Bathymetry estimation in littoral areas by fusing multi-spectral satellite data and depth samples from AUVs

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Introduction

Battlespace Preparation (BP) is a priority NATO requirement. Its focus is on synthesizing a 4-D picture of the Battlespace by combining remote sensing and *in-situ* samples with numerical models to provide GEOMETOC data at the locations, times and scales needed to support. Challenging tasks include shallow water bathymetry estimation at high resolution in denied areas [1], needed by forecast models of the surf area in support of amphibious landing operations.

The problem is approached by fusing high resolution multi-spectral and multi-sensor satellite imagery in the visible [2] through regression algorithms trained by using depth *in situ* measurements collected by autonomous underwater vehicles (AUVs). The main goals of this study are:

- Evaluating algorithms which use top of the atmosphere (TOA) data in high visibility conditions
- Provide estimation of depth uncertainty

A data set collected near the coasts along the southern Tyrrhenian Sea during the NURC BP07 experiment has been used to test and validate the proposed methodology.

Methods

Bathymetry is estimated by fusing TOA radiances from simultaneous acquisitions of multi-sensor, multi-spectral data. The processing system **(fig. 1)** includes image co-registration, land masking, enhancement and fusion of the spectral TOA radiances.

The inversion algorithm $f(\underline{x},\underline{\theta})$ **(fig. 2)** has a parameter vector $\underline{\theta}$ that is estimated through a suitable training algorithm. A multi-linear regression (MLR) and a radial basis function neural network (RBF-NN) [3] [4] are considered for comparison.

Co-located depth samples from AUVs and satellite radiances are used to estimate the coefficients of the MLR through least-squares and the RBF-NN parameters through a procedure based on forward selection. Samples from an independent hydrographic survey are used as testing set for assessing the generalisation performance of both.

The enhancement step may include a selection algorithm to choose the most informative sensor channels.

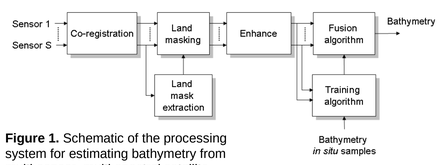
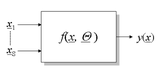


Figure 1. Schematic of the processing system for estimating bathymetry from multi-sensor, multi-spectral satellite imagery.



$$\underline{x} = \left[\underline{x}_1^T, \ldots, \underline{x}_S^T\right] \qquad \underline{x}_k = \left[x_{1,k}, \ldots x_{N_k,k}\right]^T$$

k sensor number
S total number of sensors
N_k number of spectral bands sensor k
$x_{\ell,k}$ spectral TOA reflectance of sensor k in band ℓ ($\log_{10}$ of)
y depth ($\log_{10}$ of)
$\underline{\theta}$ algorithm parameter vector

Figure 2. The fusion scheme provides depth estimates from the enhanced TOA radiances. MLR and RBF-NN algorithms are considered for comparison.

BP07 experiment

The MREA/BP'07 sea-trial is a multidisciplinary experimental effort to address the battlespace preparation concept. It took place in late April-early May 2007 southward of Elba Island in the Mediterranean Sea **(fig. 3a)**. The focus is on establishing an integrated 4-D Recognized Environmental Picture (REP) of a shallow-water environment in support of two types of naval operations: Anti-Submarine Warfare (ASW) and Amphibious Operations (AOs). For this purpose, heterogeneous data sources **(fig. 3b)** were combined using standard and advanced techniques of environmental characterization covering the fields of underwater acoustics, physical oceanography and geophysics within a coherent scheme of data acquisition, processing and assimilation.

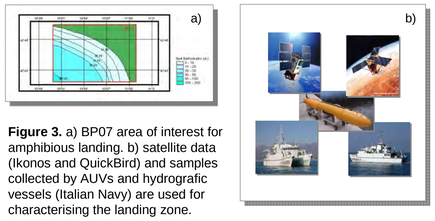


Figure 3. a) BP07 area of interest for amphibious landing. b) satellite data (Ikonos and QuickBird) and samples collected by AUVs and hydrografic vessels (Italian Navy) are used for characterising the landing zone.

Simultaneous acquisitions of QuickBird (resolution 2.4 m) and Ikonos (resolution 4.4 m) data have been used for estimating bathymetry at high horizontal resolution **(fig. 4)**. The area was characterised by high atmospheric visibility at the time of the acquisition. The estimation algorithms were trained using data collected during the NURC OEX-AUV bathymetric survey in the area chosen for the landing **(fig. 5)**. The Italian Navy bathymetric survey conducted by the Aretusa and Galatea vessels provided the data for the validation set **(fig. 6)**. Both data sets cover the first 20 m of depth.

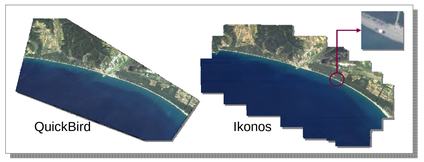


Figure 4. Simultaneous acquisition of QuickBird and Ikonos data for multi-sensor data fusion and sensor inter-calibration (see calibration tarps particular). Castiglione della Pescaia, Italy. Date: 26 April 2007. Time: 12:05 Local Time

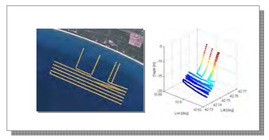


Figure 5. NURC OEX-AUV survey to collect the training dataset in the landing area

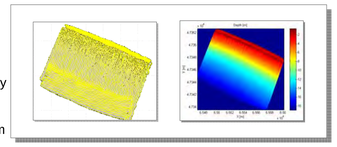


Figure 6. Italian Navy bathymetric survey during BP07. Final grid resolution: 5x5 m

Results

The results of the training of the MLR and the RBF-NN are summarised in **fig. 7**, showing the scatterplot between measured depth *versus* calculated depth, and in **tab. 1** with the statistics of the depth error (computed depth minus measured bathymetry). On the training set, the RBF-NN outperforms the MLR.

The algorithms were used to estimate the depth using pre-processed Ikonos and QuickBird data **(fig. 8)**. The estimates were compared with the validation data set from the Italian Navy survey **(fig. 9)**. The performance of the RBF-NN is confirmed with a standard deviation of the error of 0.45 m against 0.8 m of the MLR **(tab. 2)**. Depth profiles are compared in **fig. 10**.

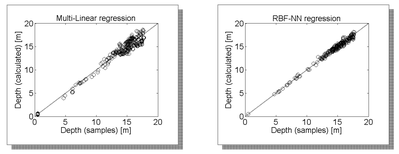


Figure 7. Results of the regression between TOA radiances and the depth samples from the OEX-AUV survey. The RBF-NN outperform the MLR in terms of dispersion, and linearity.

Algorithm	R^2	STD [m]
Multi-linear	0.980	0.770
RBF-NN	0.997	0.310

Table 1. Depth error determination coefficient, R^2, and standard deviation, STD, for the training set

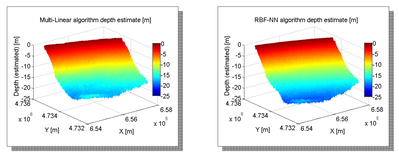


Figure 8. Estimation of the bathymetric profile for the whole area of interest using the trained algorithms.

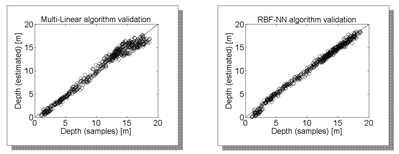


Figure 9. Scatterplots of the bathymetry values from the Italian Navy survey versus the estimated depth from satellite data. The RBF-NN outperforms the MLR on the validation set.

Algorithm	R^2	STD [m]
Multi-linear	0.94	0.80
RBF-NN	0.99	0.45

Table 2. Depth error determination coefficient R^2 and standard deviation STD, for the validation set

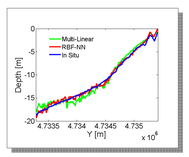


Figure 10. Depth profiles comparison between validation data set and estimated bathymetry from satellite data.

Conclusions

The problem of bathymetry estimation in denied areas was addressed by fusing passive high resolution satellite data and depth *in situ* samples collected by AUVs. Two empirical algorithms based on MLR and RBF-NN have been considered for processing TOA radiance data in high visibility conditions, collected during the NURC BP07 experiment along the western coast of central Italy. The two algorithms were trained by using a set of measurements gathered during a bathymetric survey conducted by the NURC OEX-AUV, and validated comparing the estimated bathymetry with the data set from the bathymetric survey of the Italian Navy. The results show that the RBF-NN algorithm outperforms the MLR with better error standard deviation and coefficient of determination **(tab. 2)**.

Pros and *cons* of the proposed methodology are:

pros

- Fully exploitation of the spectral information
- Exploitation of autonomous underwater vehicle flexibility in collecting measurements at sea
- No atmospheric corrections and sea bottom characterisation required.

cons

- *In situ* measurements are needed
- High visibility needed in case that atmospheric corrections are not performed.

Future work will be addressed to compare empirical algorithms with physical based inversion schemes [2], using atmospherically corrected data, and to apply the methodology to hyper-spectral data

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Acknowledgments

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