

LUT Wrap Up

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LONG-TERM GOAL

The overall goal of this work was to develop and validate a spectrum-matching and look-up-table (LUT) technique for rapidly and accurately inverting remotely sensed multi- or hyperspectral reflectances to extract bathymetry, bottom classification, and water-column optical properties.

OBJECTIVES

My colleague W. P. Bissett and I have developed (Mobley et al., 2005) and evaluated (Mobley and Lesser, 2007; Dekker et al., 2011) new techniques for the extraction of environmental information including shallow-water bathymetry, bottom classification, and water-column inherent optical properties (IOPs), from remotely sensed multi- and hyperspectral ocean-color imagery. We have addressed the need for rapid, semi-automated interpretation of such imagery. My research centered on development and evaluation of the spectrum-matching algorithms and associated software, including the generation of confidence metrics for the retrieved information.

The final task of this work was to evaluate commercially available DigitalGlobe WorldView-2 (WV2) satellite multi-spectral imagery for retrieval of bathymetry in various waters.

APPROACH

The methodology is based on a spectrum-matching and look-up-table approach in which the measured remote-sensing reflectance spectrum R_{rs} is compared with a database of spectra corresponding to known water, bottom, and external environmental conditions. The water and bottom conditions of the water body where the image spectrum was measured are then taken to be the same as the conditions corresponding to the database spectrum that most closely matches (by some chosen metric) the measured spectrum. In previous work, we have simultaneously retrieved water column IOPs, bottom depth, and bottom classification at each pixel from image remote-sensing reflectance spectra. Although this is much to ask from an R_{rs} spectrum, we have shown that all of this information is uniquely contained in hyperspectral reflectance signatures and that the information can be extracted with sufficient accuracy to meet many Naval and civilian needs.

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We have evaluated numerous options for applying the basic algorithms. These options include matching the closest k R_{rs} spectra, rather than just the closest one ($k = 1$); spectral and spatial smoothing of image spectra before processing to remove both sensor and environmental noise (such as whitecaps and sun glint); spatial smoothing of retrieved values after processing; and different spectrum-matching metrics for determining the closest match.

WORK COMPLETED

Previously developed software for database creation, image analysis, and display of results was cleaned up, extensively documented, and repackaged into one software system that is now called Comprehensive Reflectance Inversion based on Spectrum matching and TAbles Look up, or CRISTAL. A CRISTAL User's Guide and Technical Documentation was prepared (Mobley and Bissett, 2011).

The CRISTAL database generation software uses the extremely fast EcoLight-S(ubroutine) radiative transfer code (Mobley 2010, 2011), which can be optimized to run much faster than the standard EcoLight code but with a negligible difference in the computed R_{rs} .

Previous work considered only airborne hyperspectral imagery, mostly of optically clear waters (Mobley et al., 2005; Mobley and Lesser, 2007; Dekker et al., 2011). In the final phase of this work, I evaluated the CRISTAL techniques for retrievals in highly absorbing and scattering (turbid) waters using the multispectral WorldView 2 satellite imagery. That work included the development of new code to reprocess hyperspectral R_{rs} databases to create databases corresponding to the multi-spectra bands of the World View 2 imagery.

To process the WorldView-2 imagery, a hyperspectral R_{rs} database was created by CRISTAL for 0.38-0.75 μm by 0.005 μm , which covers the WV2 wavelengths relevant to bathymetry retrievals. That database was then integrated over the WV2 band response functions to degrade the hyperspectral database to the multispectral bands of the World View 2 sensor. Figure 1 shows the WV2 sensor response functions and selected hyperspectral reflectances and their WV2 multispectral equivalents.

The final reports on this work were submitted in February 2012 (Mobley and Bissett, 2012a, 2012b). The most recent versions of the CRISTAL code and documentation were given to Dr. A. Weidemann, NRL Code 7334, for beta testing and evaluation.

RESULTS

WorldView-2 multispectral imagery from two different aquatic environments was analyzed with the goal of determining if imagery from this sensor can be used for retrieval of high-spatial-resolution (~ 2 m) bathymetry in optically shallow water.

The first environment was near Lee Stocking Island, Bahamas. In these very clear tropical waters the bottom is visible to depths of 15 m. This area was chosen because previously studied imagery from the airborne hyperspectral PHILLS sensor was available for comparison with the multispectral WV2 sensor. Retrievals from both sensors were compared with acoustic bathymetry. The PHILLS imagery gave depths that were on average about 5% too shallow, with an rms depth error of 0.95 m over a depth range of 1 to 12 m. About 80% of the retrieved depths were within ± 1 m of the correct depth, and 87% were within 25% of the correct depth. For the WV2 sensor, the depths were on average about 14% too shallow, rms error = 1.1 m, 69% in ± 1 m, and 76% within $\pm 25\%$. These results are very

encouraging and indicate that the six WV2 bands in the visible and near IR contain almost as much information as the hyperspectral imagery in the 400-750 nm range.

The second environment was a coastal lagoon, St. Joseph's Bay, Florida. Figure 2 shows the WV2 false-color image of this spatially complex area. The imaged area is about 2.5 km square with a nominal pixel size of about 2 m. This water is highly absorbing due to CDOM (absorption coefficients at 412 nm are in the range of 0.5 to 1.0 m^{-1}) and highly scattering due to suspended particles (scattering coefficients are in the 0.5 to 2.5 m^{-1} range). The bottom is predominately bare sand or dense sea grass. Depths range from the shoreline to several meters; these waters are optically deep if the bottom is below 2.5 to 3 m depth.

The WV2 image for this area was atmospherically corrected by both an empirical line fit (ELF) and the TAFKAA radiative transfer code. The atmospherically corrected image spectra differed by as much as a factor of five at blue wavelengths, and both differed from spectra measured at a few points in the image area. The TAFKAA-corrected spectra are generally greater in magnitude than the ELF spectra and do not approach zero in the IR, which indicates atmospheric undercorrection. *Both atmospheric corrections for this image therefore appear to be inaccurate, and poor bathymetry retrievals were therefore expected, which was indeed the case.* Figure 3 shows the depth retrievals for the ELF-corrected image. These are qualitatively correct, but quantitative comparison with the acoustic bathymetry shows that the ELF-corrected image gave depth retrievals that are on average 122% too deep with an rms error of 0.63 m over a depth range of 1 to 5 m. Only 50% of the retrieved depths were within ± 1 m of the correct depth, and only 10% were within $\pm 25\%$ of correct. The TAFKAA-corrected image gave better results in spite of its apparent atmospheric undercorrection: 37% too deep on average, rms error = 0.56 m, 96% in ± 1 m, 48% in $\pm 25\%$, as shown in Fig. 4. Even with its atmospheric undercorrection, the TAFKAA image gave retrievals that would be useful for many applications, and which would certainly be better than just a visual inspection of an RGB image of this environment.

Analysis of just two images, one of poor atmospheric correction quality, is not sufficient to determine the accuracy with which WV2 imagery can be used to retrieve bathymetry over a wide range of environments. However, these preliminary results are encouraging and indicate that *atmospherically well corrected* WV2 imagery probably can provide useful bathymetry. Additional atmospherically well corrected WV2 images need to be analyzed before definitive statements can be made about the accuracy of WV2 depth retrievals and the effects of imperfect atmospheric corrects on those retrievals for a wide range of environments.

We certainly cannot expect that any multispectral imagery can give results as accurate as can be obtained from good quality hyperspectral imagery. However, the preliminary evaluation of WV2 multispectral imagery for two images indicates that this satellite imagery may be useful for retrieval of high-spatial-resolution (~ 2 m pixel size) bathymetry with sufficient accuracy for many purposes. However, more images must be examined and compared with ground truth before reaching any firm conclusions about the quantitative accuracy of multispectral WV2 imagery vs. hyperspectral airborne imagery. In any case, *obtaining a good atmospheric correction for WV2 imagery is the key to retrieving good bathymetry.*

IMPACT/APPLICATION

The problem of extracting environmental information from remotely sensed ocean color spectra is fundamental to a wide range of Naval 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. The initial evaluation of World View 2 multispectral imagery for high-spatial-resolution (~ 2 m) bathymetry retrieval is encouraging because this imagery is readily available to both military and civilian users. We believe that the CRISTAL methodology and software is suitable for applications to a wide range of ocean image processing problems both within the Navy and in the broader science community.

TRANSITIONS

A beta-test version of the CRISTAL software package was sent to Dr. A. Weidemann, NRL Code 7334 for evaluation and comment.

Various databases of water IOPs, bottom reflectances, and the corresponding R_{rs} spectra, along with spectrum-matching algorithms and code have been transitioned to Dr. Paul Bissett at WeoGeo, Inc. for processing his extensive collection of SAMPSON imagery acquired in coastal California and Florida waters, and for use in comparisons of CRISTAL and LIDAR bathymetry. Code for display of retrieval results was given to S. Phinn and colleagues at the Univ. of Queensland, Australia, who performed comparisons of CRISTAL and other retrieval techniques as reported in Dekker et al. (2011).

RELATED PROJECTS

This work was conducted in close cooperation with Dr. Paul Bissett at WeoGeo, Inc, who was separately funded for his contributions to the development of CRISTAL, and who was funded via a subcontract for the evaluation of World View 2 imagery for bathymetry retrieval. The development of the EcoLight-S code, which is incorporated into the final CRISTAL database generation code, was supported in part by contract N0001409C0044.

REFERENCES

- Dekker, A., S. Phinn, J. Anstee, W. P. Bissett, V. E. Brando, B. Casey, P. Fearn, J. Hedley, W. Klonowski, Z. P. Lee, M. Lynch, M. Lyons, C. D. Mobley, and C. Roelfsema, 2011. Inter-comparison of Shallow Water Bathymetry, Hydro-Optics, and Benthos Mapping Techniques in Australian and Caribbean Coastal Environments. *Limnol. Oceanogr. Methods* 9, 396-425.
- Lesser, M. P. and C. D. Mobley, 2007. Bathymetry, optical properties, and benthic classification of coral reefs using hyperspectral remote sensing imagery. *Coral Reefs*, 26: 819-829.
- Mobley, C. D., 2010. *EcoLight-S 1.0 Users' Guide and Technical Documentation*. Sequoia Scientific, Inc., 40 pages.
- Mobley, C. D., 2011. Fast light calculations for ocean ecosystem and inverse models. *Optics Express* 19(20), 18927-18944.

- Mobley, C. D., L. K. Sundman, C. O. Davis, T. V. Downes, R. A. Leathers, M. J. Montes, J. H. Bowles, W. P. Bissett, D. D. R. Kohler, R. P. Reid, E. M. Louchard, and A. Gleason, 2005. Interpretation of hyperspectral remote-sensing imagery via spectrum matching and look-up tables. *Applied Optics* 44(17), 3576-3592.
- Mobley, C. D. and W. P. Bissett, 2011. CRISTAL User's Guide and Technical Documentation. Sequoia Scientific, Inc., 97 pages.
- Mobley, C. D. and W. P. Bissett, 2012a. Evaluation of DigitalGlobe WorldView-2 Satellite Imagery for Bathymetric Mapping. Final Report on ONR Contract N00014-10-C-0209.
- Mobley, C. D. and W. P. Bissett, 2012b. Preliminary Evaluation of DigitalGlobe WorldView-2 Satellite Imagery for Bathymetric Mapping. Sequoia Scientific, Inc., Bellevue WA, 43 pages.

PUBLICATIONS

- Dekker, A., S. Phinn, J. Anstee, W. P. Bissett, V. E. Brando, B. Casey, P. Fearn, J. Hedley, W. Klonowski, Z. P. Lee, M. Lynch, M. Lyons, C. D. Mobley, and C. Roelfsema, 2011. Inter-comparison of Shallow Water Bathymetry, Hydro-Optics, and Benthos Mapping Techniques in Australian and Caribbean Coastal Environments. *Limnol. Oceanogr. Methods* 9, 396-425.
- Mobley, C. D., 2011. Fast light calculations for ocean ecosystem and inverse models. *Optics Express* 19(20), 18927-18944.
- Mobley, C. D. and W. P. Bissett, 2011. CRISTAL User's Guide and Technical Documentation. Sequoia Scientific, Inc., 97 pages.

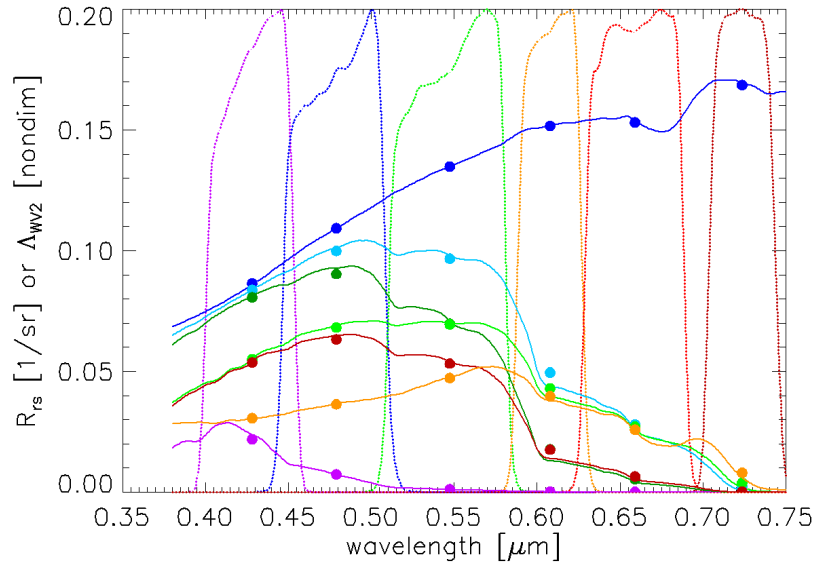


Fig 1. The dotted lines are World View 2 normalized sensor response functions $\Delta_{WV2}(\lambda)$ for the six World View 2 bands used for spectrum matching. The solid lines are example hyperspectral reflectances $R_{rs}(\lambda)$, and the dots are the equivalent World View 2 multispectral band values.

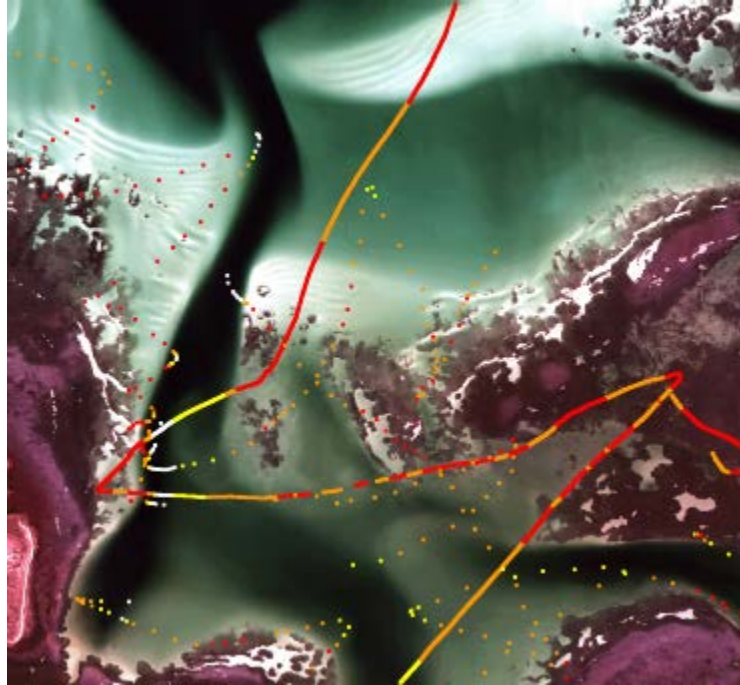


Fig. 2. False color image of the 2.5 km square area at the south end of St. Joseph Bay, Florida. The white to green areas are sand bottom; the purple areas are dense sea grass beds. The darkest channels are optically deep (> 2.5 to 3 m for these turbid waters). Pixels having an acoustic depth are color coded according to the depth range (adjusted to MLW): red is $0-1$ m; orange is $1-2$ m; yellow is $2-3$ m; white is >3 m depth.

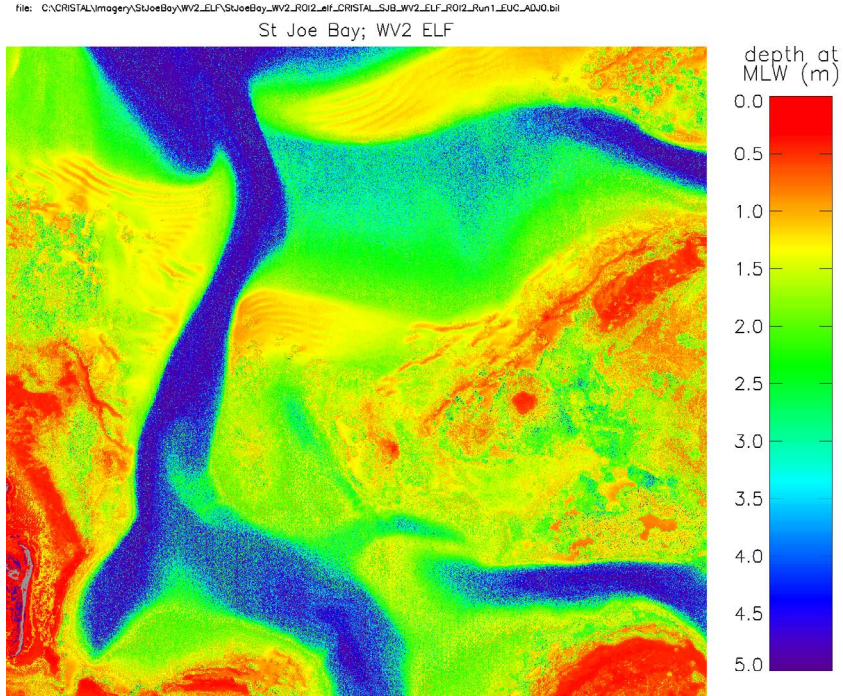


Fig. 3. CRISTAL-retrieved depths obtained from the ELF-corrected World View 2 multi-spectral image for the area shown in Fig. 2. Depths retrieved at the time of image acquisition were corrected for tidal height to get depths at mean low water.

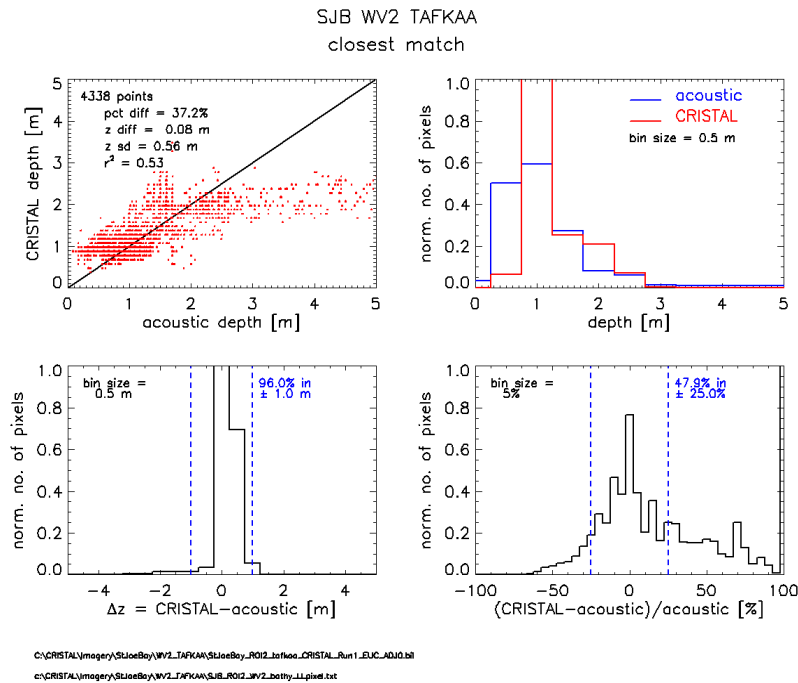


Fig. 4. Comparison of acoustic and CRISTAL-retrieved bathymetry obtained from the TAFKAA-corrected World View 2 imagery of Fig. 2.