Model-based Hyperspectral Exploitation Algorithm Development

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Grant Number: N00014-01-1-0867
http://www.cis.rit.edu/research/dirs/

LONG-TERM GOALS

Hyperspectral data has become a critical tool for use by military analysts and planners. The capture of fine spectral information enables the generation of information products which could not be produced using traditional imaging means. The challenge facing hyperspectral technology, as an operational capability, is with conversion of the raw sensor data into a useful information product that is accurate and reliable. Traditional approaches for processing hyperspectral data have largely focused on the use of statistical tools to process a hypercube, with little regard for other data that may describe the physical phenomena under which the data was collected. The long-term goal of this project has been to develop a new generation of hyperspectral processing algorithms that take advantage of underlying physics of hyperspectral image data while utilizing statistical processing techniques to generate final information products.

OBJECTIVES

The objectives of this project are to develop hyperspectral analysis tools that incorporate physics-based processing in the following application areas:

- Water quality and biological activity (littoral zone)
- Material classification and identification
- Atmospheric parameter retrieval/correction

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Model-based Hyperspectral Exploitation Algorithm Development**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Rochester Institute of Technology,54 Lomb Memorial Drive,Rochester,NY,14623**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The output of this project has been processed data sets, in some cases, information products that demonstrate the feasibility of this approach and most importantly a whole new approach to spectral analysis algorithms that incorporates the physics of the phenomenology under interrogation.

APPROACH

Traditional approaches for processing hyperspectral data have largely focused on the use of statistical tools to process a hypercube, with little regard for other data that may describe the physical phenomena under which the data was collected. The RIT MURI research team has been developing physics-based models that enable the environment, under which remotely sensed data is collected, to be better described (Schott 2000). Under this MURI project, we are using these physics-based models, along with statistical processing techniques to evaluate the effectiveness of this approach for processing hyperspectral data sets.

WORK COMPLETED

This is the final annual research report for this project. The RIT MURI team iniated research under this MURI in May 2001 and over this period, there has been substantial research progress in validating the utility of the physics-based algorithmic approach. This MURI has been a catalyst for the research team to be awarded additional research support from other sponsors. The research results generated by this MURI have been shared to the hyperspectral community via peer reviewed journal acticles, presentations at technical conferences, and the publishing of Masters and PhD theses. This project has supported over 20 graduate students, many of whom have taken positions in direct support of the defense and intelligence community. Finally, much of the research accomplished under this program contributed to *Remote Sensing: The Image Chain Approach, 2nd Edition*, (Chapter 11: Use of Physics-based Models to Support Spectral Image Analysis Algorithms), by Dr. John Schott and was published in 2007.

RIT has continued research into all three focus areas under this MURI. In the area of hyperspectral point target detection using physics-based models, there were several advances made. A new approach to the development and representation of the physics-based target spaces was developed. This method uses a design of experiment approach to identify key input parameters to the physical model and then uses a statistical model, trained on the small number of physical model results, to predict the entire target space. This method has been shown to produce accurate target spaces while achieving dramatic efficiency improvements in the time-intensive process of target space creation. In the area of atmospheric compensation and temperature / emissivity separation in thermal HSI, a hybrid approach was developed that uses both scene-derived information as well as model-derived information to achieve an estimate of the atmospheric contributions to the signal as well as the surface emissivity and temperature. The method was tested against both synthetic and real data and has been shown to achieve accuracies on the order of 1K in surface temperature and 1% in surface emissivity. The in-water radiative transfer modeling work also achieved maturity, as did the development of a method to perform simultaneous atmospheric compensation and in-water constituent estimation for littoral scenes. The in-water radiative transfer modeling work is based on a photon mapping approach combined with a more traditional ray tracing approach. Several innovative radiance field sampling schemes were developed and implemented into DIRSIG (the RIT developed scene simulation tool) to produce accurate estimates of the in-water radiance field. Phenomenological and test case validations have demonstrated the accuracy of the simulation. Work was also completed on Case II water atmospheric compensation and water constituent retrieval methods. These methods seek to extract both the aerosol and water constituents from the airborne hyperspectral imagery using a physics-based model of the observed radiance from the water column. This work has been combined with the efforts to model and understand the suspended sediment spectral phenomenology to improve the ability to predict water-leaving signatures in the littoral zone.

The primary contribution from Cornell was in providing expertise in hyperspectral radiative transfer modeling in-water with a specific emphasis on phytoplankton modeling, the effect of phytoplankton on ocean color observations and finally, developing a procedure for deriving phytoplankton characteristics (taxa, concentrations, etc.) from remote, spectral observations. The physical modeling involved adapting and extending the Ocean Optics Phytoplankton Simulator (OOPS) (Kim and Philpot, 2006b), including non-phytoplankton components (CDOM, suspended sediments, depth, bottom type, etc.). Because of the lack of detailed, taxa-specific data, it was first necessary to build a data base of IOPs and other characteristics of selected phytoplankton taxa supplementing data gleaned from the literature with laboratory measurements. Among other accomplishments were the design and construction of a backscattering meter (Kim and Philpot, 2005a) and the design of a spectral absorption meter (Kim and Philpot, 2002). Modeling required not only spectral measurements of key optical properties but also an extension of scattering code to handle larger, non-spherical particles (Kim and Philpot, 2001, 2005b, 2006a). It was possible to demonstrate that the model should be able to produce a relatively successful separation between some taxa, but that others (e.g., haptophyceae and diatoms) will be difficult to distinguish. Ultimately, the inversion procedure to derive the spectral in-water optical parameters from remote observations involved a non-linear optimization that required observations of several regions of interests (ROIs) at different depths but with the same bottom type and water quality.

During this project, UCI has made progress in several areas using physical models for the development of hyperspectral processing algorithms. UCI has developed several models for hyperspectral texture that are based on multi-band correlation functions, Markov fields, and filter-based features and developed neighbor selection methods for the Markov models and showed how each model can be used for invariant texture recognition. UCI also showed how a combined spectral/spatial model can be used for hyperspectral texture synthesis. We have used subspace models for reflectance, illumination, and atmospheric spectra for reflectance recovery. These methods utilize physically-motivated coupled subspaces and have been applied to 3D and subpixel surfaces. UCI developed physics-based models for hyperspectral distribution changes. These models have been used in conjunction with moment-invariants for registration and change detection. UCI has also developed methods for the recognition of 3D objects. This work has led to the development of generalized nonparametric models for hyperspectral distributions. A large set of experiments have shown that each of the new UCI algorithms has important advantages over previous methods.

RESULTS

- **Mapping of In-water Constituents in the littoral zone**

Photon Mapping – Adam Goodenough - (RIT PhD Student)

Significant progress has been made with the Photon-Mapping model to simulate complex hydrologic radiative transfer. This past year's activities were focused on baseline validation of the technique, data architecture design of simulation elements and their behavior, and integration of key routines into the DIRSIG environment. The validation of the technique compared several radiometric cases studies described in the seminal paper by Mobley et al. (1993). Each of these cases was simulated showing very good agreement with the different cases established by the comparative study. In cases where there were significant discrepancies, it is believed that the implemented model represented a more sophisticated treatment of the problem. Comparisons were also demonstrated against Carder et al. (2005) and Zaneveld et al. (2001) where spatial obscuration and surface effects were simulated showing agreement to the modification to the light field under these conditions. In order to achieve the correct radiometry of these simulations, substantial modifications have been made to the DIRSIG simulation framework to develop a more general and flexible representation of radiometric concepts/elements and their interaction across the different media encountered in the littoral environment. A flexible interface to the tools provides future users with a library of extensible, built-in optical property models and high-level control over computation parameters.

Because the utility of the DIRSIG-Photon Mapping simulation environment is meant to be applied across different spatial scales, a "surface sampler library" and novel BRDF integration techniques have been implemented to provide the ability to adaptively sample radiometric contributions to a scene. These tools have already been exploited in at least two other doctoral projects on unrelated topics. In addition to these radiometric improvements, a preliminary scheme to address spatial scales of wave effects has been implemented to provide the necessary fidelity in addressing a very crucial dimension of littoral modeling. In addition to follow on work that will validate the radiometry of the DIRSIG-Photon Mapping for more complex scenarios, the tools developed from this effort will play a key role in a recently awarded Intelligence Community doctoral fellowship studying the microscale radiometry of surfaces and participating media.

Littoral Zone Mapping of In-water Constituents – Jason Hamel (Masters Student), Rolando Raqueno

The suspended sediment modeling work has been a cornerstone work in its own right as well as a foundation for the atmospheric compensation work. To date, the sources of IOPs for constituents (particularly suspended sediments) do not exist in the near-IR region (800-950) because of the limitations of instrumentation and the current assumption that the returns in those regions for Case I waters are negligible. As highlighted by emerging works presented at Ocean Optics 2006, the application of atmospheric compensation techniques to Case II waters are being hindered by the lack of characterizations of previously ignored constituent (suspended sediment) in a wavelength region where in-situ and lab measurements are difficult. The modeling that resulted from the linkages between the OOPS algorithm and HYDROLIGHT produced plausible results that underscores the importance of particle size distribution, scattering phase function, and number density as major considerations in optically characterizing turbid Case II waters. The competing effects of these properties on the final radiometry can only be elucidated by modeling methods used in this research. The Mie scattering codes used in these analyses provided initial estimates that established idealized trends of particle parameter effects on the overall inherent optical properties, but have not been established as sufficiently optimum. While the current results are very telling and informative, they need to be validated either through laboratory experiments or application of more sophisticated scattering codes that are better suited for the wide size regimes encompassed by the current Mie code and more realistic particle-shape scenarios. The merit and inadequacy of this work is illustrated by its comparison to the long standing Petzold functions show in Figure 1. While there is general agreement in shape of the scattering phase function, the "spherical" assumption of the Mie code leads to artifacts that are not found in natural waters of realistic distributions.

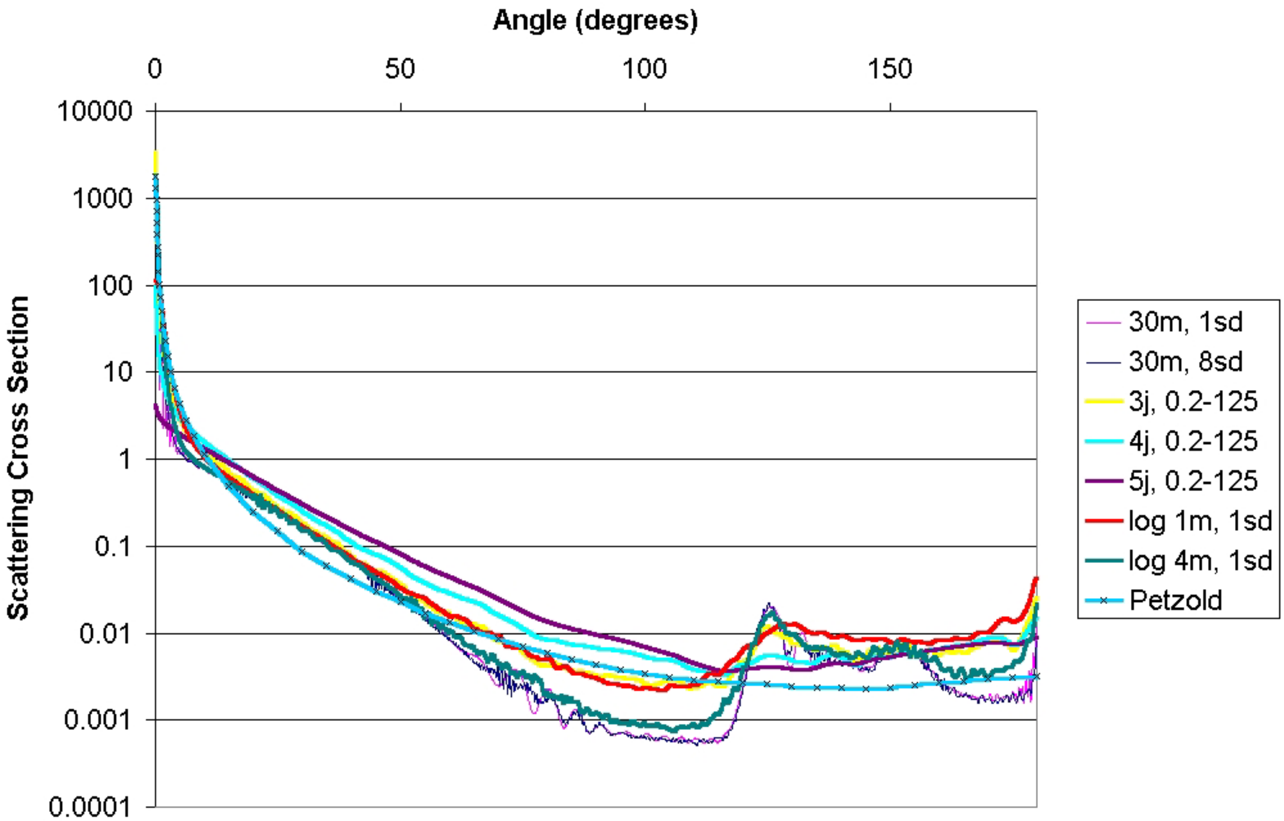

Figure 1 - Phase functions at 500nm for a variety of phase functions. Phase functions displayed in this plot: Gaussian with 30 micron mean and 1 or 8 standard deviation width; Junge from 0.2-125 microns with 3,4 or 5 Junge coefficient; Log-Normal with 1 or 4 micron mean and 1 standard deviation width; and the Petzold phase function as listed in Light and Water by Mobley.

Another trend that arose when examining the output from the Mie scattering code concerned the nature of particle scattering and the effect it has on the final apparent reflectance of a water body. As many researchers have found over the years, scattering tends to be dominated by smaller particles whose size is closer to the wavelength of light being scattered. Thus, when examining the scattering phase functions of various particle distributions, smaller particles scatter a larger percentage of their light in the 90-180 degree direction. This trend is again seen in the back scattering ratios generated during this research (Figure 2). These same trends are not observed in the final apparent reflectance of the water body though (Figure 3). The complication leading to this result is apparent when one examines the scatter cross-sections of the various particle size distributions (Figure 4). As shown in the plot, while larger particles might send a smaller percentage of the light backwards compared to smaller particles, they have a much larger area for interaction with photons. The end result can be a larger amount of total light being scattered into the backwards direction than expected from previously published work.

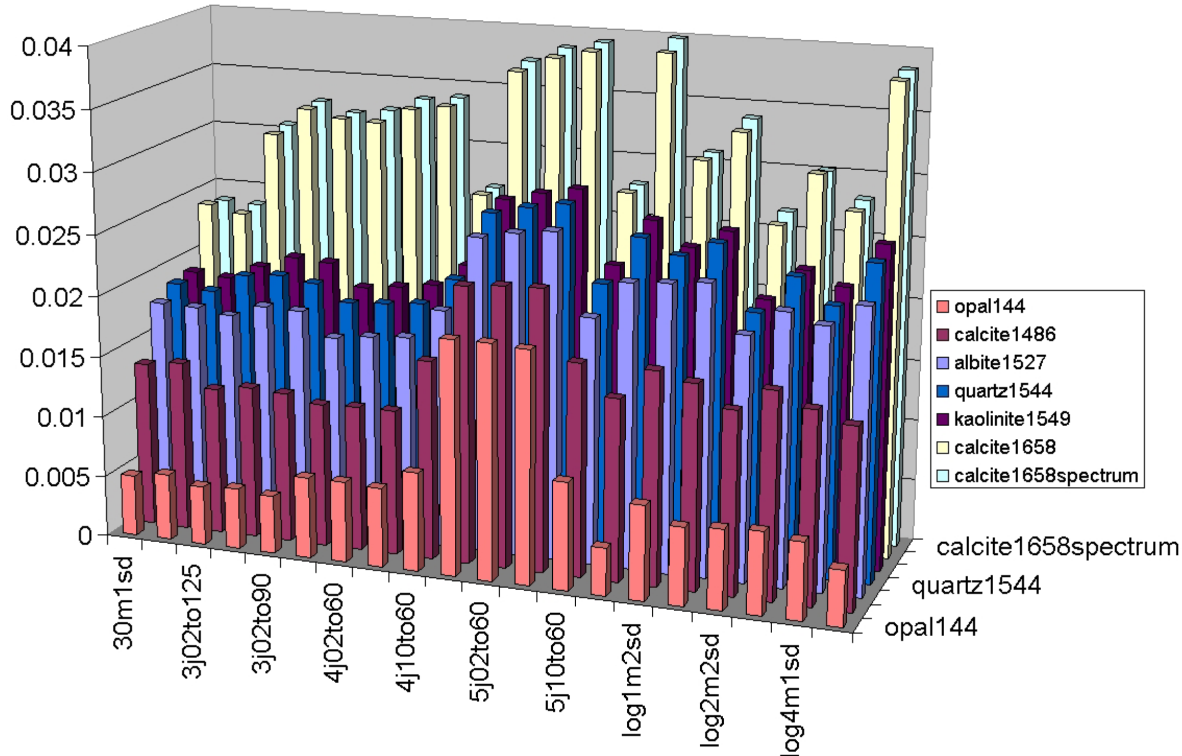

Figure 2 - Back scatter ratios at 550nm for various mineral and particle size distributions.

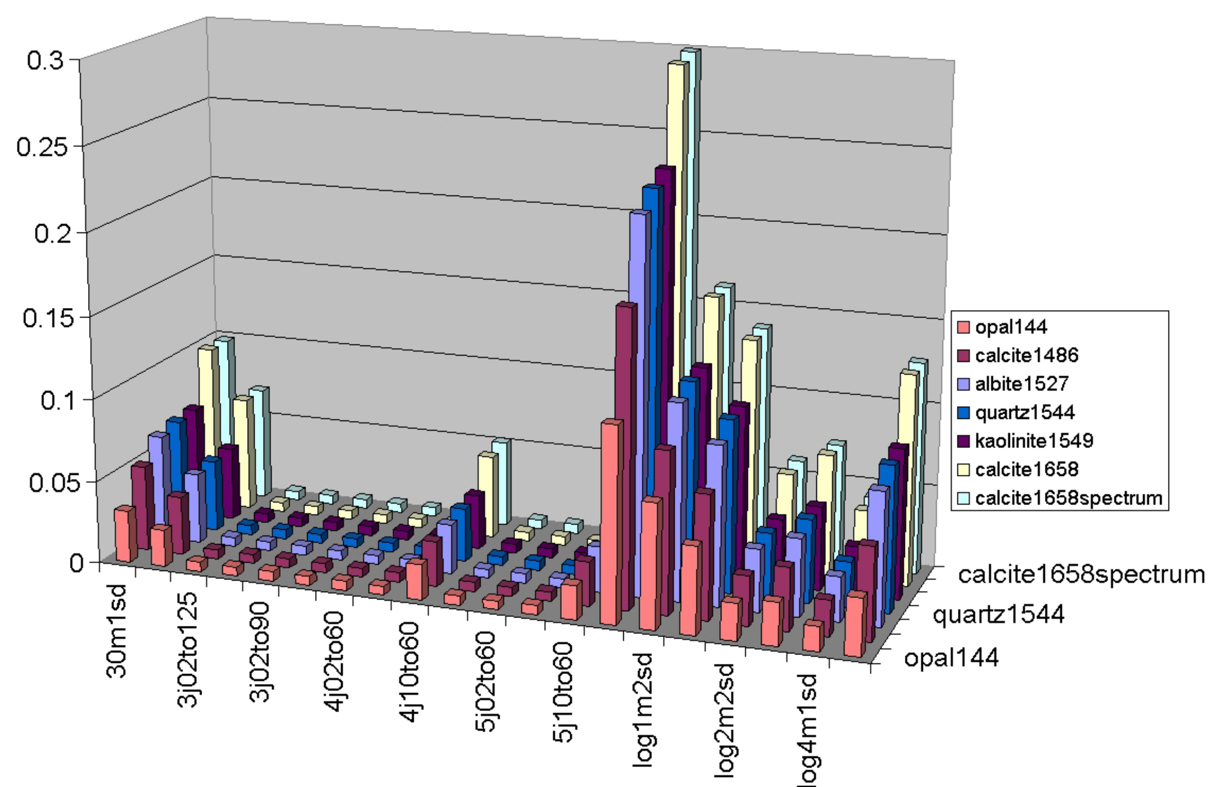

Figure 3 - Surface reflectance at 550nm for various minerals and particle size distributions.

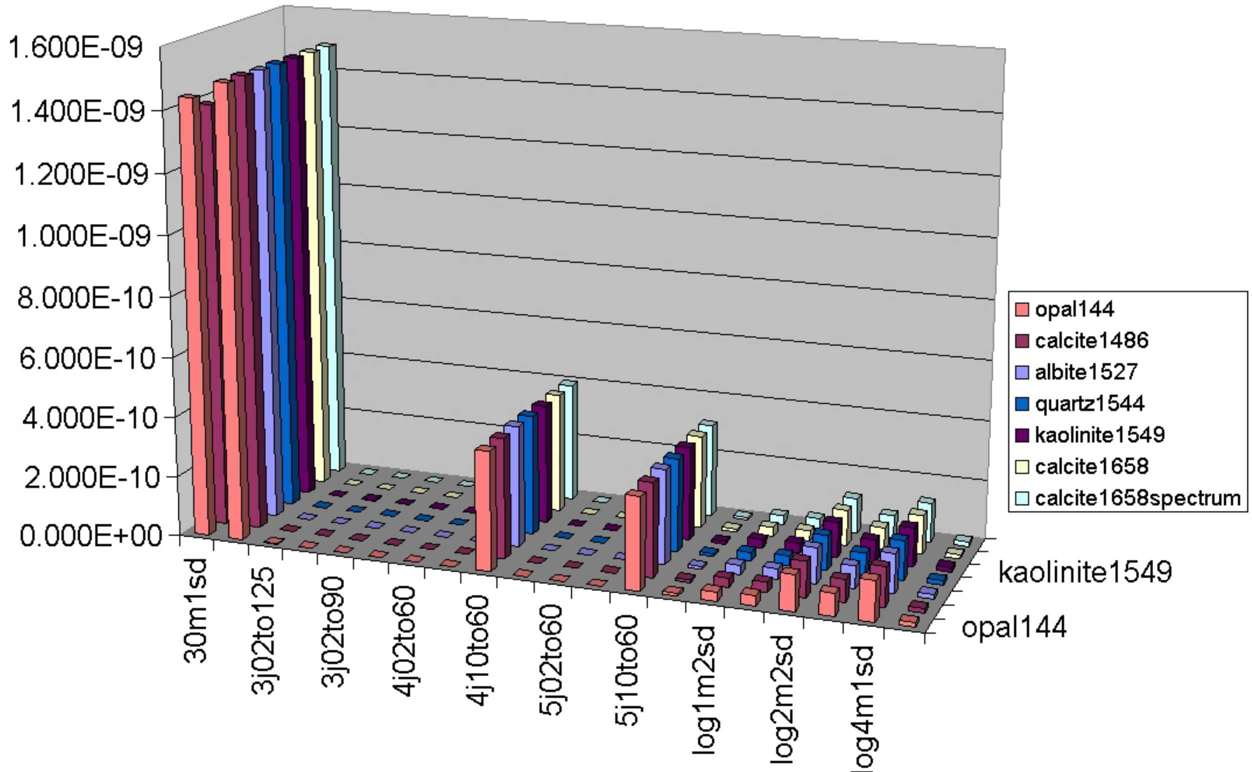

Figure 4 - Scattering cross-sections at 550nm for various minerals and particle size distributions.

In summary, this work allowed other aspects of this MURI to move forward with the caveat that we are relying on an evolving understanding of crucial elements. It also provided insight into factors of scattering phase functions that have been downplayed because of their insignificance in Case I waters.

- **Atmospheric parameter retrieval and correction**

Temperature/Emissivity Separation – Marvin Boonmee (RIT PhD Student)

This project focused on the development of an algorithmic approach to the problem of temperature / emissivity separation effects in longwave infrared hyperspectral imagery. An algorithm was developed for the purpose of land surface temperature and emissivity retrieval from long wave infrared airborne hyperspectral imagery. The optimized land surface temperature and emissivity retrieval (OLSTER) algorithm uses an iterative technique to solve the nonlinear retrieval problem. The OLSTER algorithm introduces a new method for finding near-blackbody pixels based on scene-derived methods, and also an iterative method for retrieving surface parameters using constrained optimization. Unlike the temperature / emissivity separation methods in the literature, this approach does not assume that perfect atmospheric compensation has been performed during preprocessing, and does not require spectral polishing of retrieved emissivities. The main steps include initialization, a search for near-blackbody pixels, and an iterative constrained optimization using generalized reduced gradients (GRG). Sample results are shown in Figure 5.

Much progress has been made on this research and a unique methodology for atmospheric compensation and temperature / emissivity separation in LWIR hyperspectral imagery has been developed. The algorithm is currently undergoing extensive testing on both simulated and real imagery. The method developed combines techniques using in-scene information as well as model-based information into an optimization framework. Using synthetic data, the algorithm has shown the ability to determine the land surface temperature to within approximately 1 – 2 K and the surface emissivity to within 1-2 %. The algorithm has been demonstrated to be robust to both sensor noise and spectral miscalibration effects. Figure 5 shows results from applying the algorithm to a scene collected over Camp Eastman in Rochester, NY in June 2004 with the SEBASS hyperspectral sensor. The large calibration panels in the center of the image were instrumented to measure their temperature providing a quantitative measure of the algorithm accuracy. Here, the temperatures were retrieved to within 1-2 K.

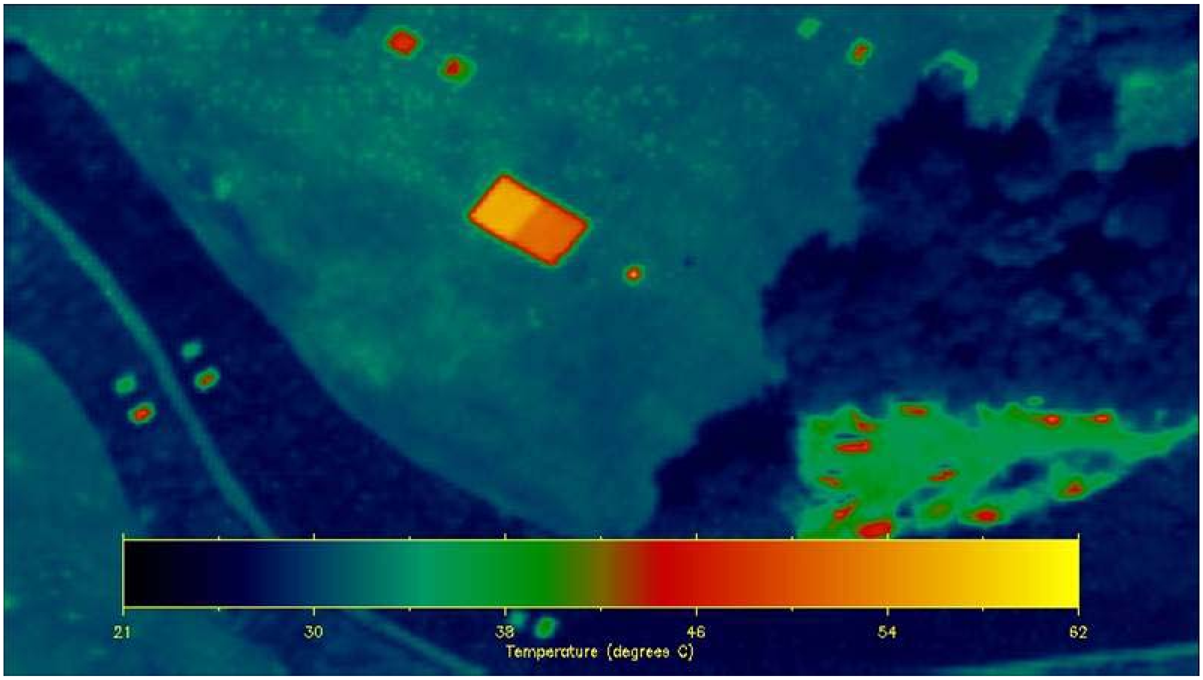

Figure 5: Estimated surface temperature for an image collected with the SEBASS LWIR hyperspectral sensor over Camp Eastman in Rochester, NY during the MegaCollect experiment conducted in June 2004. Color indicated retrieved temperature as shown in the color bar. The large objects in the center of the scene are calibration panels. The left panel is black (and thus has a higher temperature) and the right panel is gray. The small object just to the right of the panels is a heated target. Retrieved temperatures are accurate to within approximately 1-2 K.

- **Multiband texture synthesis using histogram and power spectral density matching -** Subhadip Sarkar (PhD Student) and Glenn Healey

The problem of texture synthesis has been a topic of active research. Potential applications of texture synthesis can be found in hole-filling due to occlusion, the synthesis of photorealistic scenes, foreground and background removal and texture mapping. A number of approaches have been suggested for texture synthesis of color images (DeBonet 1997, Heeger 1995, Efros 1999, Gagalowicz 1985). Although there has been a significant amount of work on color texture synthesis, multispectral and hyperspectral texture synthesis has not received as much attention. Most of the methods referenced above do not perform well for images with high spectral dimensionality. We present an algorithm that is efficient, produces realistic texture images, and can be readily extended to multispectral and hyperspectral images that contain a large number of spectral channels. The information in a texture lies primarily in the distribution of color and structure. These two aspects are captured by the color histogram and power spectral density (psd) of the texture. The histogram specifies the distribution of color in the image. The power spectral density is a second order moment which directly corresponds to the auto-correlation function of the image and contains information about the spatial structure. For a given target texture, our goal is to synthesize textures with a histogram and psd which is as close to the target as possible. We propose a synthesis scheme where the histogram and psd of the synthesized image are equalized to the target histogram and psd iteratively. This approach extends previous methods for the generation of synthetic gray scale images (Gagalowicz 1985).

Texture color distribution and structure are captured by the histogram and power spectral density (psd) of the texture image respectively. Our approach to texture synthesis is to start with a white noise image and match its histogram and power spectral density to a model texture iteratively till the errors in the histograms and psds between T and S fall below a threshold. In practice, the errors tend to become small after 5-10 iterations for most textures. Different texture samples can be obtained by using different white noise seed images. The texture synthesis algorithm was applied to a variety of real textures. A 256×256 pixel texture sample form the MIT vistex database along with the corresponding synthetic texture is shown in Figure 6. The corresponding error between histograms of the original and the synthesized textures is also shown. In another set of experiments, we compared the textures created by the Digital Imaging and Remote Sensing Image Generation (DIRSIG) (Schott 1999) synthetic image generation software with the texture synthesis algorithm. Figure 7 shows a real scene from the Wildfire Airborne Sensor Program (WASP) (Li 2005) of Camp Eastman which is near Rochester, NY. A DIRSIG generated image for the same scene is also shown in the figure. Both images consist of 3 spectral channels corresponding to the colors red, green, and blue. A region showing a 256×256 pixel sample forest texture is shown highlighted in both the images. Figure 8 compares a close-up view of the WASP texture with textures created by DIRSIG and the synthesis algorithm.

Finally, we show results of the synthesis experiments on hyperspectral data. Figure 9 shows a scene obtained by using the Hyperspectral Digital Imagery Collection Experiment (HYDICE) (Basedow 1995) sensor. The HYDICE sensor captures 221 spectral bands in the wavelength range of 400 to 2500 nm. We have mapped the channels at wavelengths 645, 560 and 455 nms (bands 50, 38 and 17) to red, green and blue respectively to create a color image of the scene. The areas containing the model textures are shown with a white square. Each area is 64×64 pixels in size. A close-up view of one of the regions along with the corresponding synthesized texture is also shown. In this work, we have developed an algorithm for multispectral texture synthesis. The algorithm works well for a variety of natural textures. We start with a synthetic texture initialized to white noise in each band and iteratively equate its histogram and power spectral density to those of a model texture. The errors typically converge after a small number of steps. The textures produced by the synthesis algorithm are computed efficiently and accurately match the model textures.

Figure 6: Synthesis of a fabric texture: (a) Original texture, (b) Synthesized texture, (c) Histogram error.

Figure 7: WASP scene and the corresponding DIRSIG scene. A forest region is enclosed within a white box in each of the images.

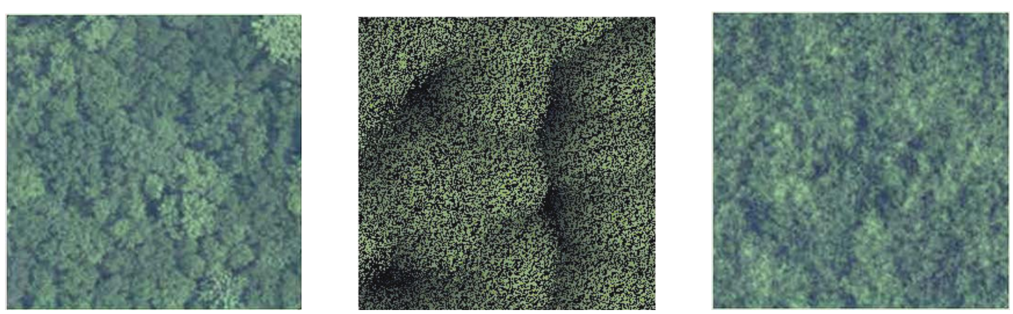

Figure 8: Comparison of our synthesized image and DIRSIG image.

Figure 9: HYDICE scene with a close up of a grass texture from the scene along with the corresponding synthetic texture.

IMPACT/APPLICATIONS

The RIT MURI Team believes that this research work can have a significant impact in how hyperspectral data is processed and how the resulting information products are generated. The invariant algorithm research is already showing promise in reducing false alarms under varying collection conditions. The water modeling activity is showing promise for a more accurate 3D representation of shallow water optical conditions, which will benefit algorithm development and testing and provide a significant advancement of in-water visualization.

TRANSITIONS

The MURI team has identified technology transfer as an important element of this project and has been a key metric to its success. This MURI has been a catalyst leading to multiple hyperspectral algorithm related research projects as listed below.

RELATED PROJECTS

- NGA University Research Initiative (NURI) – RIT project that involves the implementation of advanced hyperspectral algorithms into an ENVI software environment and then conducting robustness testing to evaluate performance. This project started June 2002 thru September 2006.

- Army Research Organization (ARO) Multidisciplinary University Research Initiative (MURI) – RIT is on a research team led by Georgia Institute of Technology to develop multi and hyperspectral processing techniques for tactical sensors (UAV and helicopter platforms). RIT's role involves the generation of physics-based models using DIRSIG that are being used for algorithm development and testing. This project initiated in October 2002.

- Intelligence Community (IC) Post Doc – In September 2005, RIT was awarded a Post Doc grant to continue the work initiated on this effort of Emmett Ientilucci in the area of physics-based hyperspectral algorithms. This was recently renewed for a third year.

- National Geospatial-intelligence Agency Research – RIT was awarded a contract in June 2007 support Naval Research Laboratory (NRL) on an algorithm related development program using the characterization of physically derived signature space.

REFERENCES

Basedow, R., Armer, D., and Anderson, M., "HYDICE system: Implementation and performance," in Proc. SPIE, 2480, pp. 258–267, (1995).

Carder, K., Reinersman, P., Costello, D., Kaltenbacher, E., Kloske, J., Montes, M., "Optical inspection of ports and harbors: laser-line sensor model applications in 2 and 3 dimensions," Proceedings of the SPIE: Photonics for Port and Harbor Security, 5780, pp. 49-58, (2005).

De Bonet, J. S., "Multiresolution sampling procedure for analysis and synthesis of texture images," Computer Graphics 31(Annual Conference Series), pp. 361–368, (1997).

Efros, A., and Leung, T. K., “Texture synthesis by non-parametric sampling,” in ICCV (2), pp. 1033–1038, (1999).

Gagalowicz, A., and Ma, S. D., “Sequential synthesis of natural textures,” Computer Vision, Graphics and Image Processing 30, pp. 289–315, (1985).

Heeger, D. J. and Bergen, J. R., “Pyramid-based texture analysis/synthesis,” in SIGGRAPH, pp. 229–238, (1995).

Kim, M. and Philpot, W., Fast Implementation of the T-matrix Nonspherical Scattering Code. in 2006 Ocean Sciences Meeting. Honolulu, Hawaii. (2006a)

Kim, M. and Philpot, W.D. Ocean Optics Phytoplankton Simulator, http://ceeserver.cee.cornell.edu/wdp2/OOPS/oops_manual.html . (2006b)

Kim, M. and Philpot, W.D., Development of a laboratory spectral backscattering instrument: Design and simulation. Applied Optics, **44**(32):6952-6961, (2005a)

Kim, M. and Philpot, W.D., Optical modeling of non-spherical particles. in Current Problems in Optics of Natural Waters 2005. St. Petersburg, Russia, (2005b)

Kim, M. and Philpot, W.D., Investigation of various integrating sphere designs for measurement of spectral absorption. in Ocean Optics XVI. Santa Fe, NM, (2002)

Kim, M. and Philpot, W.D., Optical Modeling of Phytoplankton: “Comparison between Spherical and Nonspherical Models”, International Conference on Current Problems in Optics of Natural Waters., St. Petersburg, Russia, (2001).

Lee, K., "A Subpixel Scale Target Detection Algorithm for Hyperspectral Imagery", Ph.D. Dissertation, Rochester Institute of Technology, Center for Imaging Science, 2003

Li, Y., Vodacek, A., Kremens, R. L., Ononye, A., and Tang, C., “A hybrid contextual approach to wildland fire detection using multispectral imagery,” IEEE Trans. Geosci. Remote Sens. 43(9), pp. 2115– 2126, (2005).

Mobley, C. D., Gentili, B., Gordon H. R., Jin, Z., Kattawar. G. W., Morel, A., Reinersman, P., Stamnes, K., and Stavn, R. H., "Comparison of numerical models for computing underwater light fields," Appl. Opt. **32**, 7484- (1993).

Raqueño, R., Simmons, R., Fairbanks, R., and Schott, J., "A model-based approach to hyperspectral analysis of water constituents," Presented at AVIRIS Earth Science and Application Workshop, February (2001).

Rolland, J. P., Vo, V., Bloss, B., and Abbey, C. K., “Fast algorithms for histogram matching: Application to texture synthesis,” Journal of Electronic Imaging 9(1), pp. 39–45, (2000).

Schott, J., Brown, S., Raqueno, R., Gross, R., and Robinson, G., "An advanced synthetic image generation model and its application to multi/hyperspectral algorithm development," Canadian Journal of Remote Sensing 25(2), pp. 99–111, (1999).

Schott, J.R., "Combining image derived spectra and physics based models for hyperspectral image exploitation," AIPR/IEEE Workshop, Washington DC, October (2000)

Zaneveld, J.R.V., Boss E., and Barnard, A. H. "The influence of surface waves on measured and modeled irradiance profiles," *Applied Optics.* 40(9): 1442-1449, (2001).

PUBLICATIONS (released during this reporting period)

Hamel, J., Raqueno, R. V., Schott, J. R., "Model-based Estimation of Suspended Mineral Inherent Optical Properties and Volume Spectral Reflectance for Atmospheric Compensation of Spectral Imagery in Case II Waters", Poster Session, Ocean Optics, Montreal, Canada (2006)

Ientilucci, E.J. "Two Dimensional Decision Spaces Generated from Physics Based Target Detection as Applied to Hyperspectral Imagery", International Congress of Imaging Science (ICIS), May 2006

Ientilucci, E.J., Schott, J.R., "*Physics Based Target Detection using a Hybrid Algorithm with an Infeasibility Metric*", **Invited Paper**, IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), (Toulouse, France), May 2006

Ientilucci, E.J. "Statistical *Models for Physically Derived Target Sub-Spaces*", I*n Proc. SPIE, Imaging Spectrometry XI,* Vol. 6302, (San Diego, CA), August 2006.

Kartik Chandra and Glenn Healey, ``Reflectance/illumination separation for 3D scenes,'' in Proc. SPIE 5806, 406 (2005)

Kartik Chandra and Glenn Healey, ``Recovering Surface Properties for Hyperspectral Scenes,'' in Proc. SPIE6233, 62331H (2006)

Philpot, W., (in press) "Estimating atmospheric transmission and surface reflectance from a glint contaminated spectral image," *IEEE Transactions on Geoscience and Remote Sensing*.

Schott, J. R., *Remote Sensing: The Image Chain Approach, 2nd Edition*, Chapter 11: Use of Physics-based Models to Support Spectral Image Analysis Algorithms, Oxford University Press, 2007.

Taylor, D. Z., Raqueno, R. V., Schott, J. R., "Case II Atmospheric Compensation: Simultaneous Aerosol and Water Constituent Retrieval in the NIR", Poster Session, Ocean Optics, Montreal, Canada (2006)