Physical Modeling for Processing Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Hyperspectral Data

Final Report: 1 October 2001 – 31 December 2006

Dr. Allen H.-L. Huang, Principal Investigator (PI)
Wayne F. Feltz (PM)
Cooperative Institute for Meteorological Satellite Studies (CIMSS)
Space Science and Engineering Center (SSEC)
University of Wisconsin–Madison (UW)
1225 West Dayton Street
Madison, Wisconsin 53706-1695
Phone: (608) 263-5283 Fax: (608) 262-5974
Email: allen.huang@ssec.wisc.edu Web Page: http://cimss.ssec.wisc.edu/muri/
Award Number: N000140110850
Grant Number: 144KE70

LONG-TERM GOALS

This Office of Naval Research (ONR), Department of Defense (DoD) research effort has three main long-term goals. They are: 1) to bridge the physical principles of a hyperspectral data retrieval problem with the mathematical algorithms that try to solve it; 2) mathematically quantify the location of useful information to complete a physically-driven application in the electromagnetic spectrum, and 3) develop physically-based hyperspectral data processing applications for surface material identification, atmospheric parameter retrieval formulation, and coastal water quality assessment.

OBJECTIVES

The objective of this DoD research effort is to develop and demonstrate a fully functional hyperspectral data processing system with the potential for a transition to operational deployment in a centralized and/or shipboard real-time processing environment. The system will provide specialized methods for the characterization of the atmospheric and surface material components of the battlefield environment that will take good advantage of the revolutionary capabilities of the new hyperspectral satellite missions.

APPROACH

This project involves four research objectives of this DoD ONR Multidisciplinary Research Program of the University Research Initiative (MURI) initiative. The plan charts an evolution of hyperspectral satellite capabilities, from information content, to describing mesoscale (length scales 25–1000 km) environments.

1. Mathematical Quantification of Useful Hyperspectral Information
   - UW Co-Investigators (Co-I) Dr. Jun Li, Dr. Bormin Huang, Dr. Paul Lucey, Erik Olsen, and PI Dr. Allen Huang developed methods that objectively identify the information-rich radiance channels that possess the most useful information.

2. <u>Radiative Transfer Modeling</u> (*Clear and Cloudy-Sky Emission/Absorption, Atmospheric Particulate Emission/Absorption, Surface Emission/Absorption*)
   - Dr Dave Tobin, Leslie Moy, Dr Allen Huang, and Dr Jim Davies have produced an improved clear-and cloudy-sky fast radiative transfer model for hyperspectral data processing. This involves subcontractors Dr. Ping Yang (Texas A&M Univ.), and Dr. Gary Jedlovec (Univ. of Alabama-Huntsville).
3. <u>Mathematical Retrieval Algorithm Development</u> (*Atmospheric Parameters, Suspended Particulate Detection and Quantification, Sea Surface Temperature, Surface Material Identification*)
   - Co-I's Dr. Steve Ackerman, Dr. Allen Huang, Dr. Jun Li, Dr. Paul Lucey (UH), Wayne Feltz, Chris Velden, Dr. Irina Sokolik, (Univ. of Colorado–Boulder) and Dr. John Mecikalski have developed parameter retrieval methods.
4. <u>Product Research</u> (*Ocean Surface Characterization, Lower Tropospheric Temperature, Moisture and Winds, Surface Material Products, Aerosols, Derived, Second Order Products*)
   - Co-I's Dr. Paul Lucey, Chris Velden, Wayne Feltz, and Dr. Steve Ackerman have used simulated GIFTS data within retrieval algorithms to improve and understand hyperspectral capabilities.

WORK COMPLETED

Funding over the period 1 October 2001 – 31 December 2006 through this MURI Topic #15: *"Physical Modeling for Processing of Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Hyperspectral Data"* has been used to perform basic research in the above four research areas. This research has involved UW CIMSS investigators, as well as four subcontractors outside the UW. Successful reviews of the University of Wisconsin MURI research were conducted during this grant period on 14-15 May 2002, 28-29 May 2003, 27-28 April 2004, and 7-9 June 2005. The main reporting activity occurred on 7-9 June 2005 through the *Fifth MURI Workshop* at the UW CIMSS. This workshop brought together the DoD MURI program managers, ONR science advisors, NASA, NOAA, Naval Research Laboratory, and private industry representatives, UW MURI subcontracted investigators [from the University of Alabama–Huntsville (UAH) and Texas A&M University (TAMU)] and UW and University of Hawaii (UH) MURI investigators. During this two-day meeting, all non-MURI representatives were informed of progress made in the area of hyperspectral GIFTS data simulation and retrieval algorithm development. In addition, the UW PI, Program Manager (PM), and all Co-I's obtained a more complete understanding of this MURI program. More details about this workshop are available at: <u>http://cimss.ssec.wisc.edu/muri/meetings/2005/</u> including agenda and presentations.

I. Radiative Transfer Modeling

Progress has been made with both clear- and cloudy-sky forward RTE model development for hyperspectral retrievals. The basic research involved: 1) Adding functionality to the existing GIFTS fast model, 2) Developing an improved fast "forward" RTE model, and 3) Including a proper representation of clouds (ice and liquid water) particle concentrations, and associated RTE representations of clouds of various composition, into a "cloudy-sky" RTE model.

An accurate and efficient clear sky forward model for GIFTS (and other high spectral resolution sensors) was developed with various features required for atmospheric profile and radiance data assimilation in a NWP context. Accomplishments included reproducing and upgrading the existing GIFTS fast model transmittance coefficients promulgated through 2003, incorporating an improved dependent set of atmospheric profile statistics, and development of a water vapor continuum regression made at nadir and then applied to all angles. Corresponding tangent linear adjoint code was written and tested to machine precision accuracy with a user friendly "wrap-around" code. Surface reflected radiance was also implemented within the clear sky fast model using a greatly improved two point quadature methodology.

The GIFTS (Geostationary Infrared Fourier Transform Spectrometer) fast radiative transfer model (GIFTSFRTE), initially a clear sky model, has evolved to include the radiative effects of clouds, aerosols and surface spectral emissivity. The impetus for continued model development is to provide accurate and rapid computations of the infrared emission of the Earth's surface and atmosphere, at high spectral resolution, to serve the needs of algorithm developers working to retrieve geophysical quantities from hyperspectral satellite observations. Implementation of a two-layer cloud model within the framework of the GIFTS fast model (ly2g) was completed and included the access to an ecosystem surface emissivity model (MODIS band resolution). A complete system was also implemented for computing GIFTS fast model and LBLRTM/DISORT simulated brightness temperatures for GIFTS channels and equivalent cloudy profiles.

Clouds act to reduce the signal level and may produce noise dependence on the complexity of the cloud properties and the manner in which they are treated in the profile retrieval process. There are essentially three ways to extract profile information from cloud contaminated radiances: (1) cloud-clearing using spatially adjacent cloud contaminated radiance measurements, (2) retrieval based upon the assumption of opaque cloud conditions, and (3) retrieval or radiance assimilation using a physically correct cloud radiative transfer model which accounts for the absorption and scattering of the radiance observed. Cloud clearing extracts the radiance arising from the clear air portion of partly clouded fields of view permitting soundings to the surface or the assimilation of radiances as in the clear field of view case. However, the accuracy of the clear air radiance signal depends upon the cloud height and optical property uniformity across the two fields of view used in the cloud clearing process. The assumption of opaque clouds within the field of view permits relatively accurate profiles to be retrieved down to near cloud top levels, the accuracy near the cloud top level being dependent upon the actual microphysical properties of the cloud. The use of a physically correct cloud radiative transfer model enables accurate retrievals down to cloud top levels and below semi-transparent cloud layers (e.g., cirrus). It should also be possible to assimilate cloudy radiances directly into the model given a physically correct cloud radiative transfer model using geometric and microphysical cloud parameters retrieved from the radiance spectra as initial cloud variables in the radiance assimilation process. The above three ways to extract profile information from cloud-contaminated radiances are being developed. AIRS (Aumann et. al., 2003) radiance spectra are used to illustrate how cloudy radiances can be used in the profile retrieval process.

Development of ice cloud microphysical and optical models for multispectral instruments was also accomplished to provide ice cloud bulk scattering models that are developed consistently for a suite of multi-spectral and hyperspectral instruments. A library of IR scattering properties for each habit/size bin including volume, projected area, maximum dimension, single-scattering albedo, asymmetry factor and extinction efficiency was compiled and added to the GIFTS fast model framework.

Unification of radiative transfer model from microwave to infrared was accomplished with the purpose of developing one fast RT model which spans the thermal spectrum to provide consistency in radiative calculations, multi-sensor retrievals of atmospheric profiles and cloud properties, and direct radiance assimilation applications. Figure 2 shows an example of monochromatic calculations using this unified fast RT model.

Automation of the selection of cloud layer heights, optical depths, and effective radii from mesoscale model input was also completed. Netcdf interface options were also added to make visualization easier using Unidata's IDV.

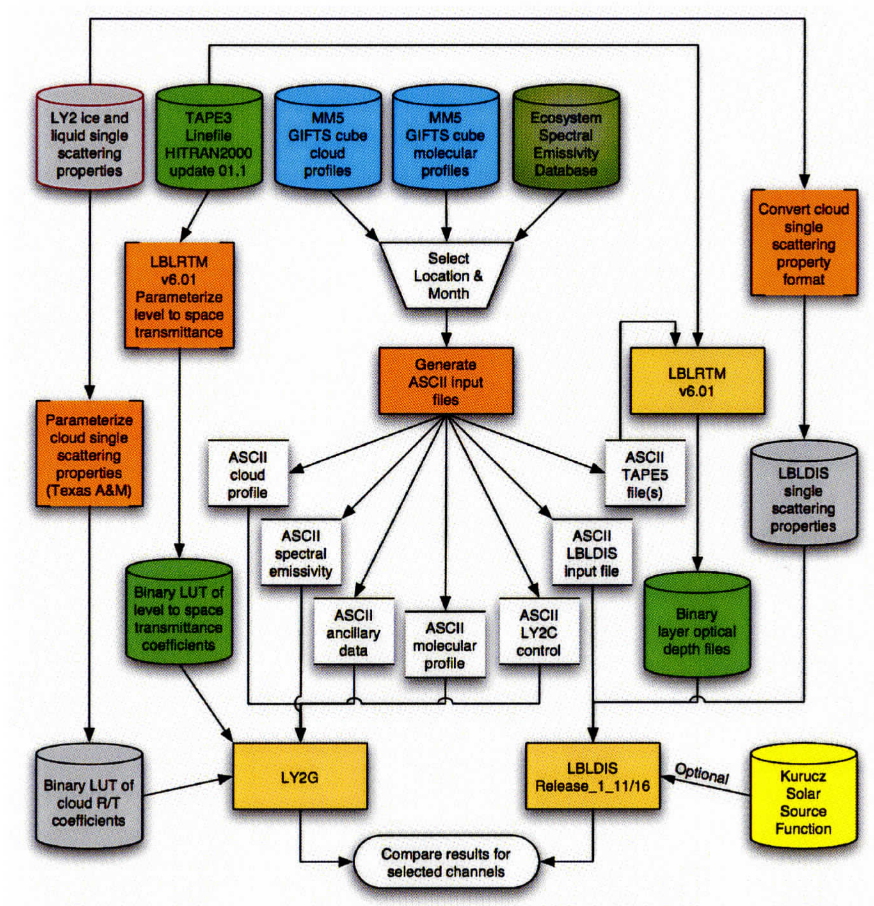

Figure 1. A schematic consistent single scattering properties and hi-res radiative transfer model implementation.

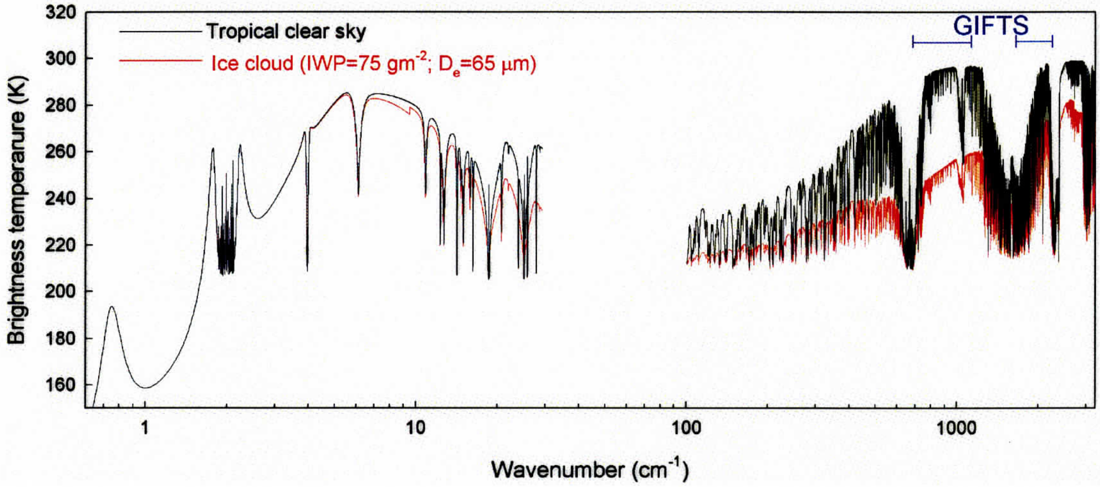

Figure 2. Monochromatic calculation of microwave and infrared spectrum from unified fast radiative transfer model.

II. Mathematical Retrieval Algorithm Development

To provide a valid proxy data set to test GIFTS retrieval applications, high resolution numerical weather prediction model runs were conducted using the MM5 and new generation WRF model to determine the ability of each to realistically simulate Mesoscale atmospheric structures. In order to properly compute the NWP fields CIMSS successfully proposed for and was granted funding through NAVY DURIP call for proposals to purchase an SGI Altix linux cluster computer system (not acquired through NAVY MURI funding). Examples of WRF and MM5 NWP simulations are shown in figure 3. The simulated temperature and water vapor profiles from the NWP output can than be used to compute infrared brightness temperature in clear and cloudy conditions with fast models described in section I. An example is shown in figure 4.

Temperature and water vapor retrievals from simulated GIFTS hyperspectral satellite data were utilized to compute atmospheric stability parameters for a convective initiation event during IHOP_2002. This was done as part of a study to demonstrate the benefits of geostationary hyperspectral satellite-derived information in mesoscale weather forecasting. WRF numerical weather prediction model temperature/moisture and cloud microphysical profiles are passed into the GIFTS forward model to acquire radiances at a very high spectral resolution (~.5 cm^{-1}) across the entire proposed GIFTS spectral range (~4.5-6.0 μm and ~8.5-15.0 μm). Simulated satellite-derived temperature/moisture profiles are obtained using clear-sky hyperspectral radiances within a regression-based retrieval algorithm. The WRF CAPE calculation can be regarded as "truth" in this case, being that the GIFTS thermodynamic profiles were created using WRF profiles as initial inputs. A comparison of two CAPE calculations yields good agreement in terms of instability axis location across the TX/OK Panhandles, but weaker agreement in terms of CAPE magnitude. These differences stem from the use of a preliminary regression-based retrieval algorithm. Recent advances by Dr. Jun Li of UW-CIMSS have resulted in the development of a physical retrieval algorithm, which has shown to provide significant improvement over the former algorithm.

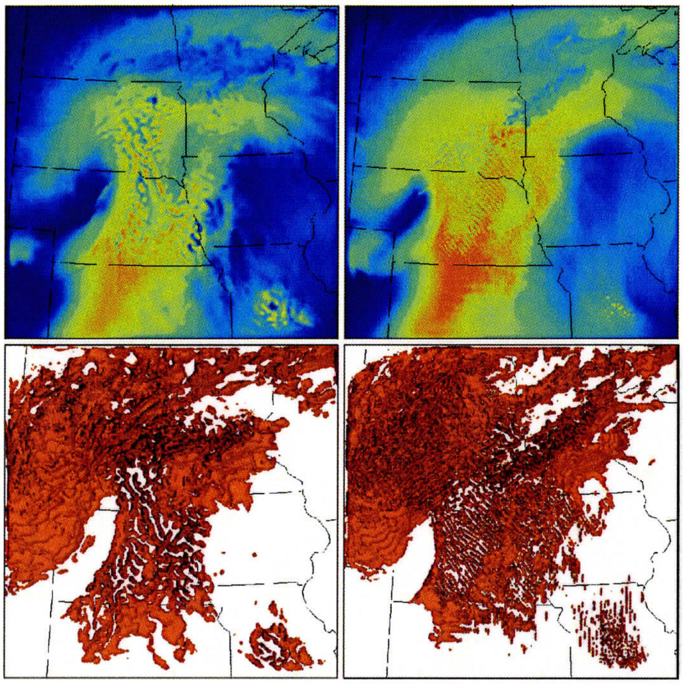

Figure 3. Examples of MM5 (right column) and WRF (left column) 2.5 km water vapor mixing ratio (top row) and liquid cloud water (bottom row) indicating improved horizontal resolution of WRF model.

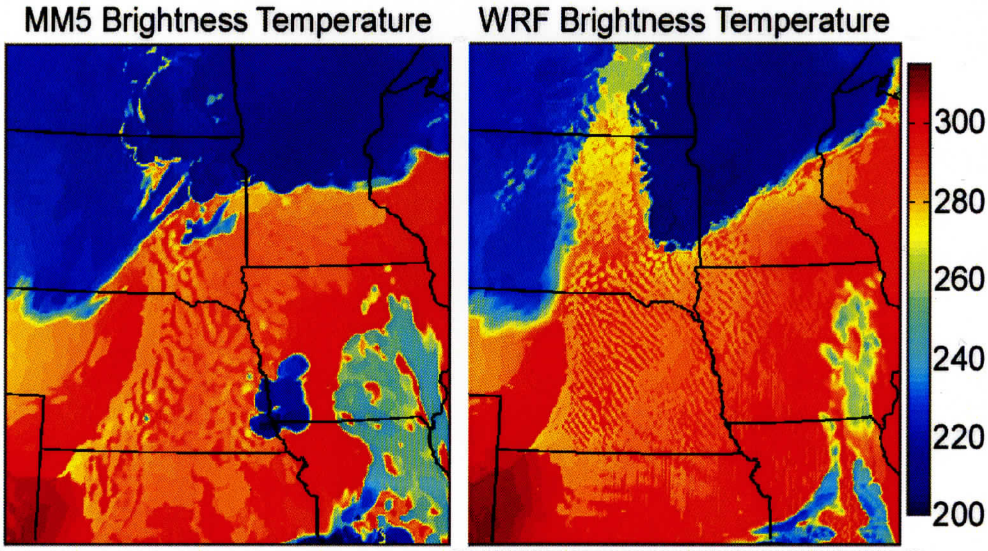

Figure 4. Simulated 10.7 micron infrared radiance from MM5 and WRF simulated thermodynamic profiles.

In addition to using simulated NWP data, a clear sky sounding retrieval algorithm has been tested using AIRS data using both regression and physical techniques. An optimal imager/sounder cloud-clearing algorithm has also been developed and published (Li et al. 2005). An optimized imager, sounder, and microwave retrieval combination was advanced and still in development.

The objective of the hyperspectral surface emissivity project was to improve the retrieval of atmospheric temperature and water vapor by improving the accuracy of training sets used in physical-statistical regression retrieval methods. In these retrieval schemes, radiosonde temperature-moisture-ozone profile and calculated radiance pairs are used to create a synthetic regression relationship for atmospheric retrievals. Over 12,000+ global profiles of temperature, moisture, and ozone were used in the training data set. Profiles are from NOAA-88, ECMWF training set, TIGR-3, ozonesondes, desert radiosondes: all with saturation checks and other QC. Radiance calculations for each training profile are made using a 101 pressure layer transmittance model. These calculations require a skin T and emissivity value for each profile.

Ongoing research at UH involves 1) improving surface ε estimates from hyperspectral measurements, and 2) using MODIS surface emissivity product to derive hyperspectral emissivity model to match the radiance spectra of the forthcoming GIFTS instrument. This work allows UW and UH to fully collaborate as UW is sharing simulated GIFTS data with UH, and UH provides improved ε algorithms to UW.

III. Meteorological Hyperspectral Product Research: Winds, Stability, Turbulence, and Volcanic Ash

The concept of deriving tropospheric winds from retrieved moisture analyses provided by hyperspectral sensors was proven through simulated GIFTS datasets and one case of NASTI aircraft measurements. One area of investigation pursued the exploration of deriving winds from AIRS hyperspectral radiance data. The first test was to attempt to track AIRS radiance features from 2 channels for one day, 7 April 2004. The AIRS channels (10.976 um, 6.764 um) chosen were close to the MODIS bands (11 um and 6.7 um) used for the real-time polar winds processing . A second test was conducted to track moisture features from height-resolved analyses derived from AIRS retrievals. Operational AIRS retrievals are done with 3x3 FOV AIRS footprints. To track these retrievals, the resolution of the data would be about 50 km per pixel. With a 100 minute orbit, a one-pixel error would correspond to about 8 m/s. This means we would not be able to detect motions slower than about 8-16 m/s (1-2 pixels). Therefore, derived fields of moisture from single FOV AIRS retrievals were used for tracking. The retrieval algorithm employed an experimental cloud-clearing routine. These moisture fields at constant altitudes will be used to target and track features in sequential images to derive vectors. Algorithm results are shown in figure 5 indicating successful tracking of AIRS derived moisture features through three successive overlapping AIRS polar overpasses. This demonstrates the feasibility of tracking hyperspectral derived water vapor features from geostationary orbit.

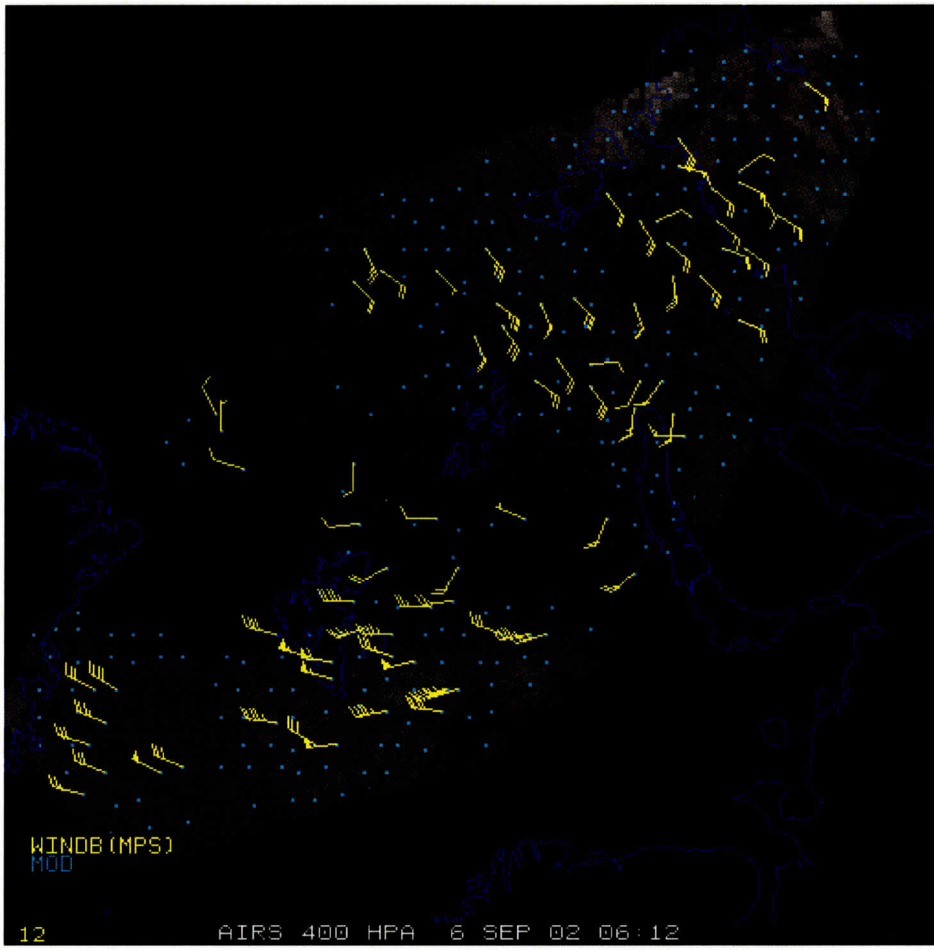

Figure 5. AIRS moisture derived retrieval targets and atmospheric motion vectors at 400 hPa using three successive polar overpasses.

Simulated hyperspectral data was used to produce thermodynamic retrievals and then derive atmospheric stability indices to provide insight to information degradation due to the retrieval methodology and spectral information sensitivity studies. Physical thermodynamic retrieval methodologies were found to be superior to statistical regression methods. Atmospheric stability comparisons greatly improved in clear sky cases as retrieved temperature and water vapor profiles yield better agreement with NWP model "truth". In addition, MURI provided resources to begin aviation hazard detection techniques using simulated and current generation hyperspectral instruments were investigated and optimized specifically for turbulence and volcanic ash.

Other UW MURI subcontractor involvement is summarized as follows: UAH has developed algorithms suitable for processing GIFTS measurements to differentiate cloudy regions from clear and identifying unique characteristics such as cloud type, and height. The TAMU continues to work heavily on cloud-sky radiative modeling, with emphasis on both ice and water clouds.

RESULTS

The meaningful technical results since from 1 October 2001–31 December 2006 are summarized:

- Full development of simulate hyperspectral data; the creation of 7 GIFTS simulation data sets.

- Continued improvements to clear- and cloudy-sky RTE models at CIMSS and TAMU for GIFTS.
- A physical non-linear algorithm for the retrieval of atmospheric T and q profiles simultaneously from GIFTS radiance spectra in clear and cloudy atmospheres.
- Development of various applications of hyperspectral data in the areas of clouds (UAH), turbulence and convection (CIMSS), and cloud properties (CIMSS).
- New computer greatly improved capacity to produce higher resolution NWP simulations needed to investigate future hyperspectral resolution capabilities
- Basic research has been honed to focus on current and future meteorological forecasting needs specifically with toward aviation hazards and severe weather conditions
- Leveraging with other hyperspectral funding (GOES-R Risk Reduction) to support general Navy, NOAA, and NASA hyperspectral science
- More than 30 conference papers and 15 journal papers published with MURI related efforts: http://cimss.ssec.wisc.edu/muri/
- This basic research provides a solid foundation for prototyping Naval hyperspectral meteorological application system

IMPACT/APPLICATIONS

The immediate application and impact of the basic research accomplished was the use of simulated hyperspectral data to formulate atmospheric parameter retrieval algorithms to form the meteorological products highlighted by DoD as valuable to Navy fleet operations.

TRANSITIONS

The algorithms described above for GIFTS continue to development for future GOES-R Hyperspectral Environmental Sounder sensor and next generation polar sensors such as CrIS and IASI. No person or institutions outside UW and UH are utilizing them. The basic research was performed to form robust atmospheric parameter products to address the Year 3-5 proposed tasks. All UW subcontractors collaborated toward completion of a full (clear-sky, cloudy-sky, surface) suite of retrieval algorithms. Student sharing between UW and UH did occur.

RELATED PROJECTS

The projects that closely related to the UW and UH MURI basic research initiative include: 1) the GIFTS development work at UW supported by NASA and NOAA, 2) student and basic research involvement with Prof. Morgan of UW for using GIFTS-IOMI for NWP, data assimilation and atmospheric parameter retrievals, and 3) the future value of this basic research to a number of UW CIMSS projects related to mesoscale nowcasting for aviation safety issues.

SUMMARY

To date, this UW and UH MURI has provided to the scientific community the first procedures for simulating and using hyperspectral radiance information from GIFTS instrument to form atmospheric products that will describe the mesoscale battlespace. These products will some day enhance the efficiency of Naval activities by providing to fleet highly-specialized meteorological information. The development of a first retrieval algorithm and a fast radiative transfer model for GIFTS, the transitioning of the AHI instrument to GIFTS spectral resolution, and the ability to simulate hyperspectal data, highlight the progress that UW and UH have made to date.

REFERENCES

Ackerman S., H-LHuang, P. Antonelli, B. Holz, H. Revercomb, D. Tobin, K. Baggett and J. Davies, 2003: Detection of clouds and aerosols using infrared hyperspectral observations. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society.

Bedka, K. M., J. R. Mecikalski, and W. F. Feltz, 2004: Analysis of convective clouds and turbulent boundary layers using hyperspectral data. Preprints, /Symposium on Observing and Understanding the Variability of Water in Weather and Climate/, Amer. Meteor. Soc., Boston, MA., Seattle, WA.

Davies J., H. Wei, P. Yang, H-L Huang, D. Turner, E. Olson, and D. Posselt, 2003: Fast model cloudy radiances for infrared hyperspectral observations. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society. .

Huang, H.-L, P. Yang, H.-L. Wei, B. A. Baum, Y.-X. Hu, P. Antonelli, and S. A. Ackerman, 2004: Retrieval of ice cloud properties from high spectral resolution infrared observations. IEEE Trans. Geosci. Remote Sens., 42, 842-853.

Huang, H.-L. et al., 2003: Minimum Local Emissivity Variance Retrieval of Cloud Altitude and Effective Spectral Emissivity – Simulation and Initial Verification. J. Appl. Meteo. (accepted)

Huang H.-L., H. E. Revercomb, J. Thom, P. B. Antonelli, B. Osborne, D. Tobin, R. Knuteson, R. Garcia, S. Dutcher, J. Li, and W. L. Smith, 2000: Geostationary Imaging FTS (GIFTS) Data Processing: Measurement Simulation and Compression. Proceedings of SPIE, William L. Smith and Yoshifumi Yasuoka, editors. *Hyperspectral Remote Sensing of the Land and Atmosphere*. 9-12 Oct. 2000, 103-114.

Huang H.-L., Dave Tobin, Jun Li, Erik Olson, Kevin Baggett, Bormin Huang[a], John Mecikalski, Bob Knuteson, Brian Osborne, Derek Posselt, Paolo Antonelli, Hank Revercomb, William Smith, and Ping Yang, 2002: Hyperspectral Radiance Simulator - Cloudy Radiance Modeling and Beyond. Optical Remote Sensing of the Atmosphere and Clouds III, SPIE, 25-27 Oct. 2002, Hangzhou, China, P180-189.

Huang H.-L., Chris Velden, Jun Li, Elisabeth Weisz, Kevin Baggett, James E. Davies, John Mecikalski, Bormin Huang, Russ Dengel, Steven A. Ackerman, Erik R. Olson, Robert O. Knuteson, Dave Tobin, Leslie Moy, Jason A. Otkin, Derek J. Posselt, Hank E. Revercomb, and William L. Smith, 2003: Infrared Hyperspectral Souding Modeling and Processing: An Overview, 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society.

Lee, Y.K., P. Yang, M. I. Mishchenko, B. A. Baum, Y. X. Hu, H-L Huang, W. J. Wiscombe, and A. J. Baran: On the use of circular cylinders as surrogates for hexagonal pristine ice crystals in scattering calculations at infrared wavelengths. Conditionally accepted pending minor revision, *Appl. Opt*., 42, 2653-2664(2003)

Li J., F.Y. Sun, S. Seemann, E. Weisz and H-L Huang, 2003: GIFTS Sounding retrieval algorithm development. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society.

Li J., H-L Huang, 2002: Boundary Layer Moisture Retrieval from Indian Ocean METOC Imaging (IOMI) mission for Geostationary Imaging Fourier Transform Spectrometer (GIFTS). Optical Remote Sensing of the Atmosphere and Clouds III, SPIE, 25-27 Oct. 2002, Hangzhou, China, P144-149.

Li, J., W. Wolf, W. P. Menzel, W. Zhang, H.-L. Huang, and T. H. Achtor, 2000: Global soundings of the atmosphere from ATOVS measurements: The algorithm and validation, *J. Appl. Meteorol.*, **39**: 1248-1268.

Mecikalski J., K. Bedka, W. Feltz, 2003: Analysis of Convective Clouds and Turbulent Boundary Layers using Hyperspectral Data. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society. .

Mecikalski, J. R. and D. J. Posselt, 2002: The developing infrastructure for hyperspectral data assimilation at the University of Wisconsin-Madison. Preprints. /Symposium on Observations, Data Assimilation, and Probabilistic Prediction/, Amer. Meteor. Soc., Boston, MA, pp 1-4.

Mecikalski, J. R., K. M. Bedka, W. F. Feltz, D. D. Turner, T. M. Weckwerth, and R. D. Torn 2003: Inferring convectively- induced roll structures and convergence in the boundary layer using profiling instruments: An application to convective initiation during IHOP_2002. Preprints, /Symposium on Observing and Understanding the Variability of Water in Weather and Climate/, Amer. Meteor. Soc., Boston, MA.

Mecikalski, J. R., K. M. Bedka, D. D. Turner, and W. F. Feltz, 2003: The identification and quantification of waves and roll turbulent structures within the convective boundary layer from high-time resolution remote sensing data. Submitted to *J. Geophys. Res*.

Moy L., D. Tobin, H. Woolf , 2003: Clear sky forward model development for GIFTS. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society. .

Otkin J., D. Posselt, E. Olson, J. Davies, W. Feltz, R. Knuteson and J. Mecikalski , 2003: Generation of Simulated Top of Atmosphere Radiance Datasets for GIFTS Algorithm Development. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American

Meteorological Society. .

Rink T., T. Whittaker and P. Antonelli : Exploring GIFTS/HES and other hyperspectral data using Python, the VisAD component library, and remote data access . 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society.

Smith W., G. Bingham, H-L Huang, J. Miller, H. Revercomb, C. Velden, D. Zhou, D. Emmitt, 2003: GIFTS – Hyperspectral imaging and sounding from geostationary orbit. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society. .

Sokolik I., 2002: Remote Sensing of Mineral Dust in the UV/Visible and IR Regions. Optical Remote Sensing of the Atmosphere and Clouds III, SPIE, 25-27 Oct. 2002, Hangzhou, China, P265-271.

Tobin, D., K. Baggett, R. Garcia, H. Woolf, H-L Huang, B. Knuteson, J. Mecikalski, E. Olson, B. Osborne, D. Posselt, and H. Revercomb, 2001: Simulation of GIFTS data cubes. Preprints, /11 Conf. on Satellite Meteorology and Oceanography,/ Amer. Meteor. Soc., Boston, MA, pp. 563-565.

Velden C., G. Dengel, R. Dengel, H-L Huang, D. Stettner 2003: Determination of wind vectors by tracking features on sequential moisture analyses derived from hyperspectral IR satellite soundings. 20th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Seattle, WA, 11-15 January 2004. Boston, MA. American Meteorological Society. .

Wei H. , Ping Yang, Jun Li, Bryan A. Baum, H-L Huang Steven Platnick, and Yong X. Hu, Retrieval of ice cloud optical thickness from Atmospheric Infrared Sounder (AIRS) measurement (to be submitted)

Yang, P., B. A. Baum, A. J. Heymsfield, Y.-X. Hu, H-L Huang, S.-C. Tsay, and S. A. Ackerman, 2003: Single scattering properties of droxtals. *J. Quant. Spectros. Rad. Transfer,* 79-80, 1159-1169.

Yang, P., H.-L. Wei, B. A. Baum, H-L Huang, A. J. Heymsfield, Y. X. Hu, B.-C. Gao, and D. D. Turner. The spectral signature of mixed-phase clouds composed of nonspherical ice crystals and spherical liquid droplets in the terrestrial window region. *J. Quant. Spectros. Rad. Transfer,* 79-80, 1171-1188(2003)

Yang, P. B.-C. Gao, W. Wiscombe, M. I. Mishchenko, S. Platnick, H-L Huang, B. A. Baum, Y. X. Hu, D. Winker, S.-C. Tsay, and S. K. Park, 2002: Inherent and apparent scattering properties of coated or uncoated spheres embedded in an absorbing host medium, 70, *Appl. Opt.* 41, 2740-2759.

Zhang, Z., P. Yang, G. W. Kattawar, S.-C. Tsay. B. A. Baum, H-L Huang, Y. X. Hu, A. J. Heymsfield, and J. Reichardt , 2003: Geometric optics solution to light scattering by droxtal ice crystals, *Appl. Opt.* (submitted)

Zhou, D. K., W. L. Smith, J. Li, H. B. Howell, G. W. Cantwell, A. M. Larar, R. O. Knuteson, D. C. Tobin, H. E. Revercomb, G. E. Bingham, J. J. Tsou, and S. A. Mango, 2003: Geophysical product retrieval methodology for NAST-I and validation, *Applied Optics* (in press).