it is feasibly possible. The results shown in section 4 show that the proposed CML-RTS solution can offer that accuracy.

The algorithm generates overlapping regular sized mosaics that cover the whole area covered by an AUV mission. These mosaics are produced at different resolutions from the highest resolution, normally tens of centimetres, to the lowest resolution, set generally at one meter.

3 SeeTrack

SeeTrack is a post processing tool for rapid on-site data reduction, analysis and data fusion of sensor data, including sidescan, forward look sonar, imaging sonar and video. SeeTrack's data products can be directly exported to a larger 4D Cube database. The 4D Cube concept can be thought of as a database that stores and displays geo-referenced data in a common world frame (WGS-84) and time frame (UTC). The 4D Cube will display all raw and processed data products and also outputs from complex models. SeeTrack can be described as the *AUV's 4D Cube*. AUV operators can use SeeTrack on the ground to quickly visualise and analyse the AUV's payload data.

It is a highly modular system and it is designed to perform on both notebook and desktop environments, see figure 1. It has been successfully employed during 2000 and 2001 in the US Field Battle Experiments, NATO SACLANTCEN GOATS 2000 trials, Kernel Blitz 2001, AUV Fest 2001 and, as reported in this document, NATO SACLANTCEN BP'02.

SeeTrack now also offers the ability to merge multiple geo-referenced images into a single layer. This ability allows for the LSMs to be easily loaded and handled. Each LSM becomes a layer in SeeTrack.

SeeTrack can also load multiple layers for all the different resolutions and optimise the visualisation process by choosing the appropriate resolution and viewable area given the zoom settings.

Alternatively, SeeTrack can also optimally provide multi-resolution browsing capabilities using the MrSID software application from LizardTech, Inc. This solution reduces the storage needs.

4 Results

The following results were obtained by processing the side-scan sonar returns and navigation records gathered by the REMUS vehicle the 21st of May 2002 during the BP'02 experiments. These show the qualitative significance of the LSMs obtained when using the CML-RTS strategy to improve the navigation solution. The system's accuracy and other quantitative properties have been demonstrated elsewhere [3].

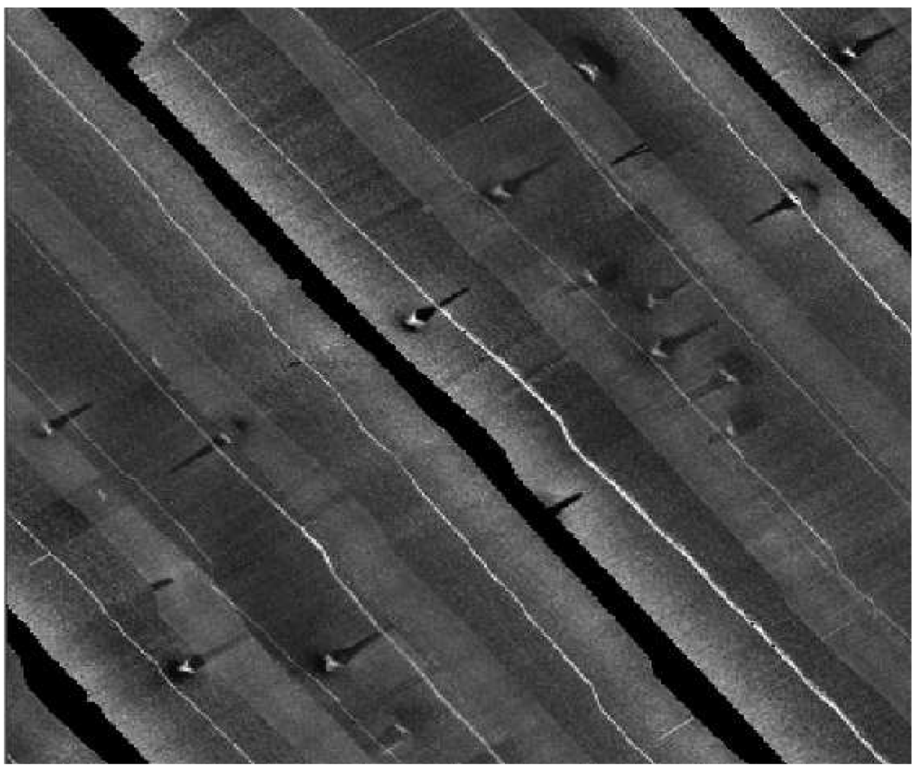

Figure 3. Unprocessed vehicle navigation: The resulting mosaic displays more objects than there really are in the scene.

The vehicle mission ran a lanwmower pattern over an area of approximately 1150 metres in length and 575 metres wide. The data was used to produce a large scale mosaic.

Initial results used the output from the vehicle's navigation computer. These results showed discrepancies when geo-referencing superimposed legs, see figures 3 and 4. Figure 3 shows a region with multiple man-made objects. These are not properly co-registered and appear multiple times in the same region of the LSM. Figure 4 shows the boundary between two different types of sea bed. This boundary is not a smooth boundary as would normally be expected.

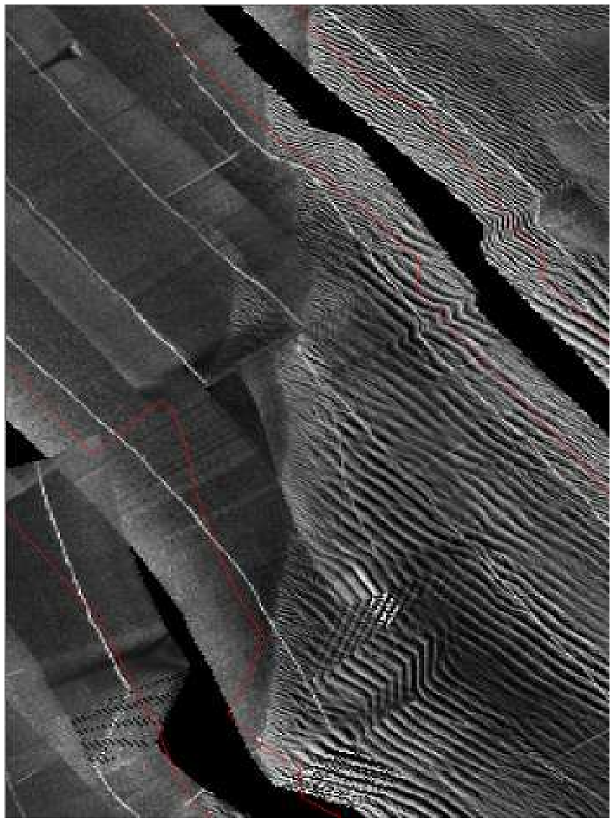

Figure 4. Unprocessed vehicle navigation: The border between different sea bed types is not continuous.

These results can be directly compared to results obtained using the CML-RTS solution. Figures 5 and 6 zoom into the same regions as the previous two figures, but this time the CML-RTS LSM is used. Figure 5 now clearly shows that the multiple objects have been properly co-registered. Some of these can be seen to have two clear shadows.

The final result shown in figure 7 shows the LSM, obtained using the CML-RTS solution, displayed in SeeTrack as a single layer.

5 Conclusions

This paper shows a system that processes side-scan sonar returns and navigation data to create LSM. The system uses a CML-RTS technique. The operator is able to extract land-

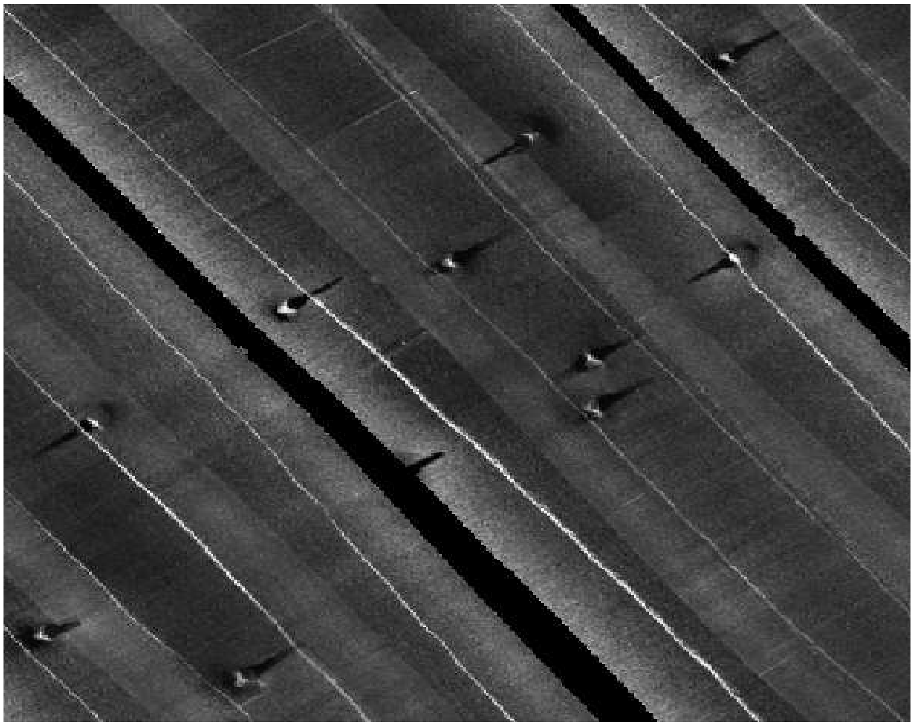

Figure 5. CML-RTS vehicle navigation: The resulting mosaic displays the right number of objects that appear in the scene.

marks from the side-scan sonar data and match them to aid the mosaic creation process. The resulting LSM can be viewed in SeeTrack as a single layer. SeeTrack can be used to efficiently load the viewable data and it chooses the best resolution.

The OSL has recently extended the system presented in this paper to provide automatic landmark extraction and data association facilities [9]. This work builds on the OSL's broad experience in Computer Aided Detection and Computer Aided Classification [10, 11] and landmark feature descriptors and data association algorithms [4, 12].

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References

1. Y. Petillot, K. Lebart, A. Cormack, and D. M. Lane. SeeTrack, a system for post mission analysis of AUV data products. In E. Bovio, R. Tyce, and H. Schmidt, editors, *GOATS 2000 Conference. SACLANTCEN CP-46*, pages 159–167, La Spezia, Italy, August 2001.
2. R. Smith, M. Self, and P. Cheeseman. Estimating uncertain spatial relationships in robotics. In I. Cox and G. Wilfong, editors, *Autonomous Robot Vehicles*. Springer-Verlag, 1990.

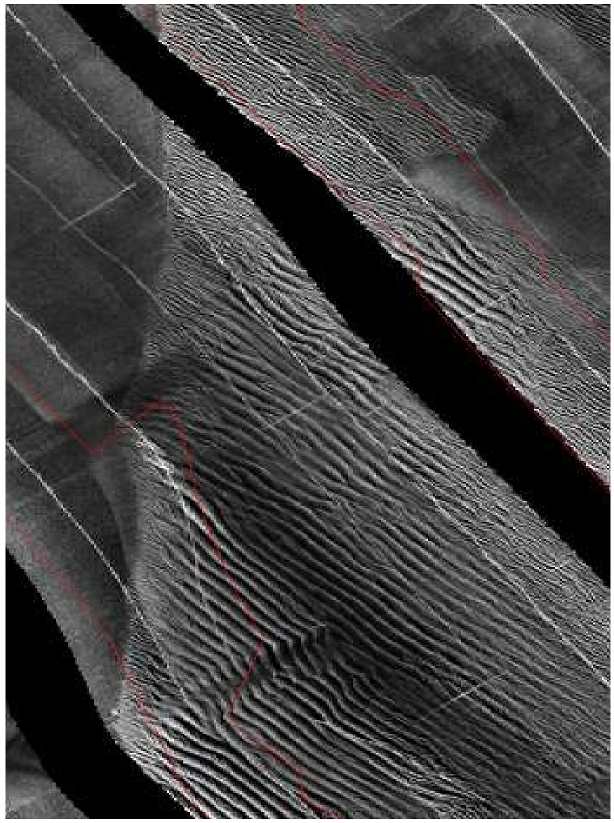

Figure 6. CML-RTS vehicle navigation: The border between different sea bed types is now continuous.

3. I. Tena Ruiz, S. de Racourt, Y. Petillot, and D. M. Lane. Concurrent mapping & localisation using side-scan sonar. *Submitted to the Journal of Oceanic Engineering*, January 2003.
4. I. Tena Ruiz. *Enhanced Concurrent Mapping and Localisation Using Forward-Looking Sonar*. PhD thesis, Heriot-Watt University, Edinburgh, Scotland, September 2001.
5. P. S. Maybeck. *Stochaistic models, estimation, and control. Volume 2*, volume 141 of *Mathematics in Science and Engineering*. Academic Press, 1982.
6. Y. Bar-Shalom and T. E. Fortmann. *Tracking and Data Association*, volume 179 of *Mathematics in Science and Engineering*. Academic Press, 1988.
7. M. W. M. G. Dissanayake, H.F. Durrant-Whyte, S. Clark, and M. Csorba. A solution to the simultaneous localisation and map building (SLAM) problem. Technical Report ACFR-TR-01-99, the University of Sydney, Sydney, Australia, January 1999.
8. A. Gelb, editor. *Applied Optimal Estimation*. The M.I.T. Press, Cambridge, MA, USA, 1974.
9. I. Tena Ruiz, S. Reed, Y. Petillot, J. Bell, and D. M. Lane. Concurrent mapping & localisation using side-scan sonar for autonomous navigation. In *Upcoming 13th International Symposium on Unmanned Untethered Submersible Technology*, New Hampshire, USA, August 2003.
10. I. Tena Ruiz, D. M. Lane, and M. J. Chantler. A comparison of inter-frame feature measures for robust classification in sector scan sonar image sequences. *IEEE Journal of Oceanic Engineering*, 24(4):458–469, 1999.

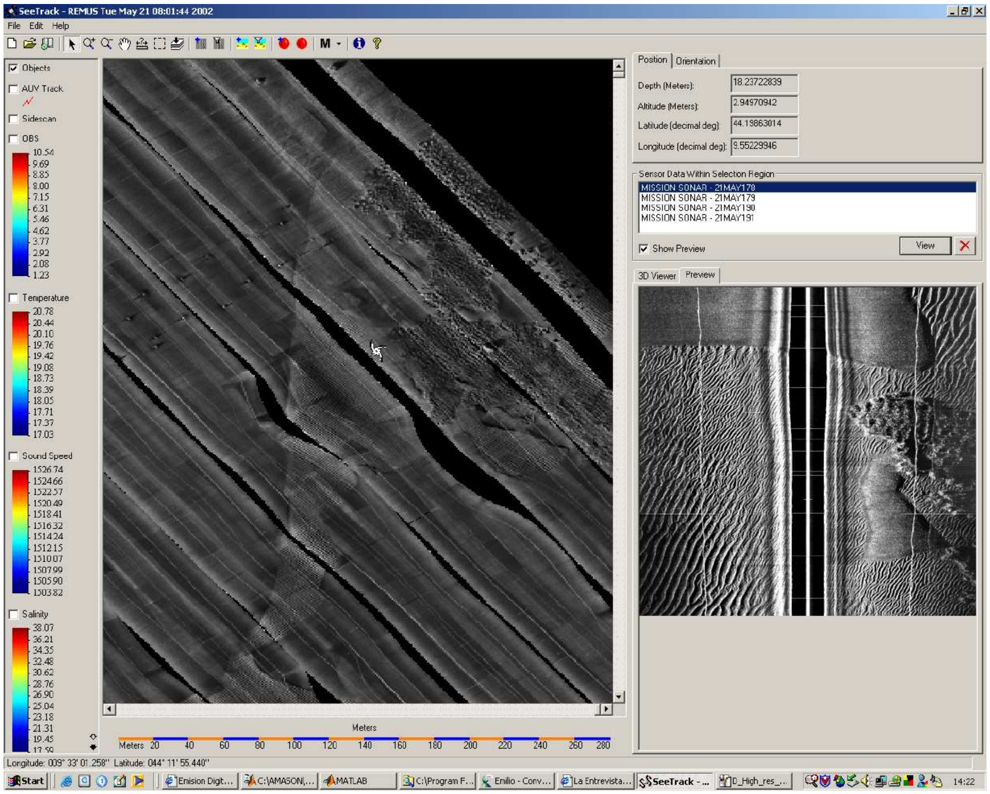

Figure 7. LSM in SeeTrack

11. S. Reed, Y. Petillot, and J. Bell. An automatic approach to the detection and extraction of mine feautures in sidescan sonar. *IEEE Journal Oceanic Engineering*, 28(1), January 2003.

12. I. Tena Ruiz, Y. Petillot, D. M. Lane, and C. Salson. Feature extraction and data association for AUV concurent mapping and localisation. In *Proc. IEEE Internationnal Conference on Robotics and Automation (ICRA'01)*, pages 2785–2790, Seoul, Korea, May 2001.