8.4

MODIS INFRARED CHANNEL SPECTRAL RESPONSE FUNCTION CALIBRATION WITH CO-LOCATED AIRS OBSERVATION

Haibing Sun[2], W. Wolf [2], C. Barnet[1], Lihang. Zhou[2] and M. Goldberg[1]

[1]NOAA/NESDIS/ORA
5200 Auth Road, Camp Springs, MD 20746 USA
[2]QSS Group Inc, Lanham, MD, USA

1. Introduction

Moderate-Resolution Imaging Spectroradiometer (MODIS) is the key remote sensing instrument on the AQUA and Terra Satellites. MODIS has 36 channels covering the spectrum region from visible, to short wave infrared and far infrared. The calibration of MODIS includes both a pre-launch calibration and on-orbit calibration. For the visible and short infrared channel, the SpMA (Spectral Measurement Assembly) is applied to perform the on orbit spectral response monitoring, but for the infrared channel 20-36 (3.6 – 14.358µm), there is no way to monitor the instrument spectral sensitivity. Recent research about the MODIS observations suggest that instrument relative spectral response function (RSF) may shift with frequency in these 16 infrared channels [Tobin et al 2005]. To obtain precise on-board MODIS RSF which is important in the integration retrieval, such as AIRS-MODIS cloud clearing algorithms [Huang et al 2004], we have created a technique to use AIRS data with the MODIS data on AQUA to determine the MODIS RSF.

The Atmospheric Infrared Sounder (AIRS) is a high spectral resolution spectrometer on board the EOS Aqua spacecraft that measure the upwelling infrared radiance. It has 2378 bands in the thermal infrared (3.7 - 15.4 µm) and 4 bands in the visible (0.4 - 1.0 µm). The primary spectral calibration of the AIRS spectrometer is based on the cross-correlation between spectral features observed in the upwelling radiance spectrum with pre-calculated spectra. And additional spectral reference source is provided to aid pre-launch testing in the thermal vacuum chamber during spacecraft integration and for quality monitoring in orbit. AIRS provides high spectral resolution infrared radiances while MODIS provides high spatial resolution collocated radiances at sixteen broad infrared bands. The AIRS high spectral resolution observations within the low spectral resolution MODIS band can provide detailed spectral information of the atmosphere which then provides the possibility to use AIRS high spectral resolution to retrieve the MODIS spectral response function.

In this paper, the algorithms use co-located AIRS data to retrieve the MODIS RSF is presented. It is a part of the NESDIS contribution for the GEOSS system. Section 2 is a description of the mathematic model of the retrieval algorithms. Section 3 describes the algorithms component, section 4 present the algorithms validation results with discussion, and a short summary is given in section 5.

2. Mathematic Model of the Retrieval Algorithms

The standard techniques for measuring the spectral sensor sensitivities require the user to record the device's response to a monochromatic light across the channel spectrum band. For the MODIS infrared channels, the monochromatic light method is not readily available for the post-launch instrument calibration. An alternative approach is to formulate the problem as a constrained regression model. Instead of measuring the MODIS channel response to a narrow band monochromatic light source, the MODIS broad band spectral response function can be retrieved with a sequence of measurements of the MODIS broad band spectral response and the sensed atmosphere radiance spectrum. The MODIS broad band response of a spectral channel is related to the atmosphere spectral radiance with an integration equation, the relation is defined by the MODIS channel spectral response function. For MODIS observation of a channel i:

$$M_{rad_i} = \int A_{Rad_i} W \qquad (1)$$

in which $M_{rad\,i}$ is the MODIS response of channel i, W is the MODIS channel i RSF and $A_{Rad\,i}$ is the atmospheric spectral radiance. The continuous integration can be approximated with discrete integration:

$$M_{Rad_i} = \sum_j A_{Rad_{ij}} W_j \qquad (2)$$

in which W_j is the MODIS channel RSF at the j sampling frequency point and $A_{Rad\,i\,j}$ is the atmospheric spectral radiance at the sampling frequency point.

---

* *Corresponding author address:* Haibing Sun, Room 810 WWB, NOAA/NESDIS, 5200 Auth Road, Camp Springs MD 20746; email: Haibing.sun@noaa.gov

Equation 2.0 implies that MODIS channel RSF W can be retrieved by a simple linear regression when the MODIS broad band measurement and corresponding atmosphere spectral radiance are available. In NESDIS, AIRS and MODIS observations are collocated; the co-located AIRS data can provide the same atmosphere spectral radiance with high spectral resolution. The linear regression can be applied with co-located AIRS–MODIS observations to the MODIS channel where there is sufficient overlap with the AIRS channels [Fig 1,2]. Replacing the atmospheric spectral radiance with AIRS observation in equation 2.0, a sequence of co-located AIRS-MODIS measurement can be rewritten in a vector equation:

$$M_{Rad_i} = A\,W + \delta M \qquad (3)$$

in which $M_{Rad\ i}$ is the MODIS channel i observation vector which is composed of the MODIS observations. A is the AIRS observation matrix which is composed of AIRS observations within the MODIS band. W is the RSF vector. δM is the convolution bias introduced with limited AIRS spectral resolution and AIRS spectral gap. δM is general with small value. To simplify the algorithms at this point, we assume δM is equal to zero temporarily.

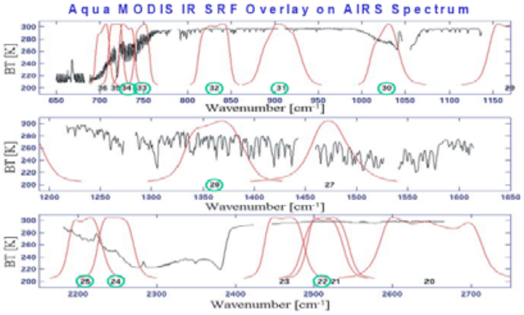


Figure 1.0 spectral overlap of AIRS /MODIS
(From Internet)

The equation 3.0 provides the straightforward retrieval algorithms for the MODIS RSF. But observation matrix A is rank deficient and inverting the equation is an ill-posed mathematic problem. The rank deficiency of A is introduced with the low dimensionality of the AIRS inter-channel spectral sampling of the atmospheric spectral radiance. The inversion of ill-posed equation will lead to the high sensitivity of the regression result to the noise. Results based upon the matrix inversion will fit the noise instead of the real MODIS RSF. In Figure 3.0, the direct inversion RSF retrieval of MODIS channel 35 is given. The results show that extra effort is necessary to retrieve with an ill-posed equation under the

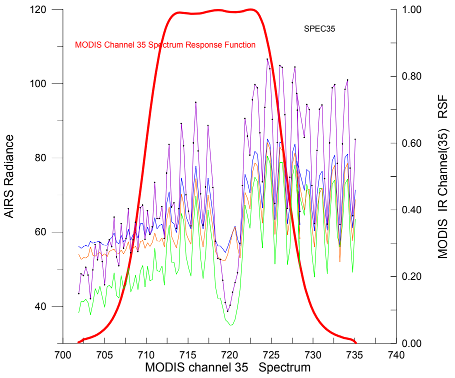


Figure 2.0

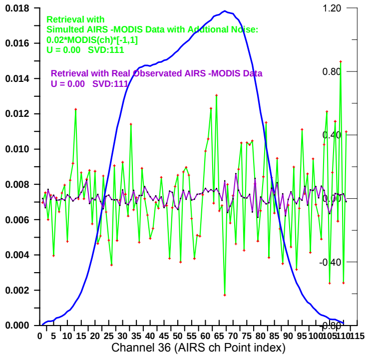


Figure 3.0

3. Constraint Retrieval Algorithms

To retrieve the MODIS RSF under the noise conditions, several noise constraint processing are embedded into the MODIS RSF retrieval algorithm to eliminate the effect of noise. These processing include: 1) Selection and pre-processing AIRS/MODIS observations used in the retrieval system to reduce the input data noise. 2) Improve the retrieval system to reduce the noise sensitivity of the retrieval system. 3) Pre-processing the retrieval result to reduce the effect of the noise.

3.1 Data Selection and Pre-processing

The noise within input data includes AIRS and MODIS instrument noise, calibration uncertainty and the bias introduced with mismatching. Both AIRS and MODIS have high radiometric accuracy requirements for achieving remote sensing goals. Accordingly, data selection and pre-processing focus on reducing the bias introduced with the mismatching.

There exist significant differences between the AIRS and MODIS spatial resolutions. In order to form a pair of AIRS and MODIS observations with the same atmospheric radiances, two processing steps are necessary: 1) Co-locate AIRS and MODIS observations. 2) Unify AIRS and MODIS spatial resolutions. The collocation algorithms with the AIRS spatial response function [Haibing sun et al 2005] are adapted to improve the coincidence of the source radiance. The purpose of applying the AIRS spatial response function in co-location include: 1) AIRS and MODIS radiance are from the same atmosphere. 2) the spatial contribution function of the atmosphere is same. To further limit the noise in the co-location processing, AIRS observations with the relative uniform atmosphere are selected. The uniform scene can be select according to the standard deviation of MODIS observations within AIRS effective field of view.

There are large spectral gaps in AIRS spectrum with MODIS bands 20, 29 and significant gaps with MODIS bands 25, 27, 28, 30 and 34. Those spectral gaps will result in a convolution bias in equation 3.0. Those convolution biases are functions of the atmosphere scene. In order to surpass the effect of the convolution bias, the AIRS-MODIS differential observation pair is used in the retrieval.

3.2 Retrieval System Improving

Given enough AIRS–MODIS observation pairs, equation 3.0 forms an over determined ill posed linear equation system. The constrained regression algorithms are developed to deal with similar problems in the retrieval of cameras RSF [Sharma et.al 1993] [Hubel et al 1994]. In the constraint algorithms, the property of camera RSF are incorporated into the equation regression processing as a constraint to overcome the noise sensitivity problem. Barnard [1995] and Fimlayson [2002] reformulate the inversing problem into a least-squares fit with a linear constraint. Barnard [2002] combine the smoothness constraint into the objective function as a regularization term. Paulus [2005] introduces truncated singular value decomposition (TSVD) to regulate the linear regressing equation.

The MODIS RSF retrieval algorithms is developed based upon Paulus ‘s algorithms and the differential observation equation is adapted to replace the observation equation. The cameral property used in the constraint is common to the majority of device sensors and can also be applied to MODIS sensor response function retrieval. The solution of the equation and the constraint can written as simple linear inequalities:

1) Bounded perdition error: $| M_i - A_{i,j} W_{i,j} | < \epsilon_i$ $I \in \{1,..N\}$

2) Sensor spectral response positivity: $W_{i,j} >= 0$

3) Sensor spectral response smoothness $| W_{i,j} - A_{i,j} W_{i,j+1} | <= T$ T is the threshold.

4) Band limitedness: $W_{i,j=0}$ $j < j_{low}$ $j > j_{high}$

Those inequalities can be combined into a single objective function. The constrained solution can be determined by minimizing the objective function f. Similar to Paulus ‘s algorithms, inequalities for the bounded perdition error and sensor spectral response smoothness constraint are combined to form the f:

$$f = \left\| A_{Rad} W - M \right\| + \mu \left\| W^T D W \right\| \qquad (4)$$

$$D = \begin{pmatrix} 1 & 0 & 0 & 0 & \ldots & \ldots & 0 \\ -1 & 2 & 0 & 0 & \ldots & \ldots & 0 \\ 0 & -1 & 2 & -1 & 0 & \ldots & 0 \\ \ldots & & & . & & & \\ 0 & & & -1 & 2 & -1 & 0 \\ 0 & . & . & 0 & -1 & 2 & -1 \\ 0 & . & . & . & 0 & 0 & 1 \end{pmatrix} \qquad (5)$$

In which μ is the weight of the smoothness constraint. To minimize the objective function f, we use the following equation:

$$\partial f / \partial W = 0 \qquad ==> \qquad W = \left(A^T A + \mu \bullet D\right)^{-1} A^T M \qquad (6)$$

To further reduce the noise sensitivity of the retrieval equation, the observation matrix A is regularized with the truncated-SVD method. The observation matrix A in equation 6 is replaced with A' which is the observation matrix where the high rank singular value is force to zero. The rank from which matrix is truncated is defined as residual rank: R_{SVD} .

$$W = \left(A'^T A' + \mu \bullet D\right)^{-1} A'^T M \qquad (7)$$

The positivity constraint and band limitedness are applied to the retrieval result to determine the result.

3.3: Retrieval Result Re-processing

To further reduce the noise effort, the retrieval results are averaged over multiple retrieval processing. Both observation noise and mismatching bias have random characteristic with zero mean, the differentiated AIRS convolution bias also approximate random noise with zero mean. The averaging over the retrieval results can effectively surpass the effect of the random noise. The collocated AIRS-MODIS data form an input dataset. In each processing, ‘M ‘observation pairs will be selected randomly from the dataset to form an over determined system (M > AIRS sample point numbers). The averaged retrieval results is the final retrieval result.

4.0 Algorithm Validation

The Algorithm Validation is performed with MODIS channel 36 RSF retrieval.

4.1 Validation Using Numerical Tests

Numerical tests are performed to validate the effectiveness of the retrieval algorithms. In the test, the co-located MODIS observation is replaced with simulated MODIS radiance. The simulated MODIS observation is the convolution product of the AIRS observation with the MODIS pre-launch measured RSF. Three numerical tests are performed with noise free simulated MODIS data. The first test is to validate the retrieval of Equation 7. The retrieval result [Figure 4] is for MODIS channel 36 RSF when ‘u’ is equal to 0 and the R_{SVD} is equal to full rank.

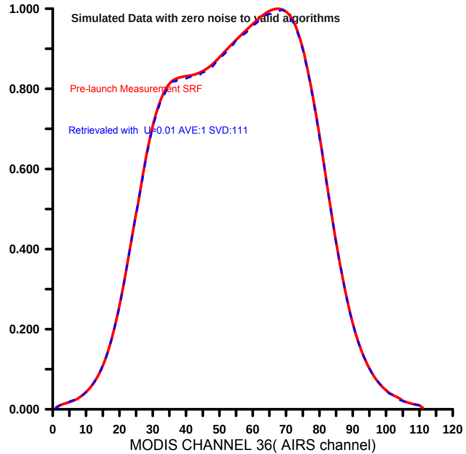


Figure 4.0

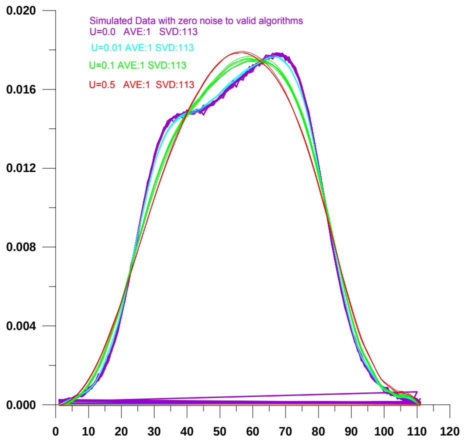


Figure 5.0

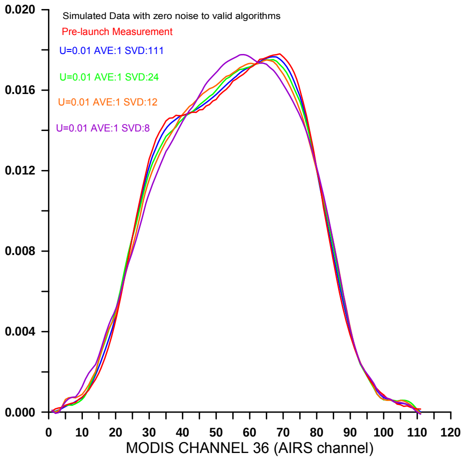


Figure 6.0

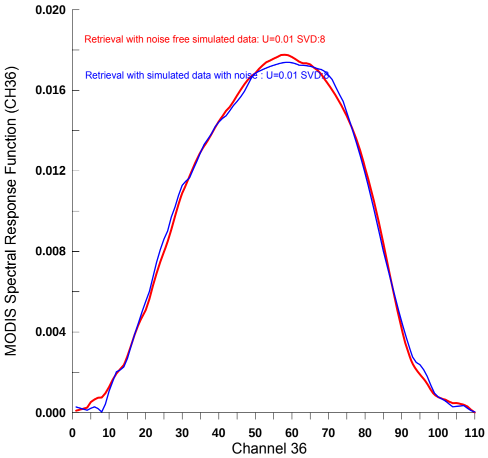


Figure 7.0

The second and third tests are to validate the effect of the two parameters in the retrieval equation: smoothness constraint weight coefficient ‘u’ and residual rank ‘$R_{SVD.}$’, Figure 5 shows the retrieval with different u (From 0.01 to 0.5) when R_{SVD} equal to full rank. Figure 6 shows the retrieval with different R_{SVD} when u equal to 0.01. Those results show that the algorithms can get the exact retrieval of MODIS RSF when there is no noise and thus no constraint necessarily added to the retrieval processing [Fig 4]. With the increasing weight of the smoothness constraint [Fig 5.0] and truncation level of AIRS observation matrix [Fig 6.0], the retrieval result will become biased related to the exact result. The bias is resulted from the surpass of the high frequency component in the retrieval when two regulations are applied. Keeping in mind that the smoothing constraint and the TSVD regulation are added to the retrieval necessarily to surpass the noise effect in the retrieval. In test four, noise is added to the simulated MODIS radiance. The retrieval result [Fig 7.0] shows that the constrained retrieval can approximate the retrieval with noise observation comparing with retrieval result with noise free observation.

4.2 Validation Using Real Observations

Retrievals using real co-located AIRS and MODIS data is performed for channel 36. The retrieval with different constraints is shown in Fig 8.0. Significant bias exists between pre-launch measurements and the constrained retrieval result. Part of the bias is introduced by the constrained processing. The smoothness constraint and the TSVD regulation in the retrieval will lead to the loss of the high frequency component in the retrieval. Higher constraint leads to more constraint related bias. The constraint is necessary for the retrieval under noise condition, but at the same time, the introduction of constraint in the retrieval will lead to the bias from the 'real' result. The practical algorithms are the compromise between more noise constraint and less constraint bias. In Figure 9.0, two constraint retrievals with the same constraint parameter are compared. One is a retrieval with MODIS observations simulated with pre-launch measured RSF. The other is the retrieval with real collocated MODIS data. There still existed bias between the two retrievals shown that the on-board MODIS spectral response function is biased from the pre-launch measurements. From the comparison of the shifted retrieval and the pre-launch measurement, most of the bias is the combination of frequency shifting and shape changing and the frequency shifting response.

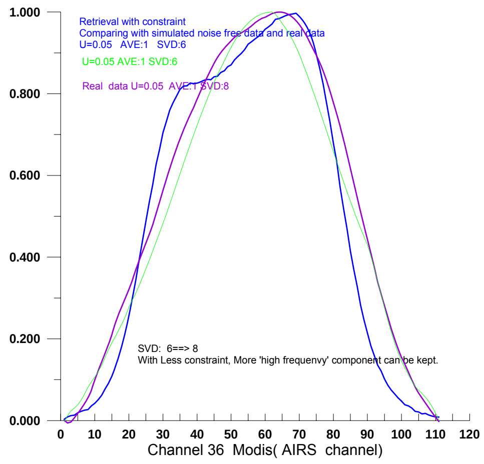


Figure 8.0

4.3 Retrieval Compensation

The bias of the MODIS on–board response function from the pre-launch measurement is relatively small and RSF shape changing is less significant compared with frequency shifting [Fig 9.0]. The bias introduced with the constrained retrieval is close to the pre-launch MODIS response function and the on board MODIS response function. A compensation correction can be applied to retrieval. The compensation correction can be calculated with pre-launch MODIS response function according to the constraint condition and the correction is added back to the retrieval under the same constraint condition[Fig 10.0]. The bias between MODIS observation and convoluted AIRS radiance are show in Fig 11. The convolution is performed with the retrieval and pre-launch measurements.

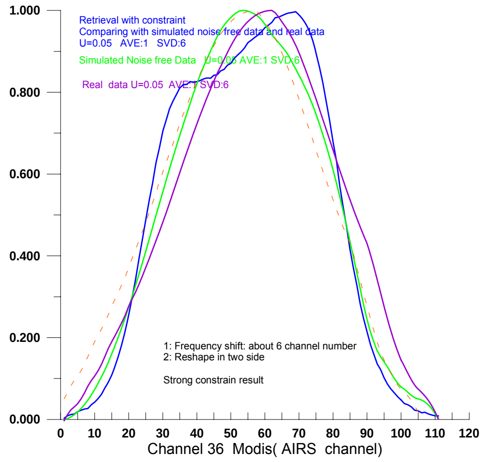


Figure 9.0

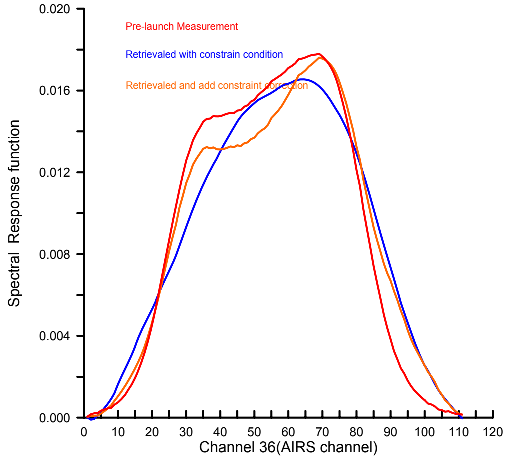
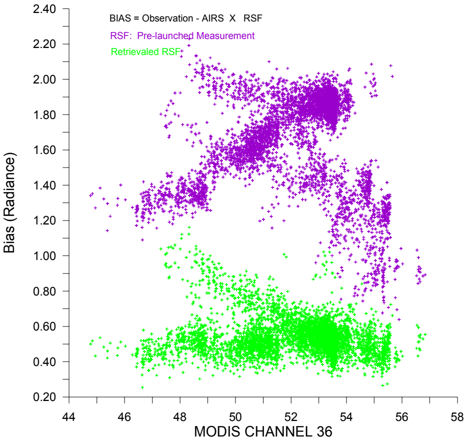


Figure 10



Radiance bias between Observation and convolution RSF

5.0 Conclusion

In this paper, an observation data based algorithm has been developed to retrieve on-orbit MODIS spectral response functions using co-located AIRS high spectral resolution observation data. The limitations and bias of the retrieval has also been presented. The preliminary results show that the constrained retrieval algorithms can provide an in-flight MODIS spectral response function.

6. REFERENCES

Finlayson G, Hordley S, Hubel P. Recovering device sensitivities with quadratic programming. The Proceedings of the IS&T/SID Sixth Color Imaging Conference: Color Science, Systems and Applications, Springfield (VA): The Society for Imaging Science and Technology; 1998. p 90–95.

Huang H-L and W .L. Smith(2004), Apperception of clouds in AIRS data, paper presented at workshop on assimilation of high spectral resolution sounders in NWP, Eur. Cent for Med –range Weather Forecasts,Reading,U,K,28 June to 1 July.

Haibing Sun, W. Wolf, T. King, C. D. Barnet, and M. Goldberg Co-location algorithms for satellite observations AMS Meeting 2006.

Hubel PM, Sherman D, Farrell JE. A comparison of method of sensor spectral sensivity estimation. Proceedings of the IS&T/SID 2nd Color Imaging Conference: Color Science, Systems, and Applications. The Society for Imaging Science and Technology; Springfield (VA): 1994; p 45–48.

K .Barnard Computational colour constancy: Taking theory into practice [MSc thesis]. Burnaby [British Columbia, Canada]: Simon Fraser University; 1995. Available from: ftp://fas.sfu.ca/pub/cs/theses/1995/KobusBarnardMSc.ps.gz.

K. Barnard and B. Funt. Camera characterization for color research. *Color Research and Application*, 27(3):153–164, 2002.

Paulus D., Hong V., Idler C., Hornegger J., Csink L.: Sensitivity Curve Approximation Using Linear Algebra. CGIV 2004, Second European Conference on Color in Graphics, Imaging and Vision, Aachen, Germany, 2004., pp. 207-212

Sharma G, Trussell HJ. Characterization of scanner sensitivity. Proceedings of the IS&T and SID's Color Imaging Conference: Transforms & Transportability of Color. Springfield (VA): The Society for Imaging Science and Technology; 1993; p. 103–107.

Sharma G, Trussell HJ. Set theoretic estimation in color scanner characterization. J Elec Imag 1996;5:479–489.

Tobin, David C.; Revercomb, Henry E.; Moeller, Christopher C. and Pagano, Thomas S.. Use of Atmospheric Infrared Sounder high-spectral resolution spectra to assess the calibration to Moderate resolution Imaging Spectroradiometer on EOS Aqua. Journal of Geophysical Research, Volume 111, 2006, Doi: 10.1029/2005JD006095, 2006. Call Number: Reprint # 5053