AIRS Deconvolution and Translation from the AIRS to CrIS IR Sounders
**** DRAFT ****

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1 Introduction

Upwelling infrared radiation as measured by the AIRS [1] and CrIS [2, 6] sounders is a significant part of the long term climate record. We would like to treat this information as a single data set but the instruments have different spectral resolutions, channel response functions, and band spans. As a step in addressing this problem we consider the translation of channel radiances from AIRS to standard resolution CrIS.

Translation from AIRS to CrIS involves more that simple resampling for two reasons. First, AIRS is a grating spectrometer with a distinct response function for each channel determined by the focal plane geometery, while CrIS is a Michaelson interferometer with a sinc ILS after calibration and corrections. Second, we can take advantage of our detailed knowledge of the AIRS spectral response functions (SRFs) and their overlap to deconvolve channel radiances to a resolution-enhanced intermediate representation.

The AIRS to CrIS translation then consists of two steps, deconvolution of the AIRS channel radiances to an intermediate grid, typically 0.1 cm^{-1}, the approximate resolution of the tabulated AIRS SRFs, followed by reconvolution to the CrIS user grid. In section 3 the reconvolution as more conventional resampling, together with channel intersection and bandpass filtering. In section 4 we show how to further improve residuals by adding a statistically based correction.

Translations are validated by comparison with calculated reference truth. To test the AIRS to CrIS translation we start with profiles spanning a significant range of atmospheric conditions. Upwelling radiance is calculated at a 0.0025 cm^{-1} grid with kcarta [4] over a band spanning the AIRS and CrIS response functions. "True AIRS" is calculated from this by convolving the kcarta radiances with the tabulated AIRS SRFs, and "true CrIS" by convolving kcarta radiances to the CrIS instrument specifications. AIRS is then translated to CrIS to get "AIRS CrIS" and compared with true CrIS. Details are presented in sections 3 and 4

2 AIRS Deconvolution

The AIRS spectral response functions model channel response as a function of frequency and associate channels with nominal center frequencies. Each AIRS channel i has an associated spectral response function or SRF $\sigma_i(v)$ such that the channel radiance $c_i = \int \sigma_i(v) r(v)\, dv$, where r is radiance at frequency v. The center or peak of σ_i is the nominal channel frequency.

Figure 1 shows a typical subset of AIRS SRFs. Note the significant overlap in the wings. This allows the deconvolution to recover resolution beyond that of the response functions considered individually. The spacing of the AIRS L1b channels is not regular; there are both gaps and close neighbors, side effects of the focal plane geometry. Both the gaps and close neighbors cause problems for a deconvolution. The AIRS L1c channel set [?] is a derived product of the 1b set with filled gaps and relatively regular (though still frequency dependent) frequency spacing, and we will use the 1c set here.

Suppose we have n channels and a frequency grid $\vec{v}$ of k points spanning the domains of the functions σ_i. The grid step size for our applications is often 0.0025 cm^{-1}, the kcarta resolution. Let S_k be an $n \times k$ array such that $s_{i,j} = \sigma_i(v_j)/w_i$, where $w_i = \sum_j \sigma_i(v_j)$, that is where row i is $\sigma_i(v)$ tabulated at the grid $\vec{v}$ and normalized so the row sum is 1. If the channel centers are in increasing order S_k is banded, and if they are not too close the rows are linearly independent. S_k is a linear transform whose domain is radiance

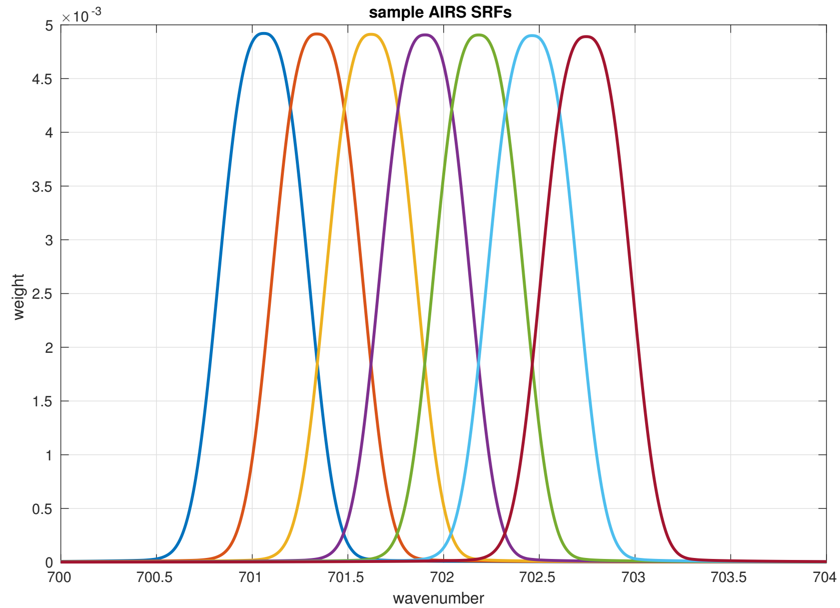

Figure 1: sample adjacent AIRS spectral response functions

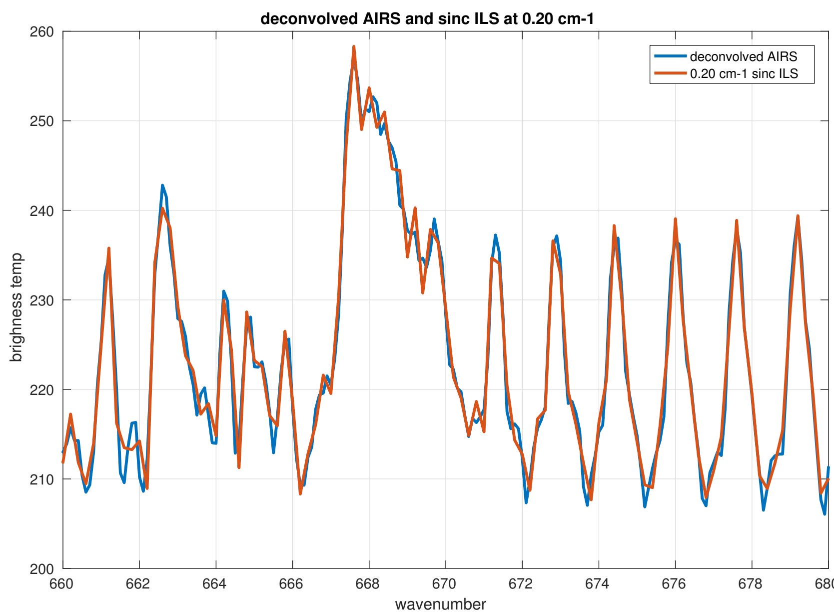

Figure 2: detail of deconvolved AIRS and kcarta 0.0025 cm^{-1} radiances convolved to a sinc ILS at 0.2 cm^{-1}

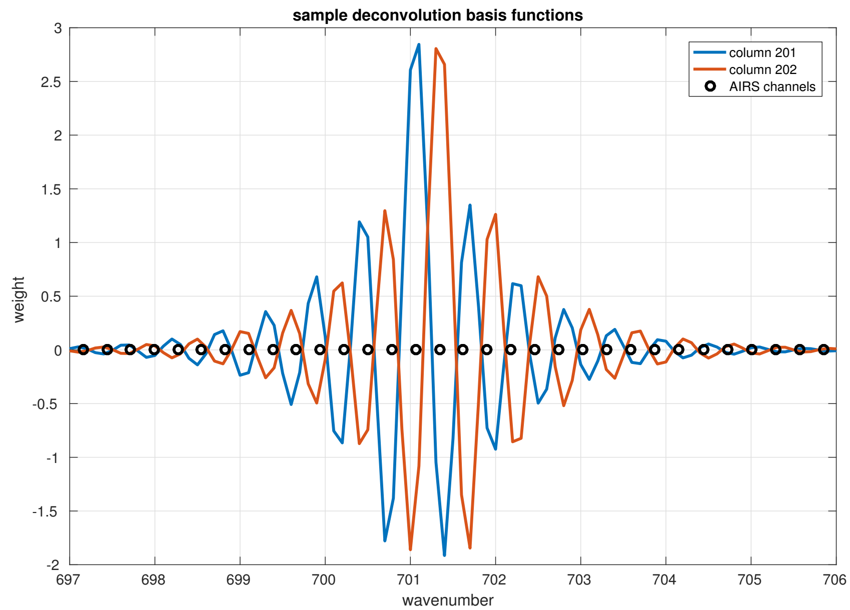

Figure 3: sample basis function for the deconvolved AIRS radiances

at the grid $\vec{v}$ and whose range is channel radiances. If r is radiance at the grid $\vec{v}$, then $c = S_k r$ gives a good approximation of the channel radiances $c_i = \int \sigma_i(v) r(v)\, dv$.

In practice this is how we convolve kcarta or other simulated radiances to get AIRS channel radiances. We construct S_k either explicitly or implicitly from AIRS SRF tabulations. The matrix S_k in the former case is large but manageable with a banded or sparse representation.

Suppose we have S_k and channel radiances c and want to find r, that is, to deconvolve c. Consider the linear system $S_k x = c$. Since $n < k$ for the kcarta grid mentioned above this is underdetermined, with infinitely many solutions. We could add constraints, take a pseudo-inverse, consider a new matrix S_b with columns tabulated at some coarser grid, or some combination of the above.

For an AIRS to CrIS translation we are mainly interested in the transform S_b with SRFs at an intermediate grid, typically 0.1 cm^{-1}, the approximate resolution of the SRF measurements. Let $\vec{v}_b = v_1, v_2, \ldots, v_m$ be a 0.1 cm^{-1} grid spanning the domains of the functions σ_i. Similar to S_k, let S_b be an $n \times m$ array where row i is $\sigma_i(v)$ tabulated at the $\vec{v}_b$ grid, with rows normalized to 1. If r is radiance at the $\vec{v}_b$ grid, then $c = S_b r$ is still a reasonable approximation of $\int \sigma_i(v) r(v)\, dv$.

Consider the linear system $S_b x = c$, similar to the case $S_k x = c$ above, where we are given S_b and channel signals c and want to find radiances x. Since $n < m < k$, as with S_k the system will be underdetermined but more manageable because m is approximately 40 times less than k. We use a Moore-Penrose pseudoinverse as S_b^{-1}. Then $x = S_b^{-1} c$ gives us deconvolved radiances at the SRF tabulation grid.

The AIRS deconvolution gives a significant resolution enhancement. Figure 2 shows LW detail of deconvolved AIRS together with kcarta radiances convolved directly to a 0.2 cm^{-1} sinc ILS. Figure 3 shows a typical basis function for the AIRS deconvolution, that is, a column of the pseudo-inverse S_b^{-1}.

3 AIRS to CrIS translation

For the CrIS standard resolution mode the channel spacing is 0.625 cm^{-1} for the LW, 1.25 cm^{-1} for the MW, and 2.5 cm^{-1} for the SW bands. The first step in the AIRS L1c to CrIS translation is to deconvolve the AIRS channel radiances to a 0.1 cm^{-1} intermediate grid, the nominal AIRS SRF resolution. Then for each CrIS band,

- find the AIRS and CrIS band intersection
- apply a bandpass filter to the deconvolved AIRS radiances to restrict them to the intersection, with a rolloff outside the intersection
- reconvolve the filtered spectra to the CrIS user grid

Translations are validated by comparison with calculated reference truth. For the results presented in this section we start with 49 fitting profiles spanning a significant range of atmospheric conditions [3, 5]. Upwelling radiance is calculated at a 0.0025 cm^{-1} grid with kcarta [4] over a band spanning the AIRS and CrIS response functions. "True AIRS" is calculated from this by convolving the kcarta radiances with AIRS SRFs, and "true CrIS" by convolving kcarta radiances to the CrIS instrument specifications. AIRS is then translated to CrIS (we call this "AIRS CrIS") and compared with true CrIS. This sort of validation assumes perfect knowledge of the AIRS and CrIS instrument response functions and so gives only a lower bound on residuals,

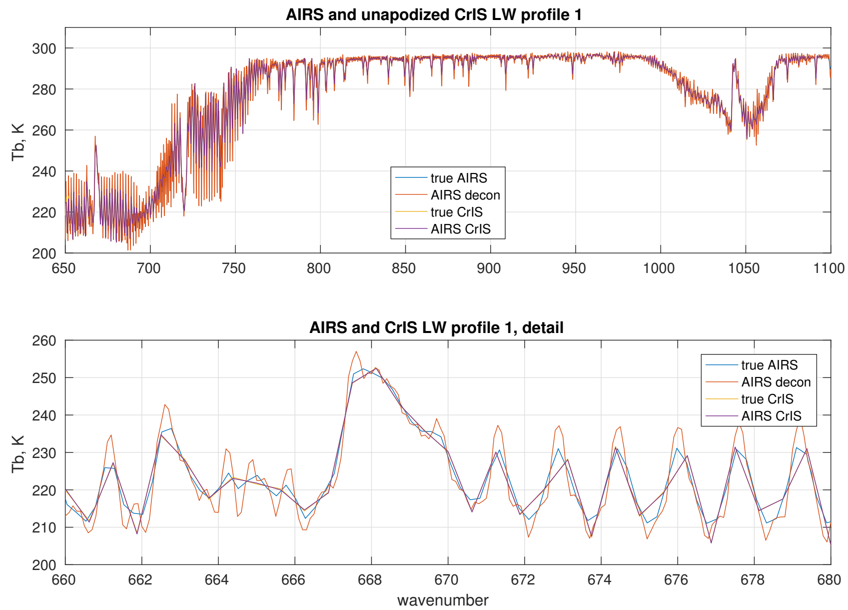

Figure 4: true CrIS, true AIRS, deconvolved AIRS, and AIRS CrIS

and on how well the translations can work in practice. The better we know the response functions, the closer practical translations can approach these limits.

Figure 4 shows true CrIS, true AIRS, deconvolved AIRS, and AIRS CrIS. In the first subplot we mainly see the greater fine structure in the deconvolution. The second subplot shows details from 660 to 680 cm^{-1}. The remaining figures show true CrIS minus AIRS CrIS for the 49 fitting profiles, with and without Hamming apodization, for each of the CrIS bands. The residuals are significantly reduced with apodization.

Deconvolution works better for the AIRS to CrIS translation than either interpolation or interpolation (rather than deconvolution) to an intermediate grid followed by convolution to CrIS radiances. For the first case we start with true AIRS and interpolate radiances directly to the CrIS user grid with a cubic spline. For the second we interpolate true AIRS to the 0.1 cm^{-1} intermediate grid with a cubic spline and then convolve this to the use CrIS user grid.

Figure 8 shows interpolated CrIS minus true CrIS for the LW band, without any apodization. While the two-step interpolation works a little better than the simple spline, both residuals are significantly larger than for the

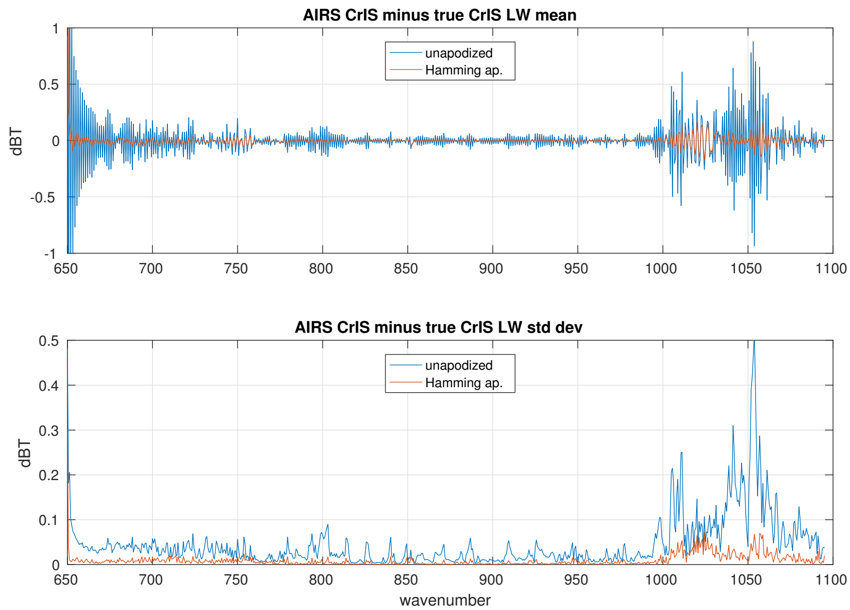

Figure 5: Mean and standard deviation of unapodized and Hamming apodized AIRS CrIS minus true CrIS, for the CrIS LW band

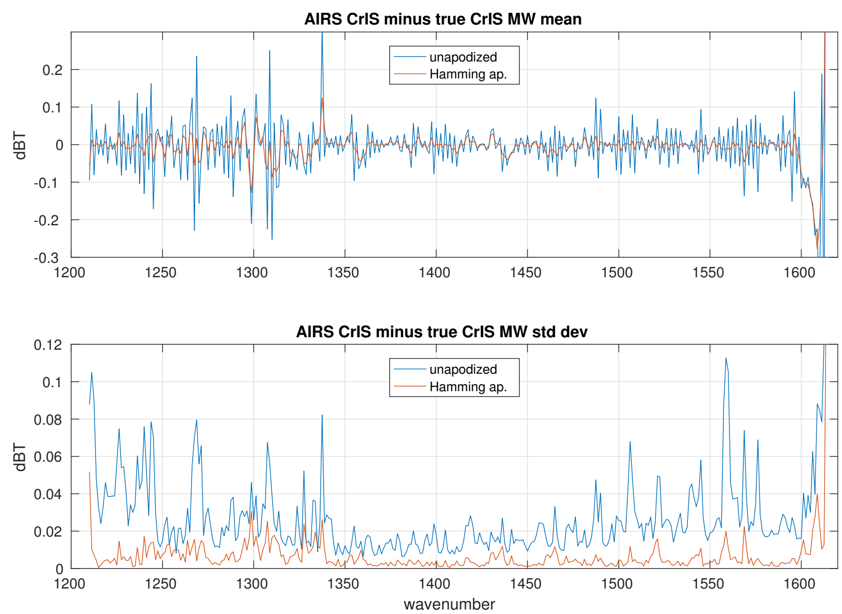

Figure 6: Mean and standard deviation of unapodized and Hamming apodized AIRS CrIS minus true CrIS, for the CrIS MW band

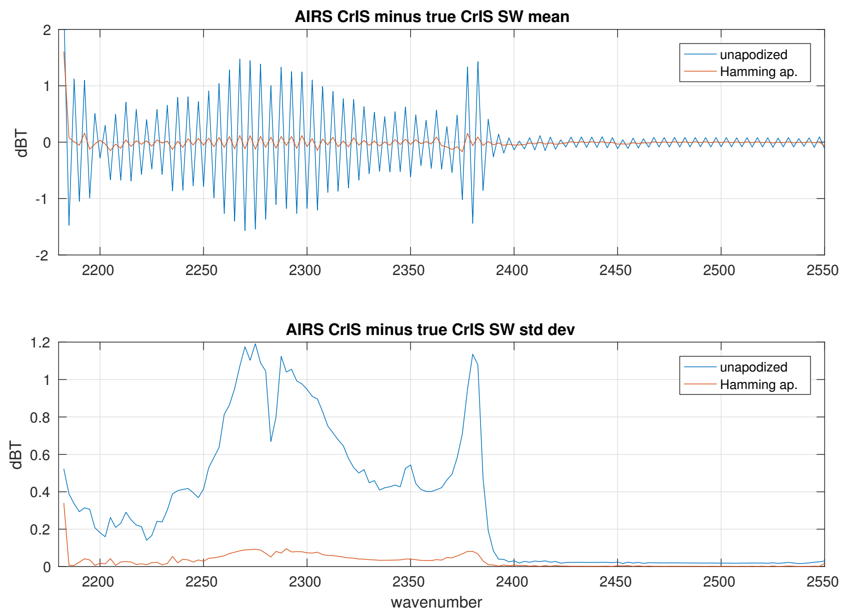

Figure 7: Mean and standard deviation of unapodized and Hamming apodized AIRS CrIS minus true CrIS, for the CrIS SW band

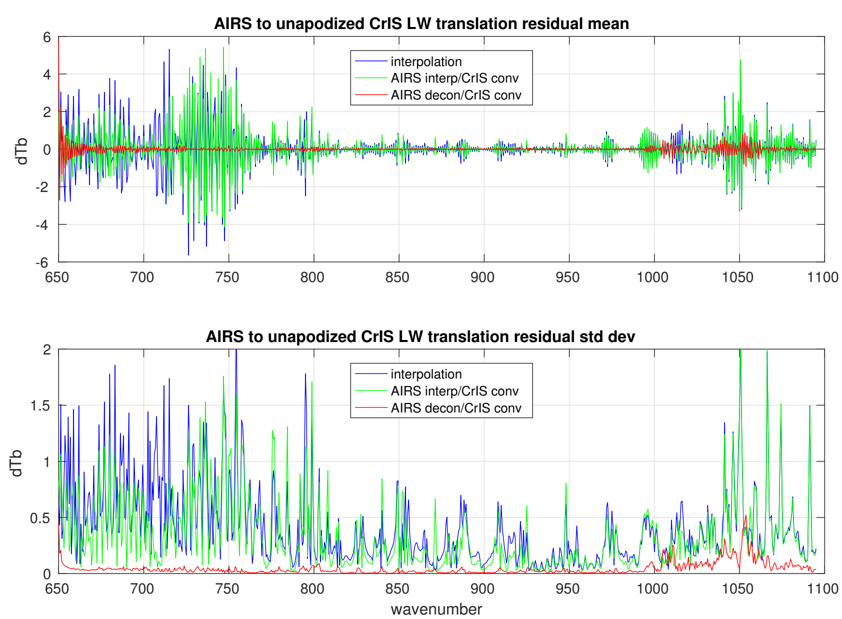

Figure 8: spline interpolation, interpolation with convolution, and deconvolution with convolution for the CrIS LW band

translation with deconvolution. Results for the MW and SW are similar. Deconvolution is significantly better for the MW, while the comparison is less clear for the SW. Comparisons with Hamming apodization show the residuals with deconvolution are significantly less for all three bands.

4 Statisitcal Refinement

References

[1] H. H. Aumann, M. T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L. M. McMillin, H. Revercomb, P. W. Rosenkranz, W. L. Smith, D. H. Staelin, L. L. Strow, and J. Susskind. AIRS/AMSU/HSB on the aqua mission: design, science objectives, data products, and processing systems. *IEEE Transactions on Geoscience and Remote Sensing*, 41:253–264, Feb. 2003.

[2] Y. Han, H. Revercomb, M. Cromp, D. Gu, D. Johnson, D. Mooney, D. Scott, L. Strow, G. Bingham, L. Borg, Y. Chen, D. DeSlover, M. Esplin, D. Hagan, X. Jin, R. Knuteson, H. Motteler, J. Predina, L. Suwinski, J. Taylor, D. Tobin, D. Tremblay, C. Wang, L. Wang, L. Wang, and V. Zavyalov. Suomi NPP CrIS measurements, sensor data record algorithm, calibration and validation activities, and record data quality. *Journal of Geophysical Research (Atmospheres)*, 118:12734, Nov. 2013.

[3] L. Strow, S. Hannon, S. De Souza-Machado, H. Motteler, and D. Tobin. An overview of the airs radiative transfer model. *Geoscience and Remote Sensing, IEEE Transactions on*, 41(2):303–313, Feb 2003.

[4] L. Strow, H. E. Motteler, R. G. Benson, S. E. Hannon, and S. D. Souza-Machado. Fast computation of monochromatic infrared atmospheric transmittances using compressed look-up tables. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 59(35):481 – 493, 1998. Atmospheric Spectroscopy Applications 96.

[5] L. L. Strow, S. E. Hannon, S. De-Souza Machado, H. E. Motteler, and D. C. Tobin. Validation of the atmospheric infrared sounder radiative transfer algorithm. *Journal of Geophysical Research: Atmospheres*, 111(D9), 2006. D09S06.

[6] L. L. Strow, H. Motteler, D. Tobin, H. Revercomb, S. Hannon, H. Buijs, J. Predina, L. Suwinski, and R. Glumb. Spectral calibration and validation of the Cross-track Infrared Sounder on the Suomi NPP satellite. *Journal of Geophysical Research (Atmospheres)*, 118:12486, Nov. 2013.