Extending VIIRS Spectral Coverage Using CrIS Radiance Measurements to Explore Potential Applications

Introduction

With a data fusion method that uses both the high-spectral resolution sounder with the high spatial resolution imager onboard the same satellite, we demonstrate the ability to construct infrared (IR) absorption narrowband radiances as well as accurate retrieval products while retaining the imager's high spatial resolution. Specifically, research is being conducted to explore the potential for using the spectral coverage from the CrIS (Cross-track Infrared Sounder) at 14km spatial resolution to create currently missing IR spectral bands at VIIRS (Visible Infrared Imaging Radiometer Suite) spatial resolution of 780m. With use of a proven data fusion method (Cross et al., 2013), we have example results for IR radiances at 4.5 µm (CO_2), 6.7 µm (H_2O) and 13.9 µm (CO_2) observed by MODIS (Moderate Resolution Imaging Spectroradiometer) and constructed by fusion at MODIS resolution using AIRS (Weisz et al. 2017). The observed- and fusion-based radiance differences tend to be small (brightness temperature root-mean-square differences are between 0.5 and 1.0 K) and unbiased. Weisz et al. (2017) also presented similar fusion results for VIIRS and CrIS. This proposal is to study four potential applications with VIIRS enhanced by fusion-based CrIS data; they are (1) improved cloud top heights and cloud thermodynamic phase using fusion-based CO_2 spectral bands, (2) high spatial resolution total precipitable water (TPW) using the full suite of fusion-based CO_2, H_2O, and O_3 spectral bands, including perhaps additional new H_2O bands, (3) improved volcanic ash characterization especially heights using fusion based SO_2 and CO_2 spectral bands, and (4) polar winds using the fusion-based H_2O spectral bands. Regional and global case studies are planned. We anticipate that this work offers the possibility of improving the continuity in derived cloud and moisture products and associated applications over generations of weather satellite sensors, and continuing applications that require IR absorption bands. It also may have implications for future imager-sounder instrument design strategies. The investigators are studying several satellite products (cloud, moisture, ash, wind) for possible fusion applications.

Extending VIIRS Spectral Coverage

Polar-orbiting weather satellite platforms include both a high spatial resolution imager, with pixel spatial resolution on the order of 1 km, and a high spectral resolution (or hyperspectral) infrared (IR) sounder, with fields of view (FOVs) of about 14 km. The imagers are designed to take measurements for a limited set of narrow wavelength bands at visible through IR wavelengths. The imager data are used, for example, to develop operational aerosol, moisture, and cloud properties. The sounder measurements are used generally to infer profiles at high vertical resolution of temperature, water vapor, and ozone and also to infer surface, trace gas, and cloud properties. Hyperspectral sounders cover a spectral range from approximately 3.6 µm to 15.5 µm (Fig. 1).

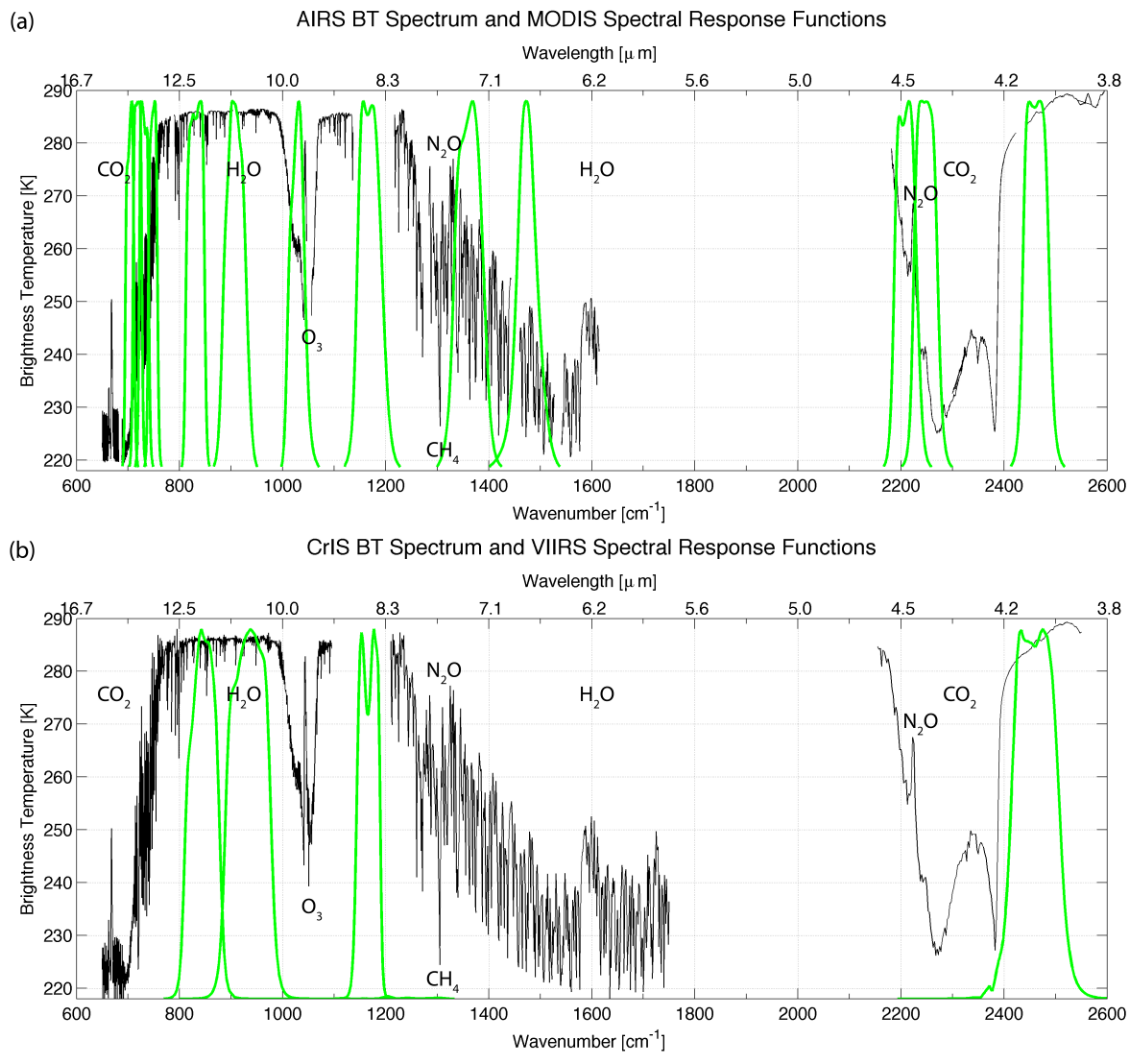

Figure 1. (a) AIRS and (b) CrIS infrared brightness temperature spectrum (black) with main absorbers indicated, and the (a) MODIS and (b) VIIRS spectral response functions (green) superimposed. The spectral response functions are scaled to fit the brightness temperature range.

There are differences in the satellite imager/sounder measurements across platforms. Some imagers (e.g. AVHRR, VIIRS) lack absorbing IR bands that are necessary to obtain accurate products such as total column precipitable water vapor and cloud properties (e.g., cloud top height, thermodynamic cloud phase). The objective of our effort is to develop a data fusion methodology based on imager-sounder pairs to construct the missing IR absorption bands, which then can enable the derivation of more consistent atmospheric products.

In a previous study (Weisz et al. 2017), we have described an imager/sounder data fusion technique to construct the MODIS-like IR absorption bands for VIIRS at high spatial resolution with the help of CrIS. The first step of the technique is a nearest neighbor search using the k-d tree algorithm on split-window (i.e., 11 and 12 µm) imager radiances, which are given at high as well as at low spatial resolution (obtained by averaging all imager pixels within each sounder FOV). For each imager pixel 5 sounder FOVs are identified as being the best match in radiance and location. In the second step, the sounder radiances, convolved using the desired spectral response functions for the imager band to be constructed, are averaged for the 5 selected FOVs and these averages represent the new fusion radiances for each imager pixel. Any MODIS band can be reconstructed for which the sounder contains radiance data; in Weisz et al. (2017) results for MODIS bands 25, 27 and 35 (centered at 4.5, 6.7 and 13.9 μm, respectively) have been presented thus demonstrating shortwave, midwave and longwave IR versatility as well as CO_2 and H_2O applicability. But in fact, the same approach could be applied to construct different and new IR absorption bands if so desired.

Local and global results of the MODIS fusion reconstructed radiances and their differences to the actual observations can be found in Weisz et al. (2017). The differences are largest at the edge of the imager granule, since the sounder swath width is smaller than that of the imager. One of the primary deficiencies outside the sounder swath is the absence of a correction for the additional atmospheric absorption caused by the increased path length; thus the constructed radiances will be higher, and the 'measured-constructed' radiance differences will be biased low. However, within the sounder swath differences are small and large-scale features are captured. Radiance differences tend to increase in regions of broken cloud or cloud edges. VIIRS/CrIS fusion results were also found to be in good agreement with MODIS radiance measurements collocated in space and close in time.

The ability to estimate high spatial resolution radiances for any existing or newly desired IR absorption band from imager/sounder pairs offers new opportunities for retrieving accurate atmospheric and surface products and for studying their impact on operational and research applications.

Current limitation and required research

Fusion results remain to be demonstrated as capable of producing imager resolution cloud, moisture, and motion products based on Suomi-NPP platform sensors as well as the MetOp sensors. Ongoing work includes merging AVHRR (Advanced Very High Resolution Radiometer) and IASI (Infrared Atmospheric Sounding Interferometer). The fusion of AVHRR with IASI (on Metop-A, Metop-B, and Metop-C (upon its launch later in 2018) will enable extension of the MODIS record once Terra is no longer operational and enable production of similar imager/sounder based products from the operational AM and PM polar orbing platforms. An imager/sounder combination on different platforms (i.e., geostationary imager and polar-orbiting sounder) would also be worth investigating, but that is beyond the scope of this proposal.

This work is to evaluate imager retrieval products (e.g., cloud mask, cloud top pressure and phase, atmospheric moisture distribution, atmospheric motions, and trace gas properties) derived from the addition of imager/sounder fusion radiance estimates. Preliminary results confirm that the fusion radiance estimates facilitate the retrieval of high-quality products of cloud top pressure and IR thermodynamic phase. VIIRS/CrIS fusion products will therefore enable continuity of cloud records from the Terra and Aqua sensors. Further products to be investigated include atmospheric moisture profiles, water vapor tracking of polar winds, and detection of trace gases like sulfur dioxide (SO_2) located within volcano plumes.

Another investigation concerns the application of the fusion technique directly to hyperspectral sounder retrieval products rather than the convolved sounder radiances. For example, total precipitable water retrieved from hyperspectral sounder (AIRS, IASI, CrIS) measurements would be provided at the imager's (MODIS, AVHRR, VIIRS) high spatial resolution. This includes a study of how best to incorporate the imager based cloud mask in the fusion technique (e.g. in the k-d tree search or as a mask in the fusion product).

The implications for the design and spectral selection of future imager/sounder pairs on research and operational instruments remain to be determined, but it is very likely that these fusion results can influence the development of future weather satellite platforms. These studies are intended to help to answer the broader implications of fusion enhancement of imager spectral coverage and product generation.

Methodology

The construction of high spatial resolution IR narrowband radiances is briefly described here and has been mainly adapted from Weisz et al. 2017; Cross et al. (2013) provide further details. The fusion method consists of two steps: (1) performing a nearest neighbor search using the k-d tree algorithm on both high spatial and low spatial resolution split-window imager radiances, and (2) averaging the convolved sounder radiances (at low spatial resolution) for the nearest neighbors selected in (1) of for each imager pixel.

Figure 2a shows the first step of the methodology, i.e., the k-d tree search, which finds the *N* sounder FOVs that best matches each imager pixel. For the results shown here *N* is set to 5. The k-d tree algorithm (e.g., Bentley 1975, Gladkova et al. 2013) is used to provide the closest matching FOVs in the training data set (here, low spatial resolution imager data) to each pixel in a query data set (here, high spatial resolution imager data). Specifically, the inputs to the k-d tree are imager split-window 11 and 12 μm radiances at both the pixel and FOV spatial resolution; for the latter the imager radiances, geographically collocated to each sounder FOV, are averaged. The corresponding imager and sounder latitude and longitude values are used as additional predictors. The k-d tree input data has therefore *npix* (number of pixels in an imager granule) and four

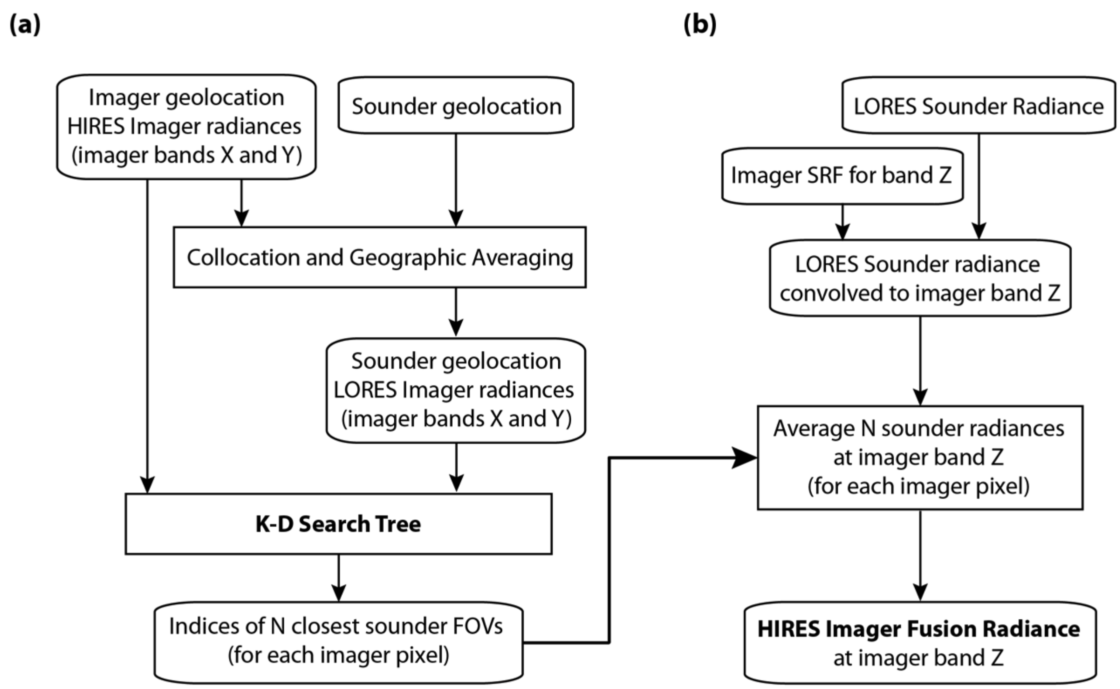

Figure 2. (a) The process for creating a multidimensional search tree using high spatial resolution (HIRES) and low spatial resolution (LORES) imager radiance and geolocation information. (b) Application of the k-d tree neighbor indices to LORES sounder radiances. Bands X and Y refer to the split-window bands, Z refers to the imager band to be constructed via the fusion process. SRF stands for Spectral Response Function.

predictors (2 bands of radiances, as well as latitudes and longitudes). It should be emphasized that the k-d tree search is solely based on imager radiances (at the pixel resolution and averaged over the FOV resolution) and not on sounder radiance information. To be clear, only the split-window bands, i.e. MODIS bands 31 and 32 and VIIRS bands M15 and M16, are used in the k-d tree application to a granule. The outcome of the first step is a matrix of dimension *npix* x *N* containing the indices of the *N* sounder FOVs that are closest in space and best match the measured imager IR radiances. For the second step (Fig. 2b) sounder radiances for each FOV are convolved with the spectral response function (SRF) for the band to be constructed at imager pixel resolution. Thus, high-spectral resolution sounder radiances are reduced to match narrow-band (i.e., imager-like) radiances while retaining the sounder spatial resolution. The mean of the convolved radiances for the *N* neighbors (associated with the indices found in the first step) is computed. This process is repeated for every imager pixel in the granule.

For evaluation, the Aqua MODIS spectral response functions for three bands are applied to the sounder radiances: band 25 (4.52 µm), band 27 (6.72 µm) and band 35 (13.94 µm). As outlined above and in Fig. 2 the mean of the convolved sounder radiances for 5 neighbors is computed and reported for each imager pixel resulting in a synthesized imager band at the imager's high spatial resolution.

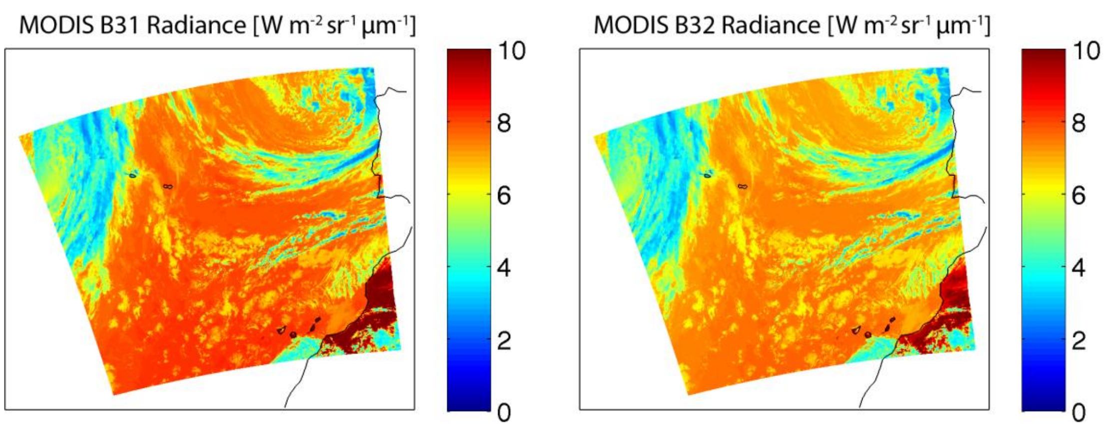

Figure 3. MODIS observed radiance for band 31 (left) and band 32 (right). For MODIS granule 1435 on 17 April 2015.

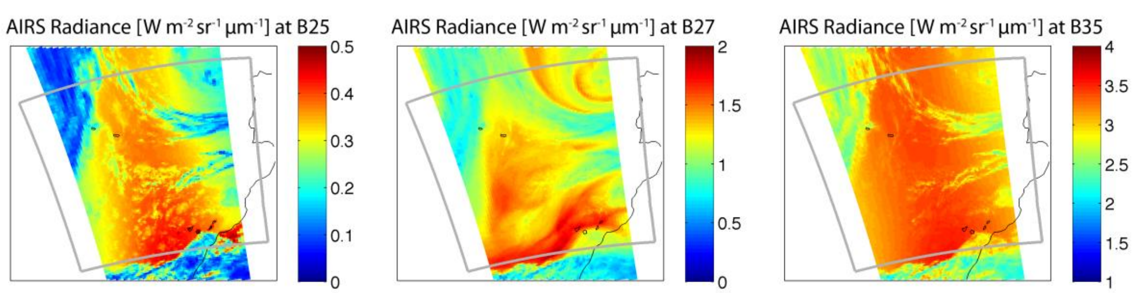

Figure 4. AIRS radiances convolved with the SRFs for MODIS bands 25 (left), 27 (middle) and 35 (right) for AIRS granules 145 and 146 on 17 April 2015. The outline of the corresponding Aqua MODIS granule (acquired at 1435 UTC) is shown in gray.

Figure 3 shows MODIS radiances for bands 31 and 32 (i.e., the bands used in the k-d tree search), whereas Fig. 4 shows the AIRS radiances convolved with the Aqua MODIS spectral response functions for MODIS bands 25, 27 and 35 (i.e., bands to be constructed). This example shows a 5-min MODIS granule, acquired at 1435 UTC on 17 April 2015, located off the coast of Morocco and Portugal, and the collocated AIRS granules 145 and 146. The outlines of the MODIS granule are shown in Fig. 4 to illustrate the differences in imager and sounder swath widths. To create the new fusion bands 25, 27 and 35 the radiance shown in Fig. 4 is averaged for the 5 neighbors, found by applying a k-d tree search on the radiance and geolocation values shown in Fig. 3. The fusion results, as well as the original observed MODIS radiance and the differences of ‘observed minus fusion’ radiance for the three bands are shown in Fig. 5.

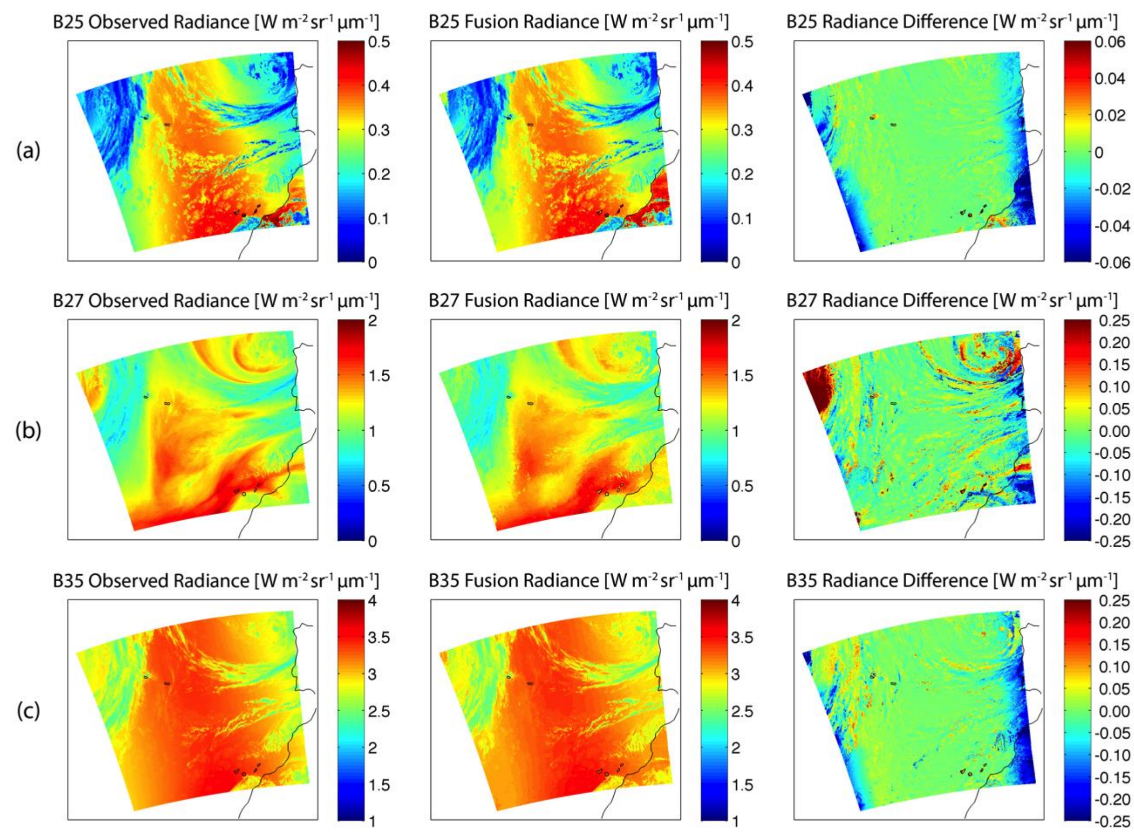

Figure 5. Original (observed) MODIS radiance (left), newly constructed fusion radiance (middle), and the ‘observed minus fusion’ radiance differences (right) for MODIS bands 25, 27 and 35 in panels a, b and c, respectively.

The means and root mean square errors (in radiance and brightness temperature units) of the differences for the three bands in a full granule as well as within the sounder swath are given in Table 1. The differences are largest at the edge of the granule, where fewer sounder FOVs are available in close vicinity. As the scan angle increases, the amount of the atmosphere observed by the sensor increases, which leads to an increase in atmospheric absorption and hence lowers radiance values. Since the sounder granule does not entirely cover the imager swath due to its smaller swath width, the fusion process does not correctly reproduce the atmospheric absorption and may also not completely capture cloud features.

Table 1. Mean and RMS of 'observed minus fusion' radiance (and brightness temperature) differences for the full MODIS granule (1435 UTC, 17 April 2017). Values for the region within the sounder swath are in parentheses.

	Band 25		Band 27		Band 35	
	Mean	RMS	Mean	RMS	Mean	RMS
Radiance [W m^{-2} sr^{-1} μm^{-1}]	-0.003 (0.012)	0.012 (0.008)	-0.003 (-0.002)	0.063 (0.051)	-0.007 (-0.001)	0.045 (0.031)
Brightness Temperature [K]	-0.24 (0.07)	0.97 (0.60)	-0.07 (-0.06)	1.48 (1.15)	-0.13 (-0.01)	0.83 (0.57)

Similar results for the addition of missing spectral bands to VIIRS using VIIRS/CrIS fusion are also demonstrated in Weisz et al. (2017). The added spectral coverage to the VIIRS allows the product algorithms to more closely adhere to those established for the MODIS product generation; it also implies that the VIIRS cloud mask can be brought into closer conformity with the MODIS cloud mask. Preliminary results show that VIIRS cloud mask improvements can certainly be expected in pixels located in atmospheric temperature inversions.

The fusion algorithm described here can be modified to include any of the imager spectral bands, as long as the spectral coverage is available in the sounder data, to establish the k-d tree selection of the best sounder FOVs to use for constructing the missing radiance at a given imager pixel. Finally, the same k-d selection of sounder FOVs for a given imager pixel can be used to establish a sounder product rather than a radiance.

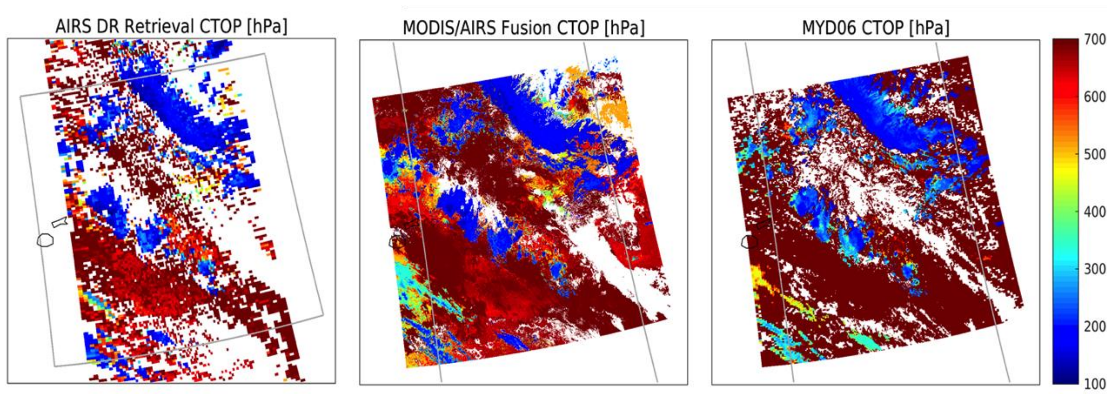

Figure 6. AIRS Dual Regression CTOPs (left), MODIS/AIRS fusion CTOPs derived directly from the sounder product without engaging fusion radiances (middle), and MODIS Collect 6 CTOPs (right).

An early attempt to create fusion products (not radiances) from sounders is demonstrated in Fig. 6, which shows AIRS Dual Regression (Smith et al. 2012, Weisz et al. 2013) retrievals of cloud top pressure (CTOP), MODIS/AIRS fusion CTOPs, and MODIS Collect 6 CO_2 slicing CTOPs. The fusion CTOP product closely resembles the MODIS CO_2 slicing CTOP; differences are expected because the underpinning algorithms (Dual Regression versus CO_2 slicing) are different but nevertheless there is evidence of similar depiction of small-scale gradients that the sounder product alone does not show. Additionally, the sounder product, when fused with the imager, shows more skill in depicting mid-level clouds by taking advantage of the AIRS larger information content.

Four applications are being studied, each with a representative number of case studies, with

VIIRS enhanced by fusion based CrIS data:

1. Improved cloud top heights and phase using fusion based CO_2 spectral bands – cloud top pressures (CTOPs) derived from VIIRS/CrIS fusion radiances are being compared to Collect 6 MODIS CO_2 slicing CTOPs. As part of this work, improvements in the VIIRS cloud mask derived from the addition of missing spectral bands are also being documented.

2. High spatial resolution TPW using the full suite of fusion based CO_2, H_2O, and O_3 spectral bands (and also perhaps additional new H_2O bands) – again comparisons are being made against Collect 6 MODIS TPW.

3. Improved volcanic ash characterization especially heights using fusion based SO_2 and CO_2 spectral bands – study of SO_2 detection associated with volcanic eruptions (e.g., Etna in Italy, Bogoslof in Iceland and Popocatepetl in Mexico).

4. Polar winds using the fusion based H_2O spectral bands – comparison of winds derived from tracers in VIIRS/CrIS fusion H_2O radiances with winds derived from MODIS H_2O radiances in Arctic and Antarctic regional case studies are planned.

The associated study and demonstration of possible fusion applications is being conducted in collaboration with the respective in-house MODIS and VIIRS product specialists (Andy Heidinger, Eva Borbas, Mike Pavolonis, and Dave Santek). Studies include (a) possible adjustment of the k-d tree search, (b) creation of new spectral bands that can exclude strong trace gas absorption lines in the response function (this will reduce the computational burden of performing radiative transfer simulations), (c) estimation of fusion product uncertainty and comparison with operational product uncertainty, and (d) generation of quality flags.

This work offers the possibility of improving the continuity in derived cloud and moisture products and associated applications over generations of weather satellite sensors, and continuing applications that require IR absorption bands. It also has implications for future imager-sounder instrument design strategies.

References

Bentley, J. L. (1975), Multidimensional binary search trees used for associative searching, In Commun. ACM 18(9), 509–517, (1975) [doi:10.1145/361002.361007].

Cross, J. I., I. Gladkova, W. P. Menzel, A. Heidinger, and M. D. Grossberg (2013), Statistical estimation of a 13.3 µm Visible Infrared Imaging Radiometer Suite channel using multisensor data fusion, *J. Appl. Remote Sens.* 7 (1), 073473 (2013) [doi:10.1117/1.JRS.7.073473].

Gladkova I. et al. (2013), Statistical estimation of a 13.3 micron channel for VIIRS using multi-sensor data fusion with application to cloud-top pressure estimation, Proc. AMS 29th Conference on Environmental Information Processing Technologies, Austin, TX (2013).

Smith, W. L. Sr., E. Weisz, S. V. Kireev, D. K. Zhou, Z. Li, and E. E. Borbas (2012), Dual-regression retrieval algorithm for real-time processing of satellite ultraspectral radiances. *J. Appl. Meteor. Climatol.*, 51, 1455 - 1476.

Weisz, E., W. L. Smith Sr., and N. Smith (2013), Advances in simultaneous atmospheric profile and cloud parameter regression based retrieval from high-spectral resolution radiance measurements. *Journal of Geophysical Research -Atmospheres*, Vol. 118, Issue 12.

Weisz, E., B. Baum and W. P. Menzel (2017), Fusion of satellite-based imager and sounder data to construct supplementary high spatial resolution narrowband IR radiances, *J. of Applied Remote Sensing*, Volume 11, Issue 3, 2017.