Multispectral decomposition for the removal of out-of-band effects of visible/infrared imaging radiometer suite visible and near-infrared bands

Bo-Cai Gao* and Wei Chen
Remote Sensing Division, Naval Research Laboratory, Washington, D.C. 20375, USA
*Corresponding author: gao@nrl.navy.mil

Received 13 February 2012; accepted 6 April 2012; posted 13 April 2012 (Doc. ID 162785); published 14 June 2012

The visible/infrared imaging radiometer suite (VIIRS) is now onboard the first satellite platform managed by the Joint Polar Satellite System of the National Oceanic and Atmospheric Administration and NASA. It collects scientific data from an altitude of approximately 830 km in 22 narrow bands located in the 0.4–12.5 μm range. The seven visible and near-infrared (VisNIR) bands in the wavelength interval between 0.4–0.9 μm are known to suffer from the out-of-band (OOB) responses—a small amount of radiances far away from the center of a given band that can pass through the filter and reach detectors in the focal plane. A proper treatment of the OOB effects is necessary in order to obtain calibrated at-sensor radiance data [referred to as the Sensor Data Records (SDRs)] from measurements with these bands and subsequently to derive higher-level data products [referred to as the Environmental Data Records (EDRs)]. We have recently developed a new technique, called multispectral decomposition transform (MDT), which can be used to correct/remove the OOB effects of VIIRS VisNIR bands and to recover the true narrow band radiances from the measured radiances containing OOB effects. An MDT matrix is derived from the laboratory-measured filter transmittance functions. The recovery of the narrow band signals is performed through a matrix multiplication—the production between the MDT matrix and a multispectral vector. Hyperspectral imaging data measured from high altitude aircraft and satellite platforms, the complete VIIRS filter functions, and the truncated VIIRS filter functions to narrower spectral intervals, are used to simulate the VIIRS data with and without OOB effects. Our experimental results using the proposed MDT method have demonstrated that the average errors after decomposition are reduced by more than one order of magnitude. © 2012 Optical Society of America

1. Introduction
The visible/infrared imaging radiometer suite (VIIRS) instrument [1], Flight Unit 1 (FU1), is now onboard the first satellite platform managed by the Joint Polar Satellite System (JPSS) of the National Oceanic and Atmospheric Administration (NOAA) and NASA and collects scientific data from an altitude of approximately 830 km in 22 narrow bands located in the 0.4–12.5 μm range. The VIIRS instrument is, in many aspects, similar to the moderate resolution imaging spectroradiometer (MODIS) instruments [2,3] currently on board the NASA Terra and Aqua Spacecrafts. A number of VIIRS bands are similar to those of the MODIS instrument but with small differences in band center positions and full widths at half maxima. The seven VIIRS visible and near-infrared (VisNIR) bands at a “moderate” spatial resolution of 750 m in the wavelength interval between 0.4 and 0.9 μm, referred to as M1–M7 and listed in Table 1, have important applications for global
remote sensing of ocean, land, and atmosphere. These bands are known to suffer from the out-of-band (OOB) responses—a small amount of radiances far away from the center of a given band that can pass through the filter and reach detectors in the focal plane.

Figure 1 shows the normalized filter transmittance curves (at the peaks of filter functions) for the seven bands [4]. The VIIRS filter data can be obtained freely from the website http://www.star.nesdis.noaa.gov/jpps/index.php. The M1 filter curve (red) peaks near 0.41 μm, but has non-negligible transmittances in the spectral region between 0.6–0.95 μm. A proper treatment of the OOB effects is necessary in order to obtain calibrated at-sensor radiances data [referred to as Sensor Data Records (SDRs)] from measurements with these bands and subsequently to derive higher-level data products [referred to as the Environmental Data Records (EDRs)]. Significant errors will be introduced in the EDR data products, particularly in EDRs over dark oceans, if the OOB effects are not well addressed.

We have recently developed a new technique called the multispectral decomposition transform (MDT), which can be used to correct/remove the OOB effects of VIIRS VisNIR bands and to recover the true narrow band radiances from the measured radiances with OOB effects. The development of MDT is based on linear system theory. An MDT matrix is derived from the laboratory-measured filter transmittance functions. The recovery of the narrow band signals is performed through a matrix multiplication—the production between the MDT matrix and a multi-spectral vector. Simulations of VIIRS data with and without OOB effects have been made using hyperspectral imaging data, the complete VIIRS filter functions, and the truncated VIIRS filter functions at narrower spectral ranges. The MDT method is applied to the simulated VIIRS data with OOB effects to derive the OOB-corrected data. The derived data are then compared with the simulated VIIRS data without the OOB effects to evaluate quantitatively the performance of the MDT method.

This paper is organized as follows: Section 2 gives a brief review of previous investigations on OOB effects. Section 3 describes the MDT method for spectral decomposition and introduces an MDT matrix for the VIIRS instrument based on an optimal strategy of filter partition. Section 4 describes the simulation of VIIRS data using hyperspectral-imaging data measured from aircraft and satellite platforms and presents quantitative results on decomposition of OOB effects from applications of the MTD method to the simulated data. Section 5 gives a brief discussion and summary.

2. Previous Research

The presence of OOB effects is not unique to the VIIRS instrument. The Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) [5,6] satellite instrument also has OOB effects. Prior to the launch of the SeaWiFS instrument into space in 1997, Gordon [6] developed a methodology for dealing with broad spectral bands and significant OOB responses. Later, a simple correction method, which is based on the Gordon methodology, to remove the spectral band effects of the SeaWiFS on the derived normalized water-leaving radiances and ocean near surface chlorophyll concentration is developed and implemented in the operational SeaWiFS data processing system [7]. It should be pointed out that the OOB corrections are not made to SeaWiFS-measured top-of-the-atmosphere (TOA) radiances. Instead, the corrections are made to the derived ocean color data products. The SeaWiFS correction scheme works quite well over fairly clear ocean waters [7]. However, the correction scheme is not applicable for SeaWiFS data products over turbid coastal waters or over land, where the shapes of the TOA spectral radiance distributions are very different from those over clear waters.

In order to examine the effects of spectral response functions of individual instrument bands on their TOA radiances, Barnes and Butler [8] described a radiative transfer (RT) modeling based technique to simulate the TOA hyperspectral radiance spectra. Using the simulated data, they evaluated the SeaWiFS OOB effects over different types of surface targets, such as blue ocean waters, deserts, and grasslands. Because hyperspectral imaging data measured from aircraft and satellite platforms, such as those with the airborne visible infrared imaging spectrometer (AVIRIS) instrument [9] from an ER-2 aircraft at an altitude of 20 km and the hyperspectral imager for the coastal ocean (HICO) instrument [10] from the International Space Station, are now readily available, we have decided to use the measured TOA spectral radiance data, instead of the RT model calculated data, to study the VIIRS OOB effects.

For the purpose of mitigating the OOB effect for VIIRS data acquired over clear ocean waters, researchers at Northrop Grumman followed the SeaWiFS data processing procedures [7] and developed the concept of effective relative spectral response (RSR). With this approach, the wavelength dependence of Rayleigh scattering is taken into consideration when generating look-up tables for retrieval algorithms. Because the spectral radiance curves of other types of surfaces, such as shallow waters, green vegetation, and clouds are very different from that of the clear water spectrum, new approaches need to be
developed to mitigate the OOB effect for VIIRS data measured over surfaces other than clear waters. The MDT technique described below can, in principle, be used to correct/remove the OOB effects of VIIRS VisNIR bands and to recover the true narrow band radiances from the measured radiances with OOB effects over any type of surface.

3. Multispectral Decomposition Transform

A. VIIRS M1–M7 Filter Characteristics

The VIIRS VisNIR band specifications are tabulated in Table 1. A set of spectrally contiguous filter transmittance curves (normalized at the peak of the filter transmission) is shown in Fig. 1. These filter transmittance curves, such as M5, show significant OOB responses. The cause of the OOB responses is due to a large angle scattering of radiances in the integrated filter assembly that overlies the VisNIR focal plane array. As a result, the OOB effect for a given band comes from a contiguous spectral range instead of very limited narrow spectral intervals. Because the OOB effects come from a contiguous spectral range, we can apply linear system theory to deal with the issues of the OOB effect and to recover the narrow band signals.

B. Partition of a Linear Optical System

In general, a multispectral instrument, such as VIIRS, can be considered a system that accepts an input and produces an output in response. Such a system is linear because the measured optical signal \( s_k = s_l(i, j) \), where \( i \) and \( j \) are pixel indexes] from a sensor can be expressed by

\[
s_k = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} h_k(\lambda)s(\lambda)\,d\lambda, \tag{1}
\]

where \( \hat{s}_k \) and \( s(\lambda) \) are the measured (with OOB effects) and original signals of a pixel, respectively.

\( h_k(\lambda) \) is the normalized response (or transfer) function of a optical system (optical filters) with the wavelength \( \lambda \in [\lambda_{\text{min}}, \lambda_{\text{max}}] \) as a variable. The above superposition integral expresses a relationship between original and measured signals with the optical filters.

If the range of the integral between the cut-off wavelengths \( \lambda_{\text{min}} \) and \( \lambda_{\text{max}} \) is grouped into several sub-ranges, the sub-range partitions of the total integral are given by

\[
\hat{s}_k = \sum_{l=1}^{n} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} h_k(\lambda)s(\lambda)\,d\lambda,
\]

where \( n \) is the number of bands, and \( \lambda_{\text{min}}^{(l)} \) and \( \lambda_{\text{max}}^{(l)} \) are minimum and maximum wavelengths of the sub-range of the \( l \)th filter. The total spectral range from \( \lambda_{\text{min}} \) to \( \lambda_{\text{max}} \) is a summation of all sub-ranges, i.e.,

\[
\begin{align*}
\lambda_{\text{max}} &= \lambda_{\text{max}}^{(1)} + \lambda_{\text{max}}^{(2)} + \cdots + \lambda_{\text{max}}^{(n)} \\
\lambda_{\text{min}} &= \lambda_{\text{min}}^{(1)} + \lambda_{\text{min}}^{(2)} + \cdots + \lambda_{\text{min}}^{(n)}
\end{align*}
\]

Using an average value of the response function between \( \lambda_{\text{min}}^{(l)} \) and \( \lambda_{\text{max}}^{(l)} \) to replace the response function \( h_k(\lambda) \) in the integral, we have

\[
\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} h_k(\lambda)s(\lambda)\,d\lambda = \bar{h}_k l \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} s(\lambda)\,d\lambda = \bar{h}_k l \Delta \lambda_l \hat{s}_l,
\]

where \( \Delta \lambda_l = \lambda_{\text{max}}^{(l)} - \lambda_{\text{min}}^{(l)} \). The average of the response functions is given by

\[
\bar{h}_k l = \frac{1}{\Delta \lambda_l} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} h_k(\lambda)\,d\lambda, \tag{2}
\]

and the narrowband signal that is an average of all signals within the sub-band \( \Delta \lambda_l \) is defined by

\[
\hat{s}_l = \frac{1}{\Delta \lambda_l} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} s(\lambda)\,d\lambda. \tag{3}
\]

The measured \( k \)th band signal is a summation of all average narrowband signals and is given by

\[
\hat{s}_k = \sum_{l=1}^{n} \bar{h}_k l \Delta \lambda_l \hat{s}_l. \tag{4}
\]

The average signals between \( \lambda_{\text{min}}^{(l)} \) and \( \lambda_{\text{max}}^{(l)} \) defined in Eq. (3) are the intended narrowband signals. The measured signal with OOB effects is a superposition of all narrowband signals. The coefficient factors and parameters in Eq. (4) can be calculated using the response functions that are dependent on the characteristics of the filters of a particular instrument. Equation (4) is a mathematical expression of the physical effects of the OOB response. Our task is
to resolve the average narrowband signals from Eq. (4).

C. MDT Matrix
A vector form of multispectral images (s ∈ {s, s}) is defined by

$$\mathbf{s} = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{pmatrix}. \quad (5)$$

Each component of the vector in Eq. (5) is a single band image. Substituting Eq. (4) into Eq. (5), we have

$$\hat{\mathbf{s}} = \frac{\sum_{l=1}^{n} a_{1l} \hat{s}_l}{\sum_{l=1}^{n} a_{2l} \hat{s}_l} = \Lambda \hat{\mathbf{s}},$$

where $a_{kl} = \hat{h}_{kl} \Delta \lambda_l$. It is clear that the narrowband image vector can be solved by

$$\hat{s} = \Lambda^{-1} \hat{\mathbf{s}}. \quad (6)$$

The inverse matrix $\Lambda^{-1}$ is called the MDT matrix for recovering the narrowband signals from the measured signals with OOB effects. All elements of the matrix $\Lambda$ depend on the response functions of the filters, sub-band widths, and positions of the filters. Therefore, the spectral transform matrix can be fully determined by the characteristics of the filters.

Assuming an ideal case that the normalized response functions of the filters for the total wavelength range from $\lambda_{\text{min}}$ to $\lambda_{\text{max}}$ are given by

$$h_k(\lambda) = \frac{1}{\Delta \lambda_l} \begin{cases} \frac{\lambda^{(l)}_{\text{min}}}{\lambda^{(l)}_{\text{max}}} & \text{if } \lambda^{(l)}_{\text{min}} \leq \lambda \leq \lambda^{(l)}_{\text{max}}, \\ 0 & \text{otherwise} \end{cases},$$

and the subband widths are uniform, the matrix $\Lambda$ and the MDT matrix $\Lambda^{-1}$ are identity matrices. The input and output signals are identical for this ideal system.

D. MDT Matrix for VIIRS
Using Eq. (6), the recovered narrow band signals can be calculated by the MDT matrix and the measured multiband image vector (with OOB effects). In this section, we describe the numerical computations of the MDT matrix for the VIIRS VisNIR filters.

The seven band filter transmittance functions, as shown in Fig. 1, indicate that the filter widths and positions are not uniform. Based on careful analyses of the shapes of these filter functions, we have a non-uniform partition. The resulting wavelength ranges and cutting off positions for the seven bands are shown in Table 2. The wavelengths of the sub-ranges $\lambda_{\text{min}}^{(1)}$ of filter 1 and $\lambda_{\text{max}}^{(7)}$ of the filter 7 need to extend to the lowest and highest boundaries within the total cut-off wavelength range. The transmittance function for filter 4, shown in Fig. 1, has more out of band response than the other filters. A narrower wavelength range that covers only the portion of the central transmittance region for this particular filter is selected.

The transmittance functions of the VIIRS filters in Fig. 1 are normalized at the peak. All response functions defined in Eqs. (1) and (2) must be normalized using the transmittance functions of the VIIRS filters in Fig. 1 before the computation for the MDT matrix. The normalized response functions $h_k(\lambda)$ is given by

$$h_k(\lambda) = \frac{H_k(\lambda)}{\hat{H}_k},$$

where $H_k(\lambda)$ and $\hat{H}_k$ are the transmittance functions of the VIIRS filters in Fig. 1 and it’s mean value between the total wavelength range from $\lambda_{\text{min}}$ to $\lambda_{\text{max}}$.

The MDT matrix $\Lambda^{-1}$ for the VIIRS instrument based on the wavelength partition in Table 2 and the transmittance functions of the filters in Fig. 1 have been computed through a mathematical inversion by Gauss-Jordan elimination, and is given by

$$\begin{pmatrix} 1.0283 & -1.32656 \times 10^{-3} & -9.64811 \times 10^{-5} & -6.26276 \times 10^{-4} & -5.26322 \times 10^{-3} & -4.13883 \times 10^{-3} & -1.68423 \times 10^{-2} \\ -1.86106 \times 10^{-3} & 1.00977 & -4.52782 \times 10^{-4} & -1.48041 \times 10^{-3} & -2.13087 \times 10^{-3} & -1.01843 \times 10^{-3} & -2.82691 \times 10^{-3} \\ -9.56242 \times 10^{-4} & -5.95628 \times 10^{-4} & 1.01368 & -1.48632 \times 10^{-3} & -3.24938 \times 10^{-3} & -2.04484 \times 10^{-3} & -5.34673 \times 10^{-3} \\ -1.1785 \times 10^{-3} & -4.70933 \times 10^{-4} & 1.20242 \times 10^{-2} & 1.0327 & -7.46696 \times 10^{-3} & -3.84353 \times 10^{-3} & -3.47807 \times 10^{-3} \\ -5.78424 \times 10^{-4} & -1.04277 \times 10^{-3} & 2.35638 \times 10^{-3} & -5.14373 \times 10^{-3} & -1.10684 & -3.31716 \times 10^{-3} & -4.40333 \times 10^{-3} \\ -4.38729 \times 10^{-4} & -4.00096 \times 10^{-4} & -6.33179 \times 10^{-4} & -1.00671 \times 10^{-3} & -3.99606 \times 10^{-3} & -1.01061 & -1.43453 \times 10^{-3} \\ -2.23718 \times 10^{-4} & -1.35422 \times 10^{-4} & -1.89362 \times 10^{-4} & -2.13841 \times 10^{-4} & -3.02904 \times 10^{-4} & -2.41025 \times 10^{-4} & -1.00131 \end{pmatrix}$$

<table>
<thead>
<tr>
<th>VIIRS Band</th>
<th>$\lambda_{\text{min}}^{(1)}(\mu\text{m})$</th>
<th>$\lambda_{\text{min}}^{(7)}(\mu\text{m})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.391</td>
<td>0.429</td>
</tr>
<tr>
<td>M2</td>
<td>0.429</td>
<td>0.463</td>
</tr>
<tr>
<td>M3</td>
<td>0.463</td>
<td>0.522</td>
</tr>
<tr>
<td>M4</td>
<td>0.522</td>
<td>0.596</td>
</tr>
<tr>
<td>M5</td>
<td>0.596</td>
<td>0.724</td>
</tr>
<tr>
<td>M6</td>
<td>0.724</td>
<td>0.782</td>
</tr>
<tr>
<td>M7</td>
<td>0.782</td>
<td>1.001</td>
</tr>
</tbody>
</table>
Fig. 2. Image of (a) a true color AVIRIS acquired over the coastal area of New Jersey on 12 July 1998 and (b) examples of radiance spectra of pixels covered by clear water, turbid water, and green vegetation.

Fig. 3. VIIRS image simulated with an AVIRIS hyperspectral data set acquired over the coastal area of New Jersey on 31 July 2001, two sample VIIRS multiband radiance data over turbid ocean waters and clear deep ocean waters, and errors before (uncorrected errors) and after decompositions (corrected errors) relative to the simulated corresponding VIIRS data without OOB effects.
All main diagonal elements in the MDT matrix for the VIIRS instrument are greater than and nearly equal to one. Almost all nondiagonal elements for the OOB corrections are negative because the measured signal with an OOB effect for a particular band is a superposition of all other band signals. A decomposed signal must be extracted from the measured signals with OOB effects. The correction amount is dependent on the characteristics of the filters. The fourth row with larger correction amounts in the MDT matrix corresponds to a poor filter such as filter 4, as shown in Fig. 1.

It is noted that the summation of all column elements in the MDT matrix is equal to unity, i.e.,

\[ \sum_{i=1}^{n} (A^{-1})_{kl} = 1. \]

Therefore, the correction coefficients in the MDT matrix for each band are also normalized. To avoid overflow results for the multiplication between the MDT matrix and the spectral image vector, a data type with double precision is used for the computation.

4. Simulation Results

We have used hyperspectral imaging data measured with the AVIRIS and HICO along with the VIIRS filter functions to simulate the VIIRS data with and without the OOB effects. Figure 2(a) is a true color image of an AVIRIS scene acquired over the coastal area of New Jersey on 12 July 1998. Figure 2(b) shows examples of radiance spectra over areas covered by clear water, turbid water, and green vegetation. The shapes of these spectra are very different. The contiguous spectra are quite suited for the simulation of multiband VIIRS data. Simulations of VIIRS data with OOB effects are made by convolving the measured spectrum on a pixel-by-pixel basis with the complete VIIRS filter functions (Fig. 1). Mathematically, the simulated multispectral images without the OOB effects are given by the following:

\[ s_k = \frac{\int_{\Delta \lambda} h_k(\lambda)s(\lambda)d\lambda}{\int_{\Delta \lambda} h_k(\lambda)d\lambda}, \]

where \( s(\lambda) \) is interpolated by either AVIRIS or HICO hyperspectral image data, and \( s_k = s(i,j,k) \) is the nominal band signal on a pixel with wavelengths as shown in Table 1. The spectral bandwidths \( \Delta \lambda \) in the integral for the \( k \)th band filter extend to the left and right side of a 1% level of the filter’s response. The simulated data with OOB effects and without OOB effects are compared to quantify the

![Figure 4](image_url)

Fig. 4. Similar to Fig. 3, except that the multiband data points are extracted from pixels covered by green vegetation and land as marked in the image.
OOB effects over different types of surface targets, such as clear waters, turbid waters, green vegetation, sand, and soil.

The proposed method for the multispectral decomposition is applied to two simulated VIIRS multispectral imaging data sets with OOB effects. The decomposed multispectral images are also compared with the corresponding simulated VIIRS data sets without OOB effects. Relative error measures on a pixel and band is defined by

$$e_{ijk} = \frac{\tilde{s}_k(i,j) - s_k(i,j)}{s_k(i,j)}.$$ 

where $s_k(i,j)$ is a $k$th band image without OOB effects. Mean values of the relative errors of the image data with OOB effect and the image data after decomposition for all pixels and bands are defined by $\langle |\tilde{e}| \rangle$ and $\langle |\tilde{e}| \rangle$, respectively.

Figure 3 shows a VIIRS image simulated with an AVIRIS hyperspectral data set acquired over the coastal area of New Jersey on 31 July 2001. Two sample VIIRS multiband radiance data over turbid ocean waters and clear deep ocean waters, as marked in the image, are shown in the middle portions of the plot. The errors in the presence of OOB effects and after corrections relative to the simulated corresponding VIIRS data without OOB effects are shown in the right portion of the plot. Before the correction, the relative errors for the M1 band and for both types of waters are approximately $-2.3\%$, and that for the M5 band about $1.3\%$. After decomposition (corrected), the errors for both types of waters are significantly reduced. Figure 4 is similar to Fig. 3 except that the multiband data points are extracted from pixels covered by green vegetation and land as marked in the image. It is seen that the relative error before the correction for the M5 band (centered at 0.672 $\mu$m) for the green vegetation pixel is approximately $4\%$. This band receives a large amount of OOB contributions from the near-IR spectral region because green vegetation is highly reflective above 0.7 $\mu$m. The relative errors after the correction are reduced dramatically.

Figure 5 shows a VIIRS image simulated with a HICO hyperspectral data set acquired over the Gulf of California on 1 December 2009. Two sample VIIRS multiband radiance data over turbid waters and clear waters, as marked in the image, are shown in the middle portions of the plot. The errors before (uncorrected errors) and after decompositions (corrected errors) relative to the simulated corresponding VIIRS data without OOB effects are shown in the right portion of the plot. Before the correction, the relative errors for the M1 band and for both types of waters are approximately $-2.3\%$, and that for the M5 band about $1.3\%$. After decomposition (corrected), the errors for both types of waters are significantly reduced. Figure 4 is similar to Fig. 3 except that the multiband data points are extracted from pixels covered by green vegetation and land as marked in the image. It is seen that the relative error before the correction for the M5 band (centered at 0.672 $\mu$m) for the green vegetation pixel is approximately $4\%$. This band receives a large amount of OOB contributions from the near-IR spectral region because green vegetation is highly reflective above 0.7 $\mu$m. The relative errors after the correction are reduced dramatically.
simulated data without OOB effects are shown in the right portion of the plot. Before the correction, the relative errors for the M1 band and for both types of waters are approximately $-2.3\%$. The relative errors before corrections for M5 and M6 bands and for the turbid water pixels are approximately $1.5\%$. After corrections, the errors for both types of waters are significantly reduced and the error curves are flat. Figure 6 is similar to Fig. 5 except that the multiband data points are extracted from pixels covered by green vegetation and desert sand as marked in the image. It is seen from the right portion of the plot that the relative errors after the corrections are also significantly reduced.

The average relative errors of the image data with OOB effects for the two AVIRIS and HICO simulated images are shown in Table 3. Similarly, the average relative errors of the OOB-corrected image data by the proposed MDT method for the same test images are listed in Table 3. For reference purposes, the errors for uncorrected data, OOB-corrected data, and for several surface types, such as ocean water, clouds, land, and vegetation, are listed separately. The ratios of average errors after corrections over those before corrections, $\langle \hat{e} \rangle / \langle \hat{e} \rangle$, are listed in the last column of Table 3. It is seen that after the correction the average errors for deep waters and turbid waters for both the AVIRIS and HICO-simulated data are reduced by more than one order of magnitude.

### Table 3. Average Relative Errors of the Uncorrected and OOB-Corrected Simulated Multispectral Images of the VIIRS Instrument Using AVIRIS and HICO Hyperspectral Imaging Data

<table>
<thead>
<tr>
<th>Data</th>
<th>$\langle \hat{e} \rangle$ (%)</th>
<th>$\langle \hat{\hat{e}} \rangle$ (%)</th>
<th>$\langle \hat{e} \rangle / \langle \hat{\hat{e}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVIRIS All</td>
<td>0.903</td>
<td>0.0841</td>
<td>0.093</td>
</tr>
<tr>
<td>AVIRIS Deep Water</td>
<td>1.07</td>
<td>0.0783</td>
<td>0.073</td>
</tr>
<tr>
<td>AVIRIS Turbid Water</td>
<td>1.02</td>
<td>0.0571</td>
<td>0.077</td>
</tr>
<tr>
<td>AVIRIS Land</td>
<td>0.594</td>
<td>0.103</td>
<td>0.173</td>
</tr>
<tr>
<td>AVIRIS Vegetation</td>
<td>0.901</td>
<td>0.179</td>
<td>0.199</td>
</tr>
<tr>
<td>HICO All</td>
<td>0.890</td>
<td>0.0820</td>
<td>0.092</td>
</tr>
<tr>
<td>HICO Deep Water</td>
<td>0.935</td>
<td>0.0812</td>
<td>0.087</td>
</tr>
<tr>
<td>HICO Turbid Water</td>
<td>1.10</td>
<td>0.0670</td>
<td>0.061</td>
</tr>
<tr>
<td>HICO Land</td>
<td>0.294</td>
<td>0.114</td>
<td>0.388</td>
</tr>
<tr>
<td>HICO Vegetation</td>
<td>0.519</td>
<td>0.102</td>
<td>0.196</td>
</tr>
</tbody>
</table>

5. Discussion and Summary

In this paper, an MDT method for removing the OOB effects is proposed based on linear system theory. An MDT matrix is derived using the filter transmittance functions for recovering narrowband signals. The spectral filter decomposition processing can be performed simply by a production between the MDT matrix and the data.
matrix and a multispectral image vector. The MDT matrix depends only on the characteristics of the filters for an optical instrument. An MDT matrix for the VIIRS instrument has been obtained. Hyperspectral imaging data measured from high altitude aircraft and satellite platforms, the complete VIIRS filter functions obtained from pre-launch laboratory measurements, and the truncated VIIRS filter functions to narrower spectral intervals, are used to simulate the VIIRS data with and without OOB effects. Our experimental results using the proposed MDT method have demonstrated that the average OOB effects after decomposition are reduced by more than one order of magnitude. It should be pointed out that, after the launch of VIIRS into space and subsequent data collection, the spectral reflectances of VIIRS mirrors in the space environment has been changing. The instrument is expected to stabilize in a few months. As a result, the stabilized spectral response curves of VIIRS bands in the space environment in the near future are expected to be slightly different from those shown in Fig. 1. A new MDT matrix needs to be derived using the stabilized VIIRS filter response curves for recovering narrowband signals from space-based VIIRS measurements.

The research reported here was partially supported by the U.S. Office of Naval Research and by the Joint Polar Satellite System of NOAA and NASA.

References