SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Reprint Series **CMRE-PR-2019-017**

On-board real-time assessment of acoustic environmental parameters relevant to the estimation of sonar performance for autonomous underwater vehicles

Kevin D. LePage, Manlio Oddone, Michele Micheli,
Christopher Strode, Alessandra Tesei

May 2019

Originally presented at:

2018 OCEANS – MTS/IEEE Kobe Techno-Ocean (OTO)
doi: 10.1109/OCEANSKOBE.2018.8559267

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

On-board real-time assessment of acoustic environmental parameters relevant to the estimation of sonar performance for autonomous underwater vehicles

Kevin D. LePage
Research Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
kevin.lepage@cmre.nato.int

Manlio Oddone
Research Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
manlio.oddone@cmre.nato.int

Michele Micheli
Engineering Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
michele.micheli@cmre.nato.int

Christopher Strode
Research Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
christopher.strode@cmre.nato.int

Manlio Oddone
Research Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
manlio.oddone@cmre.nato.int

Michele Micheli
Engineering Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
michele.micheli@cmre.nato.int

Alessandra Tesei
Research Department
NATO Centre for Maritime Research and Experimentation
La Spezia, Italy
alessandra.tesei@cmre.nato.int

***Abstract*—CMRE is evaluating the use of autonomous robots for the detection and tracking of underwater targets. Robotic detection and localization comes with many challenges, not the least of which is the requirement to maximize the probability of detection of targets while minimizing the rate of false alarm. In order to do this, underwater robots performing detection and localization will require some form of on board decision engine to guide their trajectories while performing their missions. Many of the autonomy frameworks for determining these trajectories being developed at CMRE are based on a comprehensive model for multistatic active performance called the Multi-Static Tactical Planning Aid, which predicts how the probability of detection of underwater targets varies in complex environments with range dependent sound speed profile and bathymetry. However, there are residual parameters of the model, such as bottom scattering strength and bottom loss, which must be tuned in order for MSTPA to provide predictions which are in accordance with the actual sonar performance being observed by the robot. In response to this need, a client-server version of MSTPA, MSTPA Lite, has been streamlined for application of embedded processors on the robots, and additional data products for the comparison of MSTPA Lite with observations have been added to the on-board real-time signal processing. With these modifications it is now possible for the robots to update the MSTPA Lite model in-mission to provide better agreement between predictions and observations, therefor informing on-board autonomy algorithms with better information on which to base helm decisions. Results are shown for data collected near La Spezia Italy in October 2017.**

Keywords*—autonomous underwater vehicle, AUV, autonomy, rapid environmental assessment, REA, multistatic tactical planning aid, MSTPA, MSTPA Lite rapid acoustic prediction service, RAPS, environmental services, active sonar, bistatic sonar, towed array, TAS, variable depth sonar, VDS, thin client, micro services, web-based architecture, embedded signal processing

I. INTRODUCTION

Autonomous robots may offer advantages for performing tasks in underwater detection and localization missions. One concept of operations being explored at the NATO Centre for Maritime Research and Experimentation is a network composed of one or more ships with active sonar sources working together with Autonomous Underwater Vehicles (AUVs) acting as receivers. From an sonar environmental assessment standpoint bi- or multi-static networks of this type offer the advantage that many of the environmental parameters controlling active sonar performance are readily measured in real-time on board the AUVs, including the scattering strength of the bottom and surface, the reflection loss of the bottom and surface, and the (possibly anisotropic) noise distribution.

In this paper we discuss recent work at CMRE where the standalone Multi-Static Tactical Planning Aid (MSTPA) performance prediction tool developed for desktop computers [1] has 1) been federated and reconfigured into a client-server architecture called MSTPA Lite, and 2) streamlined for implementation onto embedded processors on board the Centre's AUVs. We also discuss the enhancement of the Centre's real-time embedded signal processing algorithm [2], to deliver enhanced real-time products relevant to the estimation of active environmental, such as reverberation maps and direct blast and noise level estimates.

With the relevant environmental acoustic measurements available on the vehicle, and with the embedded real-time performance prediction tool providing estimates of direct blast levels and reverberation, it is possible to compare the observations with predictions with an eye towards tuning the free parameters. Being implemented in the MOOS robotic middleware, the continuously changing experimental geometry is automatically taken into account, with the AUV position and depths being provided by on-board sensors while the source parameters are provided by the source ship to the AUV via underwater communications.

Results are shown for the estimation of parameters controlling transmission loss and bottom scattering strength for several diverse environments, showing the strong intra and inter-site variability that has been encountered during deployments of CMRE's unmanned multistatic active network.

II. ARCHITECTURE OF ENVIRONMENTAL SERVICES

A. Modification of CASCAINPro to provide environmental acoustic measurements

CASCAINPro is the real-time embedded signal processor that performs beamforming and matched filtering on the data collected by the arrays towed by CMRE's AUVs. As outlined in [1], CASCainPro has been modified to provide R/T data products to aid in environmental characterization.

1) Reverberation Level map

Figure 1 shows schematically how CASCainPro generates a georeferenced reverberation+noise map. The matched filtered beam-time series shown in the upper left panel of both figures is mapped to the local Latitude-Longitude grid via a bistatic mapping. For arrays without left/right ambiguity rejection, the reverberation is mapped onto both sides of the array axis.

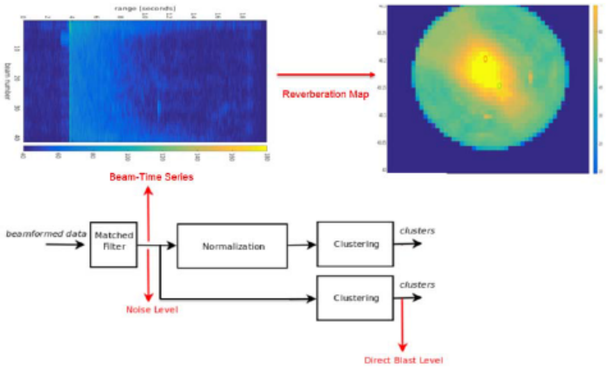

Fig. 1. Real-time processing for acoustic feature extraction showing the mapped reverberation+noise level (upper right).

2) Signal Level extraction

The signal or direct blast level is also extracted after the contact formation and clustering processes. The highest level contact generated by this process is invariably the direct blast (unless the wrong signal processing parameters are used for the matched filter). The level of this contact constitutes the one-way signal level from the source to the bistatic receiver, either deployed from the NRV Alliance or from one of the AUVs. For the bistatic AUV receivers, the direct blast level contains critical information about the source level of the source and the surface and bottom loss, depending on the sound speed profile.

For instance, for isovelocity waveguides the direct blast level scales as $r^{3/2}$ and is proportional to the square root of the derivative with respect to the grazing angle θ of the log of the bottom + surface loss tangents $\alpha_b+\alpha_s$, while for downward refracting waveguides the direct blast level scales as

$$r^{-1}\int exp(-\alpha\theta r/r_c)d\theta \tag{1}$$

where r_c is the cycle distance $2c\theta/(dc/dz)$ and θ is the grazing angle of the ray in question at the bottom. In future work it is hoped that these differences can be discerned in the log-range plots of the direct blast energy level.

Finally the noise level in the matched filter band is derived by the average power in the noise before the arrival of the direct blast. An example of the direct blast and noise level estimates are shown in Figure 2.

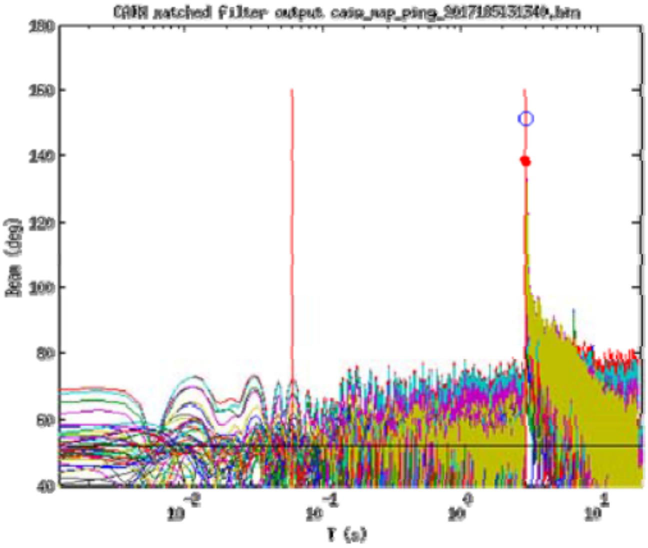

Fig. 2. CASCainPro direct blast and noise level measurements for the AUV Harpo .

B. Method for updating Environmental Model

The individual elements of the sonar equation are delivered to the environmental inversion suite on board the vehicle. These elements include

- *DB* Signal or direct blast level, a function of source level *SL*, the gridded three dimensional sound speed profile, and surface and bottom loss tangents α_s and α_b, all of which are scalars (the surface and bottom loss are currently assumed to be geographically independent)

- RL_b Reverberation level caused by the bottom, a function of *SL*, the gridded 3-D SSP, surface and bottom loss tangents α_s and α_b, and the gridded bottom scattering strength parameter μ(lat, long)
- RL_s Reverberation level caused by the surface, a function of SL, the gridded 3-D SSP, surface and bottom loss tangents α_s and α_b, and the scalar wind speed which determines the surface scattering strength
- *EL* Echo level, a function of the *SL*, the 3-D gridded SSP, the bottom and surface loss tangents and the target scattering strength.

One thread of the environmental inversion process is to compare the range-dependent measured direct blast levels to the predicted levels *DB*, eventually determining the recommended corrections to the source level and the bottom loss tangent. Once determined, these corrections may be used to update the input parameters for *SL* and α_b in MSTPA-Lite. This is done through the pMSTPAIA process. It is anticipated that this will be done only once or twice during the mission, towards the beginning but after the direct blast has been measured over a sufficient diversity of geometries to tease apart the bottom loss tangent correction from the source level correction.

A second thread is to create a clutter map on a grid common to MSTPA Lite and CASCainPro for every ping in order to generate a map of the scattering strength deficit. It is not necessary to update MSTPA Lite with this scattering strength deficit map, since RL_b scales linearly with scattering strength (in power) and so the deficit correction may be applied directly to the MSTPA result. The deficits are stored over all the pings. The reasons for this are 1) that the geometry changes throughout the mission and therefore different parts of the bottom are likely to be measured throughout the mission, and 2) some of the scattering deficits are likely to be strongly influenced by noise from nearby shipping on some beams, while their measurements of the underlying bottom scattering strength may still be useful on other beams. The map of the bottom scattering strength for each grid point will be selected from amongst the lowest valid measurements, under the hypothesis that integrated scattering measurements over the grid computed by CASCainPro are very likely to reveal the underlying reverberation in a few of the cases, and that these will be for noise-free beams and therefore the most valid of the measurements.

To regularize this creation of the scattering strength deficit maps, the noise level will be added to the MSTPA Lite *RL* predictions before dividing into the CASCainPro measurements of the reverberation.

Note that under this approach both RL_s and α_s will be determined a priori from the wind speed using Kirchhoff reflection coefficient for forward scattering and Mackenzie [2] for the sea surface scattering.

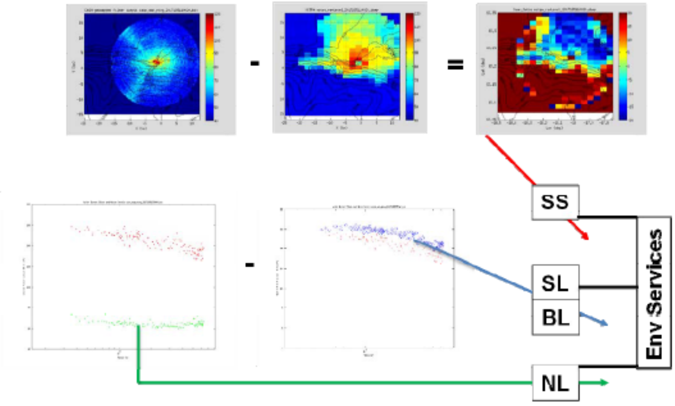

Fig. 3. Block diagram outlining method for Updating Environmental Mode with components of the CAIN signal processing chain.

These two parallel threads are illustrated schematically in Figure 3, where the top row shows the creation of the scattering deficit map, and the bottom row shows the difference between the measured and predicted direct blast levels, and Figure 4, which shows how the median scattering strength deficit is used over time to create noise-free estimates of the reverberation level to inform on board ASW decision support. The left-hand column shows the measured (top) and predicted (bottom) reverberation at the beginning of the process and the right-hand column shows the result after 19 minutes, where a median scattering strength deficit map generated over the last 19 pings is used to make the environmental prediction for the current ping (lower right-hand panel).

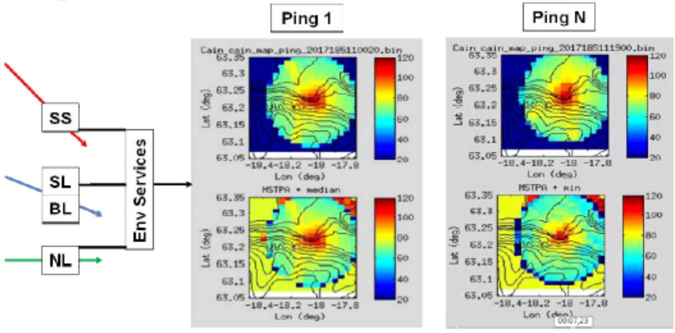

Fig. 4. Results of updating Environmental Model (initial data Top left. Initial forward prediction Bottom Left. Data +19 minutes Top Right. Forward prediction+19 minutes Bottom right).

III. EXAMPLE

A. *Experimental location*

An experiment was conducted in October of 2017 in La Spezia to the southwest of Palmaria Island. The geometry is shown in Figure 5. The area is characterized by bathymetry sloping from the northeast to the southwest at depths between 90 and 140 m until the shelf break which roughly bisected the CMRE-BOX along it minor axis.

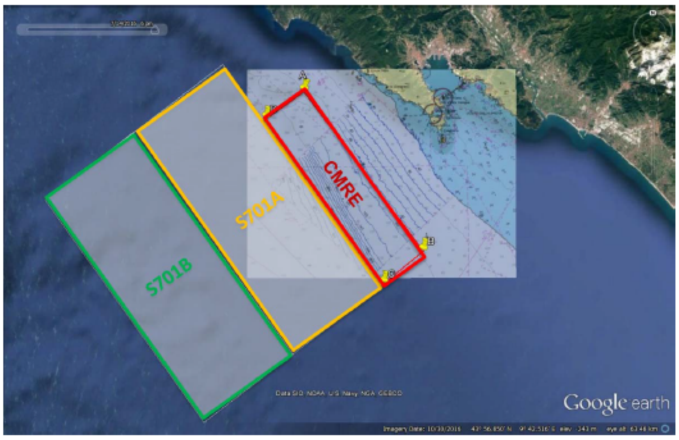

Fig. 5. The experimental area off of La Spezia. CMRE assets were deployed in the red CMRE box.

The sound speed profiles measured in the CMRE box are shown in Figures 6 and 8 showing a convex surface mixed layer sound speed of close to 1527 m/s with a depth of approximately 40 m, followed by a decreasingly sharp gradient in the pycnocline, which overall extended to 80-100 m depth.

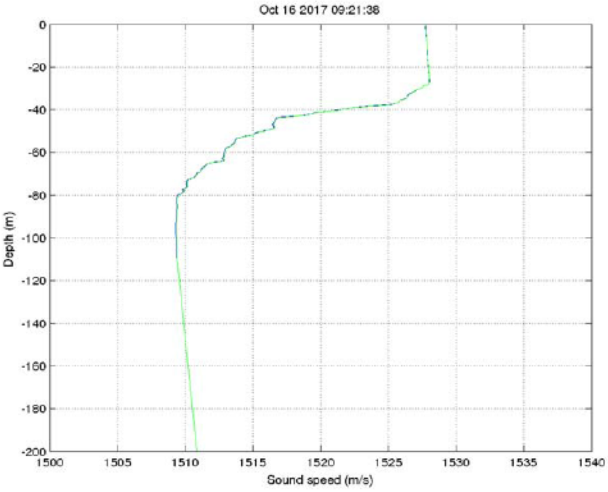

Fig. 6. Measured sound speed profile for La Spezia for 16 October 2017.

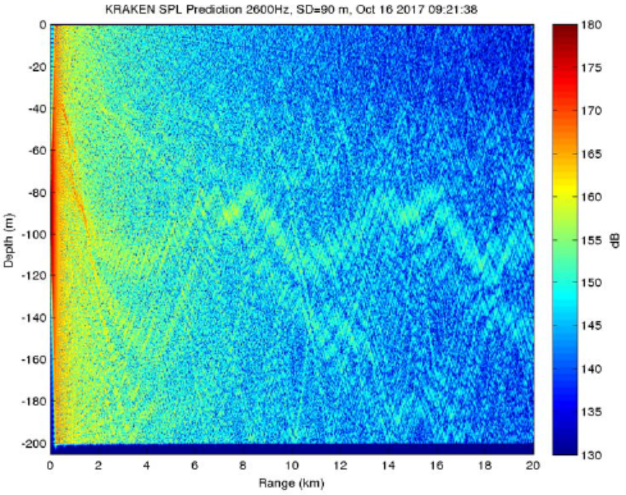

Fig. 7. Transmission loss prediction at 2.6 kHz for SSP measured in La Spezia on the 16th of October 2017. Water depth is assumed to be 200 m deep. The source depth is 90 m.

In this work, the bottom is assumed to be silty sand [3] with a sound speed of 1660 m/s, a density of 1.8 g/cm^3 and a bulk attenuation of 1.1 dB/λ.

Transmission loss estimates for the area were produced to show the effect of the sound speed profile for a deep source depth of 90 m used during the experiment. The results are shown in Figure 7 and 9 and show that very little energy penetrates to the surface for deep source depths beyond ranges of 10-12 km.

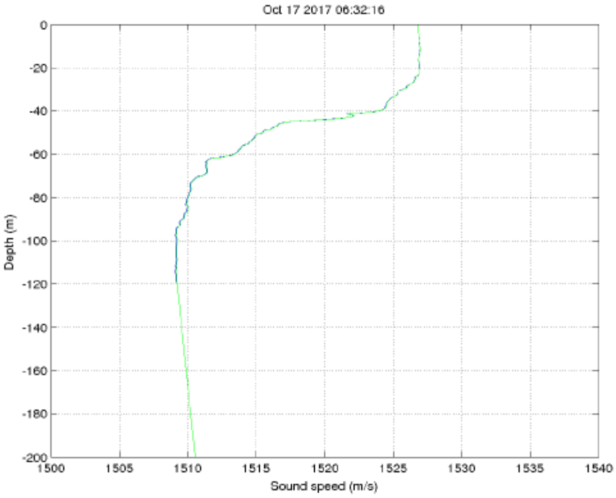

Fig. 8. Measured sound speed profile for La Spezia for 17 October 2017.

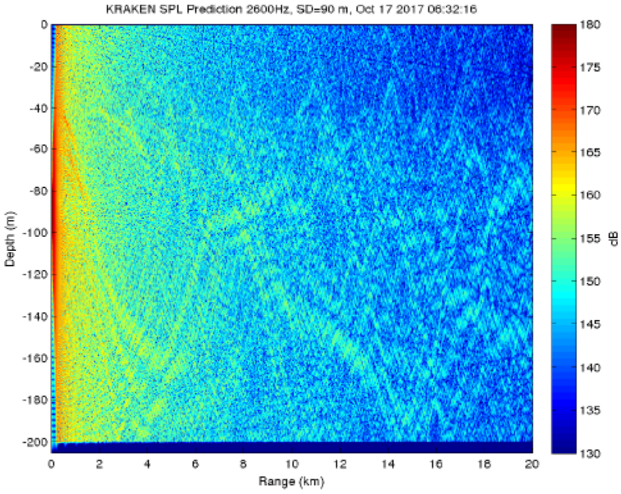

Fig. 9. Transmission loss prediction at 2.6 kHz for SSP measured in La Spezia on the 17th of October 2017. Water depth is assumed to be 200 m with a 90 m source depth.

B. *Environmental service results*

We review environmental service results for the La Spezia site, showing the predicted, measured and corrected direct blast level and the measured in band noise level, the MSTPA Lite prediction for the bottom reverberation, the measured reverberation+noise coming out of CASCainPro, the median bottom scattering strength deficit for the experimental site and the adjusted MSTPA Lite reverberation prediction after applying the scattering strength deficit.

As with the transmission loss predictions shown in Figures 7 and 9, the MSTPA Lite predictions are calculated assuming that the sea surface is flat and that the bottom is silty sand. Thorp seawater attenuation [4] is used. The source level for the predictions is 217 dB re mPa @ 1 m with a signal duration of 1 s, corresponding to the experimental waveform. MSTPA Lite is used with "interference" and "smearing" both ON. The first parameter allows the accurate prediction of convergence zones in deep water and focusing of bottom bounce downward refracted paths in shallow water [5]. The latter parameter accounts for the fact that bottom and surface interacting paths arrive later in a target ensonification, reducing the peak amplitude of the return [6].

In future work we will adjust the bottom parameters, along with surface reflection loss based on observed wind speed, to obtain the best agreement between the modelled and observed direct blast levels. It is probable that even with full system calibration a source level "nuisance" parameter, accounting for system coherence and spreading losses, will still be required.

The resulting scattering strength deficit maps can be thought of as bottom scattering maps. For this site, the scattering strength deficit is slowly varying and may point to a regional variation in bottom properties.

Figures 10 and 11 show the predicted, measured and corrected direct blast levels are shown for experimentation conducted on the 16th of October in La Spezia using AUV Harpo. The data were collected between 1320:20Z and 1531:40Z. Notice that the modelled direct blast levels for a source level of 217 are 28 dB higher than measured by CASCainPro. As mentioned above, the discrepancy is believed to be a result of a lack of full calibration of the transmit system on the NRV Alliance and/or the receiver array and CASCainPro processing on Harpo. As a result of internal discussions, at this time a full calibration is expected to yield approximately 20 dB of additional level to the output of CASCainPro. This being the case, the remaining 8 dB would be additional transmission loss due to bottom loss exceeding the loss provided by the bottom properties used in MSTPA Lite, which are for a fast bottom of silty sand. The bottom in La Spezia is quite a bit softer and lossier. On-board through-the-sensor bottom characterization using MSTPA Lite is an area for future work and will require the invocation of simplified geoacoustic inversion methods.

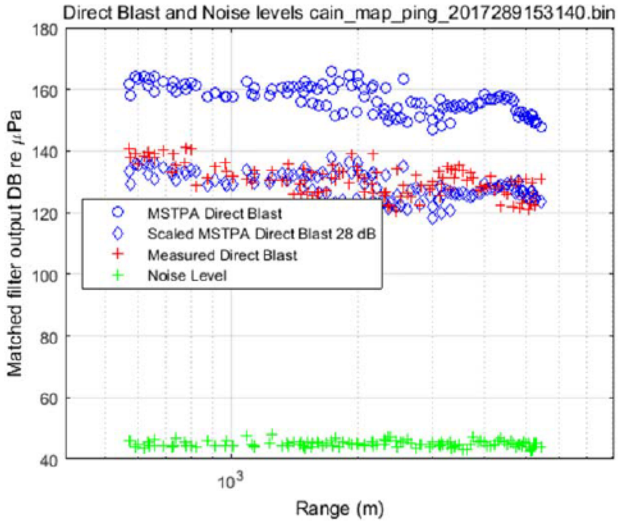

Fig. 10. Predicted vs measured directed blast sound pressure level vs range for 16th of October in La Spezia.

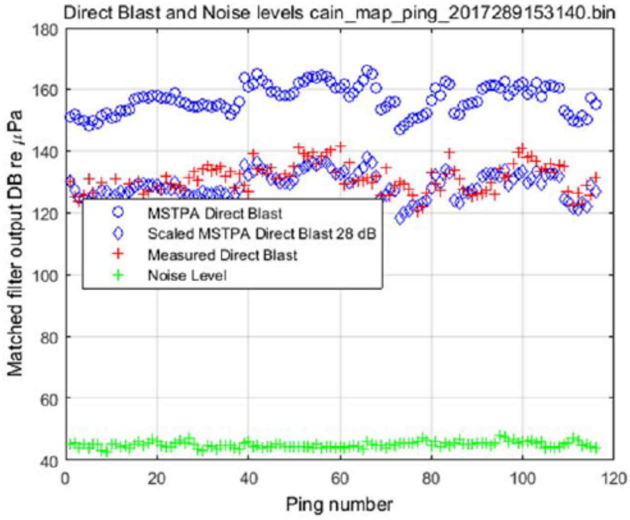

Fig. 11. Predicted vs measured directed blast sound pressure level vs ping for La Spezia.

The bottom scattering map generated by Harpo is shown for the ping at 1531:40Z in Figure 12. Notice that the experimentation occurred at the edge of the shelf break, and that there is an area of higher reverberation to the northwest while offshore to the south west the reverberation is lower.

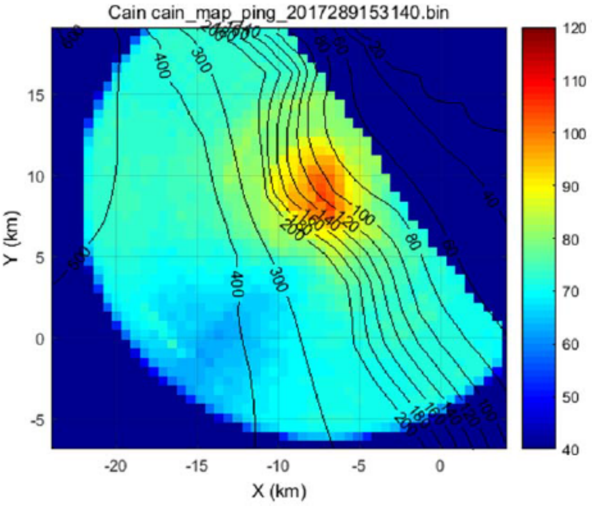

Fig. 12. Measured reverberation at 153140Z on the 16th of Oct 2017.

In Figure 13 the MSTPA Lite reverberation prediction for the La Spezia site is shown for a bottom scattering strength Lambert parameter of -27 dB. Note the rapid drop-off of reverberation to the southwest and a slight increase to the north and northeast (shoreward) due to steepening bottom interacting paths.

Figure 14 shows the median bottom scattering strength parameter deficit built up over 116 pings over the course of 2:10 hours. The deficit map is rather smooth but has an amplitude variation over the operations area of more than 20 dB. The increased scattering under the footprint of the sonar system is one major feature. A second feature is the very low bottom scattering strength off shore, while a slight increase of bottom scattering strength to the north and northeast is also observed.

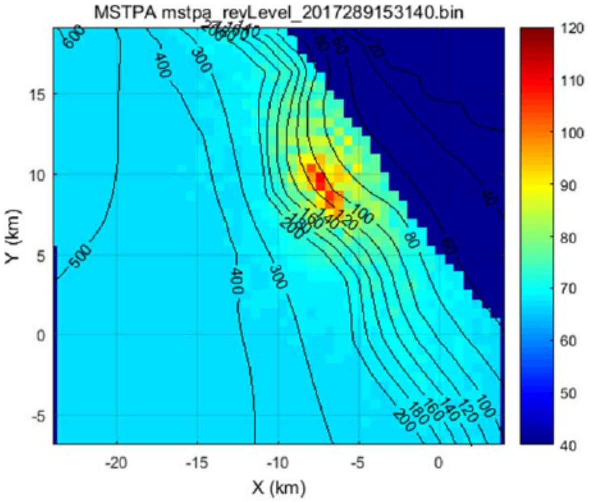

Fig. 13. Reverberation Predicted by MSTPA for La Spezia using the 16th of October SSP in Figure 28.

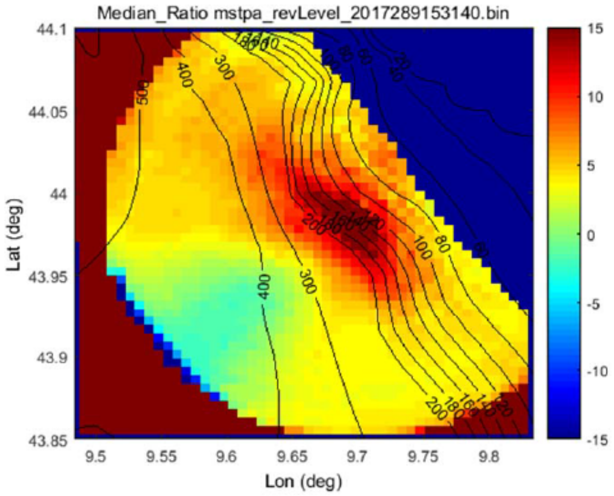

Fig. 14. Median scattering strength (SS) deficit for La Spezia built over 116 pings on the 16th of October between 1320:20Z and 1531:40Z.

The corrected MSTPA Lite prediction for the reverberation level is shown in Figure 15. Comparison with CASCainPro result in Figure 12 shows that many of the features of the observed scattering map for the area are predicted by MSTPA Lite when corrected by the median bottom scattering deficit shown in Figure 50. Note that the target feature in the CASCainPro result at long range to the southwest, likely associated with cross talk with other sonars in the area is, however, absent from the prediction. Since sonar cross talk is not part of the environmental assessment, it removal from the regional prediction is a positive result.

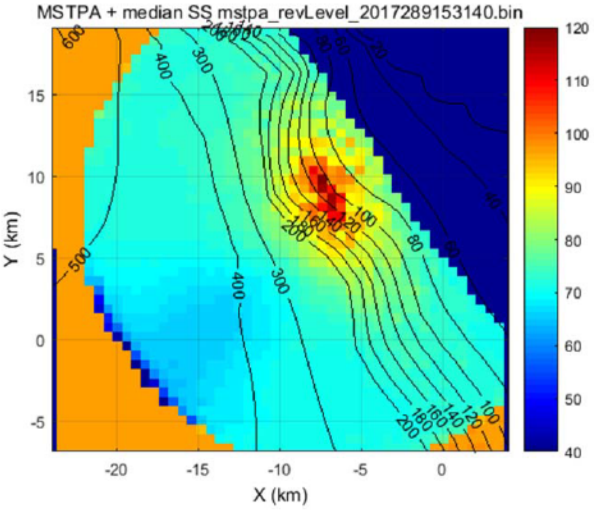

Fig. 15. MSTPA reverberation prediction for La Spezia waters on the 16th of October 2017 as corrected by median SS estimate.

IV. SUMMARY

In this paper we have reported on the first results obtained by embedding the Multistatic Tactical Prediction Aid onto unmanned vehicles. The MSTPA Lite version of the tool, based on the recently developed Rapid Acoustic Prediction Service (RAPS) architecture, allows the tool to be run in real time on CMRE's Ocean Explorer embedded systems. In addition, the CASCainPro real-time signal processing software, developed to beamform and match filter acoustic time series collected on the BENS and BENS Triplet arrays towed by the OEX AUVs, has been modified to generate clutter maps and direct blast and ambient noise estimates which can be compared to the output of MSTPA Lite for the purpose of updating the environmental parameters used for on board performance prediction.

Results have been shown comparing MSTPA Lite to CASCainPro clutter map generated for an experimental site in La Spezia Italy, showing the utility of the method of developing an updated environmental model for injection into MSTPA Lite to better predict the reverberation and direct blast levels, and by extension the sonar performance in the area.

Scattering deficit maps have been created for these different environments, shown the utility of the method of developing an updated environmental model for injection into MSTPA Lite to better predict the reverberation and direct blast levels, and by extension the sonar performance in areas of operations.

V. CONCLUSIONS

The ability of unmanned systems to learn about their environments through their sensors is fundamental for enabling environmentally adaptive machine decision. For the underwater detection and localization problem, unmanned underwater vehicles fielded by CMRE are now being provided with an embedded on-board environmental decision aid capable of running in real time. This decision aid, known as the Multistatic Tactical Planning Aid – Light version (MSTPA

Lite) and based on the Rapid Acoustic Prediction Service (RAPS) federated service orient architecture, is very light on overhead, scales linearly across available computational resources (CPUs/cores), and is capable of accepting as input environmental parameters such as bottom and surface loss and scattering strength, bathymetry, sound speed profiles, and ambient noise levels. Due to its seamless interface with the Mission Oriented Operating Suite-Interval Programming (MOOS-IvP) robotics middleware and autonomy framework running on board the vehicles [7], MSTPA Lite also has real time access to all of the navigational, depth and kinematic information necessary as inputs to MSTPA Lite.

In this paper we have demonstrated how many of the environmental parameters required by MSTPA Lite can be determined by processing sensor data. The Centre's real time embedded signal processing algorithm, Continuous Active Sonar – Cooperative integrated – Processor (CASCainPro) has been modified to provide environmental characterizations of ambient noise level and clutter maps as well as direct blast SEL estimates for comparison with MSTPA Lite predictions. Differences between the predicted and observed direct blast levels and reverberation maps can be used to derive scattering strength deficit maps which can be applied directly to MSTPA Lite reverberation predictions to provide reverberation and signal excess estimates in better agreement with observations.

The difference in the predicted and observed direct blast levels can be used to infer bottom properties affecting forward reflection loss, as well as determining the calibration of the entire signal production, reception and processing chain implemented on board the NRV Alliance and the Ocean EXplorer AUVs, while the scattering deficit map provides the basis for the real-time on board prediction of sonar performance to inform machine decisions over future courses of action and depths for prosecuting submarine targets

ACKNOWLEDGMENT

This work was funded by NATO Allied Command Transformation Capability Development Division, Future Solutions Branch under their "Autonomous Security Networks" Programme of Work.

REFERENCES

[1] C. Strode and M. Oddone, "Operational analysis for autonomous ASW", CMRE FR-2017-09, NATO RESTRICTED.

[2] M. Mackenzie, "Long-range shallow water bottom reverberation," J. Acoust. Soc. Am., vol. 34, no. 1, pp. 62-66, 1962.

[3] E. L. Hamilton, "Sound velocity-density relations in sea-floor sediments and rocks," J. Acoust. Soc. Am., vol. 63, no. 2, pp. 366-377, 1978.

[4] W. H. Thorp, "Analytic description of the low frequency attenuation coefficient," J. Acoust. Soc. Am., vol. 42, no. 1, p. 270, 1967.

[5] C. H. Harrison, "Ray convergence in a flux-like propagation formulation," J. Acoust. Soc. Am., vol. 133, no. 6, pp. 3777-3789, 2013.

[6] C. H. Harrison and M. A. Ainslie, "Fixed time versus fixed range reverberation calculation:," J. Acoust. Soc. Am., vol. 128, no. 1, pp. 28-38, 2010.

[7] M. R. Benjamin, H. Schmidt, P. M. Newman and J. J. Leonard, "Nested autonomy for unmanned marine vehicles with MOOS-IvP," J. Field Robot., vol. 27, no. 6, pp. 834-875, 2010.

Document Data Sheet

Security Classification		Project No.
Document Serial No. CMRE-PR-2019-017	**Date of Issue** May 2019	**Total Pages** 7 pp.

Author(s)

Kevin D. LePage, Manlio Oddone, Michele Micheli, Christopher Strode, Alessandra Tesei

Title

On-board real-time assessment of acoustic environmental parameters relevant to the estimation of sonar performance for autonomous underwater vehicles

Abstract

CMRE is evaluating the use of autonomous robots for the detection and tracking of underwater targets. Robotic detection and localization comes with many challenges, not the least of which is the requirement to maximize the probability of detection of targets while minimizing the rate of false alarm. In order to do this, underwater robots performing detection and localization will require some form of on board decision engine to guide their trajectories while performing their missions. Many of the autonomy frameworks for determining these trajectories being developed at CMRE are based on a comprehensive model for multistatic active performance called the Multi-Static Tactical Planning Aid, which predicts how the probability of detection of underwater targets varies in complex environments with range dependent sound speed profile and bathymetry. However, there are residual parameters of the model, such as bottom scattering strength and bottom loss, which must be tuned in order for MSTPA to provide predictions which are in accordance with the actual sonar performance being observed by the robot. In response to this need, a client-server version of MSTPA, MSTPA Lite, has been streamlined for application of embedded processors on the robots, and additional data products for the comparison of MSTPA Lite with observations have been added to the on-board real-time signal processing. With these modifications it is now possible for the robots to update the MSTPA Lite model in-mission to provide better agreement between predictions and observations, therefor informing onboard autonomy algorithms with better information on which to base helm decisions. Results are shown for data collected near La Spezia Italy in October 2017.

Keywords

Autonomous underwater vehicle, AUV, autonomy, rapid environmental assessment, REA, multistatic tactical planning aid, MSTPA, MSTPA Lite rapid acoustic prediction service, RAPS, environmental services, active sonar, bistatic sonar, towed array, TAS, variable depth sonar, VDS, thin client, micro services, web-based architecture, embedded signal processing

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int