Algorithm Comparison for Shallow-Water Remote Sensing

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LONG-TERM GOAL

The goal of this work was to evaluate several existing algorithms for inverting remotely sensed hyperspectral reflectances to extract environmental information such as water-column optical properties, bathymetry, and bottom classification.

OBJECTIVES

A number of investigators worldwide have developed algorithms for recovery of bathymetry, bottom classification, and water-column optical properties (in particular, absorption and backscatter coefficients) from airborne hyperspectral imagery of optically shallow waters. Each of those algorithms has its own strengths and weaknesses, or environments for which it may provide better or poorer retrievals than other algorithms. It is therefore necessary to determine the performance characteristics of all available retrieval algorithms. This objective of the present small effort was to finish an on-going comparison of those algorithms via the preparation of a paper on the comparison results.

APPROACH

A formal comparison of retrieval algorithms began in 2008 with previous funding under contract N00014-06-C-0177. In February 2009 a workshop was held in Brisbane, Australia, with sponsorship by the U.S. Office of Naval Research (ONR-Global) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO). Participants at that workshop compared the results obtained by applying their own algorithms to a common set of images. Participants then mapped out a corresponding publication, which was finished with the present funding.

Six algorithms were applied to two different hyperspectral images, one from a PHILLS sensor flown near Lee Stocking Island (LSI) in the Bahamas and one from a CASI sensor flown over Moreton Bay (MB) in eastern Australia. Each investigator applied his/her algorithm to both images and sent the results to an independent third party (S. Phinn and colleagues at the University of Queensland) for comparison with the ground-truth measurements at each site.

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WORK COMPLETED

This year's final effort on this now completed contract involved writing the paper on the rigid format required by *Limnology and Oceanography Methods*. A copy of the submitted paper (Dekker et al.) is available on request. A final report was filed upon completion of this contract.

RESULTS

The six algorithms compared in this study are as follows:

HOPE: Hyper-spectral Optimization Process Exemplar. This method is an implementation of the semi-analytical, non-linear search algorithm developed by Lee et al. (1998, 1999). The model retrieves five parameters: phytoplankton absorption at 440 nm, CDOM absorption at 440 nm, particulate backscatter at 550 nm, bottom reflectance at 550 nm, and bottom depth. Values at other wavelengths are parameterized in terms of these five parameters and assumed spectral shapes.

BRUCE: Bottom Reflectance Un-mixing Computation of the Environment. This inversion technique incorporates the HOPE model with a modification to the bottom reflectance parameterization (Klonowski et al. 2007). In BRUCE, the bottom reflectance is parameterized by a linear combination of three bottom reflectance spectra that are representative of three key benthic cover classes, namely sediment, vegetation, and coral.

SAMBUCA: Semi-Analytical Model for Bathymetry, Un-mixing, and Concentration Assessment. SAMBUCA is an implementation of the HOPE algorithm, modified to (1) retrieve water-column concentrations of chlorophyll-*a*, CDOM, and non-algal-particles, (2) account for more than one substratum cover type, and (3) estimate the contribution of the substratum to the remote sensing signal (Brando et al. 2009).

SMLUT: Spectrum-Matching and Look-Up-Table. This method is based on spectrum matching by searching through a pre-computed database of remote-sensing reflectance spectra, R_{rs}, as described in Mobley et al. (2005). The fundamental requirement of this method is that the pre-computed R_{rs} spectra incorporate the range of inherent optical properties (IOPs, namely the absorption, scatter, and backscatter spectra), bottom depths, and bottom reflectances found in the imaged environment.

ALLUT: Adaptive Linearized Look-Up Trees. This algorithm facilitates spectrum-matching inversion of any radiative transfer model parameterized by a set of real-valued and integer parameters. The method used here is identical to that described in Hedley et al. (2009), but in addition includes a local linear gradient calculation.

LYZENGA. This empirical, multi-spectral technique developed by Lyzenga (1978) can retrieve bathymetry in areas of constant water clarity and homogenous benthos/substrate composition, but it cannot retrieve water-column IOPs. Although limited to retrieval of bathymetry under restrictive environmental conditions and therefore much less general than the above techniques, bathymetry retrieved by the Lyzenga algorithm was included in this comparison study because of its historical importance and continued widespread use under certain conditions.

Each approach simplifies the fundamental physics of the inversion problem in a slightly different manner, either by simplifying the radiative transfer equation (RTE) itself or by searching a database of finite size. The resulting tradeoffs are that HOPE, BRUCE and SAMBUCA assume a limited set of absorption, backscattering, and bottom reflectance spectra, while the SMLUT and ALLUT use a limited number of combinations of bathymetry, bottom reflectance, and water column IOPs when generating the R_{rs} database for the imaged environment. The accuracy of the retrieved parameters from HOPE, BRUCE and SAMBUCA depends on the adequacy of their underlying semi-analytic models and input parameters to represent the environment, whereas SMLUT and ALLUT results rely on whether or not the R_{rs} database contains IOP and benthic/substrate spectra representative of those in the imaged area.

Figure 1 shows the bathymetry retrievals for the six algorithms as applied to the two images. The row labeled "SMLUT" refers to the spectrum-matching and look-up-table methodology developed with previous ONR funding to C. Mobley and P. Bissett. It should be noted that the SMLUT method performed quite well on bathymetry when applied to the LSI image, but did very poorly on the MB image. The reason was that the IOPs used to create the R_{rs} database for the LSI image covered the range of IOPs found there, but the IOPs used for the MB database did not adequately represent the uncorrelated absorption and backscatter spectra in the MB waters. When further IOP spectra were added to the MB database, the SMLUT results were comparable to those of the other methods, as seen in Fig. 2. Retrievals of IOPs and bottom type are discussed in the Dekker et al. paper.

Table 1 shows the widely differing run times for the various methods. For example, the SMLUT method requires long computer times to create the R_{rs} database for a given set of water IOPs, depths, and bottom types. However, this is a one-time computation after which these R_{rs} spectra are available for processing imagery from similar environments. Subsequent image-processing times are the fastest of any algorithm. Other algorithms may require no preprocessing, but run much slower than SMLUT during image processing.

This study thus compared the absolute and relative retrieval accuracies and computational efficiencies of one empirical and five radiative-transfer-based algorithms for retrieval of bathymetry, bottom classification, and water absorption and backscatter coefficients when applied to hyperspectral imagery of independent coastal sites at Lee Stocking Island in the Bahamas and Moreton Bay in eastern Australia. The assessment showed that (1) the radiative-transfer-based methods were more accurate than the empirical approach, and the accuracy and processing times of these were inversely related to the complexity of the models used; (2) all inversion methods provided moderately accurate retrievals of bathymetry, water column inherent optical properties, and benthic reflectance in areas less than 10 m deep with relatively clear water and homogenous benthic/substrate covers; (3) more accurate retrievals were obtained from the more complex and locally parameterized methods; and (4) no single method can be considered optimal for all situations.

IMPACT/APPLICATION

The problem of extracting environmental information from remotely sensed ocean color spectra is fundamental to a wide range of Navy needs as well as to basic science and ecosystem monitoring and management problems. Extraction of bathymetry and bottom classification is especially valuable for planning military operations in denied access areas.

RELATED PROJECTS

This work was a follow-on of research begun under contract N00014-06-C-0177. The other investigators were separately funded for their algorithm development and participation in the comparison exercise.

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PUBLICATIONS

Dekker, A., S. Phinn, J. Anstee , W. P. Bissett, V. E. Brando, B. Casey, P. Fearns, J. Hedley, W. Klonowski, Z. P. Lee, M. Lynch, M. Lyons, C. D. Mobley, and C. Roelfsema. Inter-comparison of Shallow Water Bathymetry, Hydro-Optics, and Benthos Mapping Techniques in Australian and Caribbean Coastal Environments. Submitted to *Limnol. Oceanogr. Methods*. [Submitted, refereed]

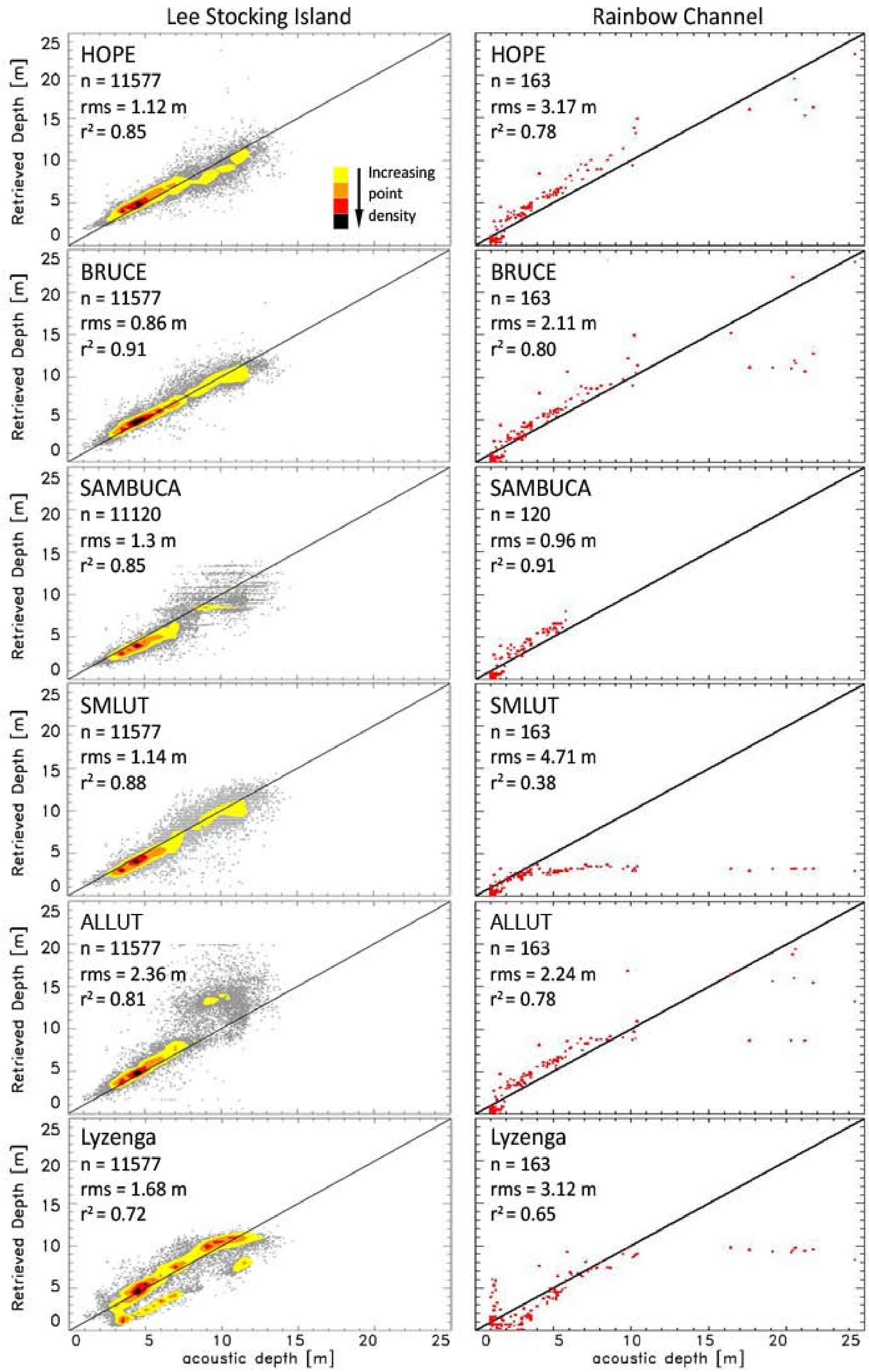

Fig. 1. Depth retrievals for six algorithms applied to two images. The left column is for the image from Lee Stocking Island, Bahamas and the right column is the image from Moreton Bay, Australia. [Figure shows scatter plots of retrieved vs. acoustic depths for each method.]

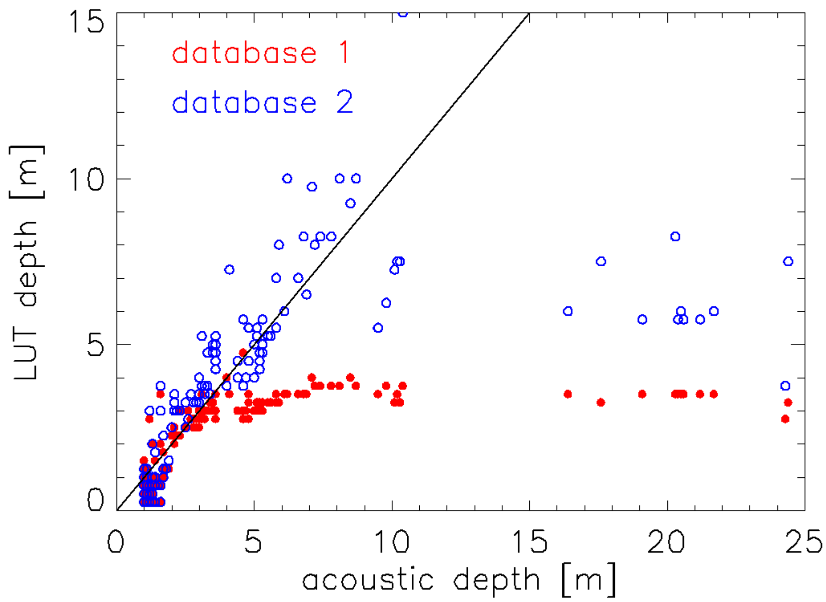

Fig. 1. SMLUT depth retrievals for the Moreton Bay image for the original database 1 (red) and for the expanded database 2 (blue). [Figure shows retrieved vs. acoustic depth, color coded according to which database was used.]

Table 1: Processing comparison for each site and method: processor nominal speed; time required for preprocessing (if any); processing time; and average processing speed in terms of number of pixels processed per second. LSI is the Lee Stocking Islands, Bahamas image, and MB is the Moreton Bay, Australia image.

Algorithm	**Site**	**Processor speed**	**Pre-processing time**	**Image-processing time**	**pixels processed per second**
HOPE	LSI	2.66 GHz		48 mins	156.39
HOPE	MB	2.66 GHz		90 mins	157.01
BRUCE	LSI	2.40 GHz		12 hours	10.43
BRUCE	MB	2.40 GHz		15 hours	15.70
SAMBUCA	LSI	*		1147 hours*	0.11
SAMBUCA	MB	*		628 hours*	0.38
SMLUT	LSI	2.00 GHz	45 hrs**	23 mins	326.38
SMLUT	MB	2.00 GHz	135 hrs**	22 mins	642.32
ALLUT	LSI	3.00 GHz	4 mins 12 s	2hrs 2 mins	61.53
ALLUT	MB	3.00 GHz	6 mins 48 s	2hrs 32 mins	92.97

* The actual processing was run over 16 processors, thus the actual time was 3-4 days.
** This is the time required for the one-time database creation.