AIRS deconvolution and the translation of AIRS to CrIS radiances

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introduction

- Upwelling infrared radiation as measured by AIRS, CrIS, and IASI is a significant part of the long term climate record.
- These instruments have broadly similar spatial sampling and spectral resolution, channel response functions, and band spans.
- We make regular use of AIRS to CrIS and IASI to CrIS translations, and have implemented and tested IASI to AIRS and CrIS to AIRS translations as well. But aside from AIRS to CrIS the methods used are for the most part conventional.
- AIRS is a grating spectrometer with a distinct response function for each channel, while CrIS is a Michaelson interferometer with a sinc response function after calibration and corrections.
- We use our detailed knowledge of the AIRS spectral response functions to deconvolve AIRS channel radiances to a resolution enhanced intermediate representation.
- This intermediate representation is then reconvolved to CrIS or other instrument specifications.

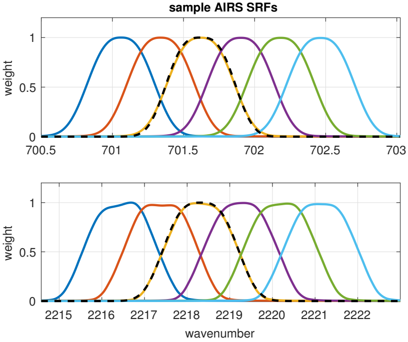
AIRS spectral response functions

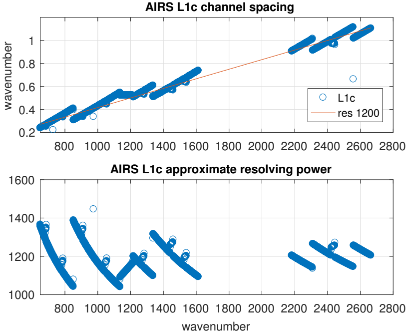
- Each AIRS channel i has an associated spectral response function or SRF $\sigma_i(v)$, a function of frequency v.
- Channel radiance $c_i = \int \sigma_i(v) r(v)\, dv$, where r is radiance at frequency v.
- The center or peak of σ_i is the nominal channel frequency.
- We can approximate the AIRS SRFs with a generalized Gaussian of the form

$$w(v, v_0, \mathrm{FWHM}) = \exp\left(-\left(\frac{(v - v_0)^2}{2c^2}\right)^{1.5}\right)$$

  where $c = \mathrm{FWHM}/(2\sqrt{2\ln 2})$ and v_0 is the desired channel center.
- The exponent 1.5 was chosen to give an approximate match to AIRS SRFs with the same FWHM and channel centers, though without the fine structure and variation.

sample SRFs and resolving power





Sample AIRS spectral response functions from the low and high ends of the band. The dashed line is the generalized Gaussian function.

AIRS L1c channel spacing and resolving power, $R = v_i/\mathrm{FWHM}_i$. The relatively regular L1c channel spacing aids the deconvolution.

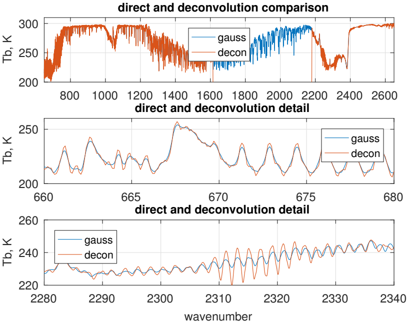
the AIRS deconvolution

- 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.
- This is the approximate resolution of the SRF measurements and is convenient for reconvolution to the CrIS user grid.
- 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.
- Note that the $\sigma_i(v)$ here are the measured SRFs, not our Gaussian approximation.
- If r is radiance at the $\vec{v}_b$ grid, then $c = S_b r$ is a reasonable approximation of $\int \sigma_i(v) r(v)\, dv$.
- We want to start with c and find r, that is to deconvolve c by solving $S_b r = c$ for r.
- Since $m < k$ the system is underdetermined.

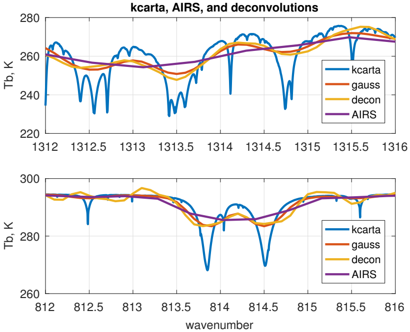
the AIRS deconvolution

- We take the Moore-Penrose pseudoinverse of S_b to get $r_0 = S_b^{-1} c$.
- This gives a minimal solution, in the sense that $||r_0||_2 \leq ||r_j||_2$ for all r_j satisfying $S_b r_j = c$.
- The condition number for S_b as built from the L1c channels is $||S_b||_2 ||S_b^{-1}||_2 = 115$, which is tolerable.
- Although our main goal is to reconvolve the 0.1 cm^{-1} intermediate representation to the CrIS or other user grids, we first compare the deconvolved radiances with reference truth from a direct convolution to the intermediate grid.
- We use the generalized Gaussian as reference truth for the 0.1 cm^{-1} intermediate grid with $\textsc{fwhm} = v_i/2000$, where v_i are the grid frequencies.
- This represents a hypothetical grating spectrometer with a resolving power of 2000, oversampled to the 0.1 cm^{-1} grid.

examples of deconvolution



Spectra from fitting profile 1 for direct convolution to the 0.1 cm^{-1} grid and for deconvolved AIRS. We see some overshoot and ringing in the deconvolution.



Details from fitting profile 1 for kcarta, direct convolution to the 0.1 cm^{-1} grid, deconvolved AIRS, and true AIRS. The deconvolution restores some detail.

deconvolution notes

- The AIRS deconvolution gives a modest resolution enhancement, at the cost of added artifacts and noise.
- The deconvolution captures some fine structure that is present in the direct convolution but not the AIRS data, and can resolves lines that are merged in the AIRS L1c spectra
- But we also see some ringing and overshoot that is not present in the direct convolution.
- These artifacts are acceptable because we do not propose using the deconvolved radiances directly; they are an intermediate step before reconvolution to a lower resolution.

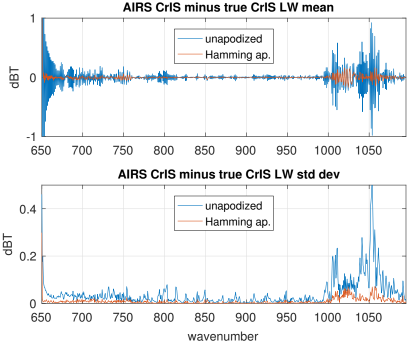
AIRS to CrIS translation

- Given AIRS deconvolution to a 0.1 cm^{-1} intermediate grid, reconvolution to the CrIS user grid is straightforward.
- For the CrIS standard resolution the channel spacing is 0.625 cm^{-1} for the LW band, 1.25 cm^{-1} for the MW, and 2.5 cm^{-1} for the SW.
- For each CrIS band, we
  1. find the AIRS and CrIS band intersection,
  2. apply a bandpass filter to the deconvolved AIRS radiances restricting them to the intersection, with a rolloff outside the intersection, and
  3. reconvolve the filtered spectra to the CrIS user grid with a zero-filled double Fourier transform
- The translation above is from AIRS to unapodized CrIS, but we will typically show both apodized and unapodizied residuals.

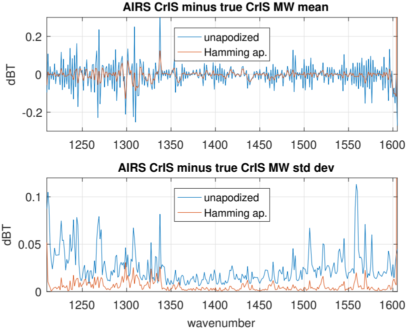
testing and validation

- Translations are tested by comparison with calculated reference truth.
- We start with a set of atmospheric profiles and calculate upwelling radiance at a 0.0025 cm^{-1} grid with kcarta over a band spanning the domains of the AIRS and CrIS response functions.
- "True AIRS" is calculated by convolving the kcarta radiances with AIRS SRFs and "true CrIS" by convolving kcarta radiances to a sinc basis at the CrIS user grid.
- True AIRS is then translated to CrIS to get "AIRS CrIS", and this is compared with true CrIS.
- For most tests we use a set of 49 fitting profiles spanning a wide range of clear atmospheric conditions, initially chosen for testing radiative transfer codes

AIRS to CrIS residuals

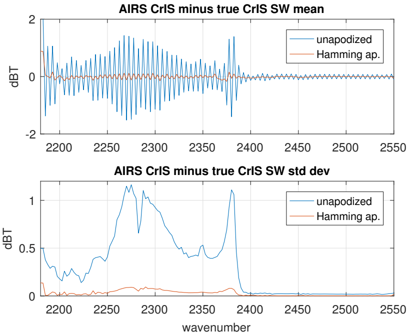


Mean and standard deviation of unapodized and Hamming apodized AIRS CrIS minus true CrIS, for the CrIS LW band

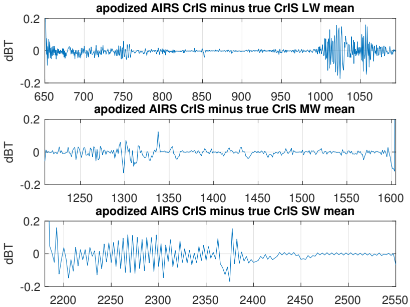


Mean and standard deviation of unapodized and Hamming apodized AIRS CrIS minus true CrIS, for the CrIS MW band

AIRS to CrIS residuals



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

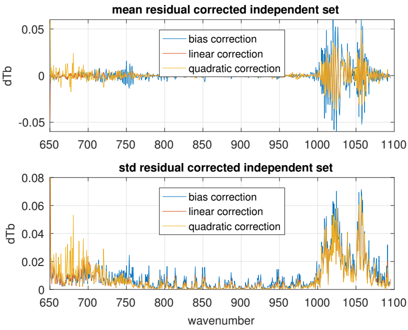


Mean of apodized residuals for all three CrIS bands, showing the residuals in greater detail.

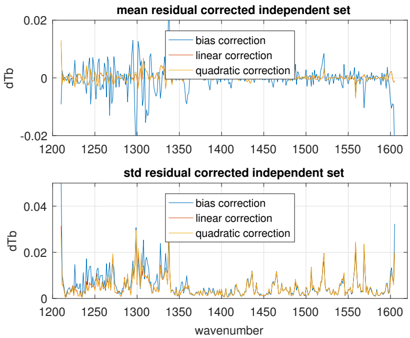
AIRS to CrIS statistical correction

- We can further reduce the residuals with a simple linear or quadratic correction, applied independently to each channel.
- We use a set of 7377 radiances calculated from all-sky AIRS profiles spanning several consecutive days as the dependent set.
- Let t_i^{TC} be true CrIS and t_i^{AC} AIRS CrIS brightness temperatures for CrIS channel i, from the dependent set.
- For the bias test we subtract the mean residual from the dependent set. For the linear test we find a_i and b_i to minimize $||a_i\, t_i^{\mathrm{AC}} + b_i - t_i^{\mathrm{TC}}||_2$, and for the quadratic test c_i, a_i and b_i to minimize $||c_i\,(t_i^{\mathrm{AC}})^2 + a_i\, t_i^{\mathrm{AC}} + b_i - t_i^{\mathrm{TC}}||_2$.
- The a weights are very close to 1, the b weight to the bias, and the c weights to zero. The linear correction worked best.
- The resulting correction is applied to the independent set, the 49 fitting profiles, for comparison with true CrIS. This gives a stricter test than splitting the more correlated 7377 profile set into dependent and independent subsets.

AIRS to CrIS statistical correction

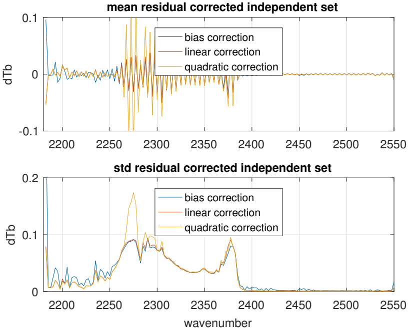


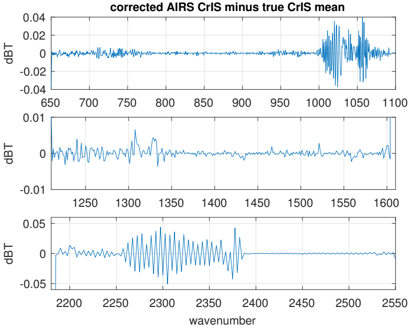
Mean and standard deviation of LW corrected apodized residuals.



Mean and standard deviation of MW corrected apodized residuals.

AIRS to CrIS statistical correction

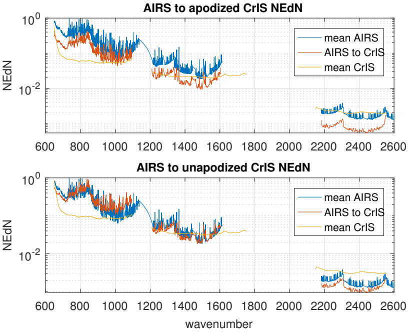




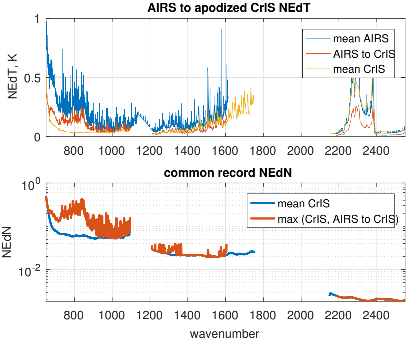
Mean and standard deviation of SW corrected apodized residuals.

Mean corrected apodized residuals for all three bands, showing the linear corrected apodized residuals in greater detail.

NEdN of the translation



AIRS, AIRS-to-CrIS, and CrIS NEdN. Apodization reduces the CrIS and AIRS-to-CrIS NEdN by a factor of 0.63.

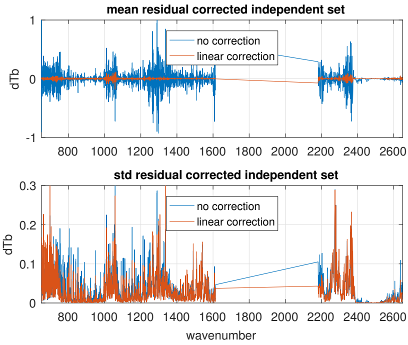


AIRS, AIRS-to-CrIS, and CrIS apodized NEdT, and the max of CrIS and AIRS-to-CrIS NEdN with CrIS shown as a reference.

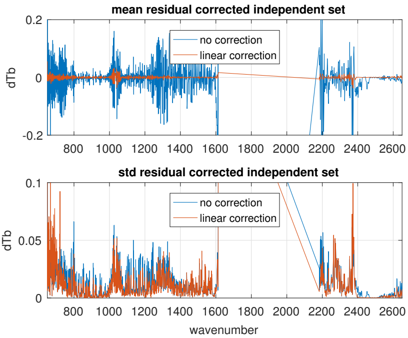
L1c to L1d translation

- The AIRS deconvolution can be used for other translations.
- We consider reconvolution to an idealized grating model for resolving powers of 700 and 1200.
- Define an AIRS L1d basis with resolving power R using the generalized Gaussian described earlier as follows:
- Let v_0 be the frequency of the first channel, and for $i \geq 0$ $\mathrm{FWHM}_i = v_i/R$, $dv_i = \mathrm{FWHM}_i/2$, and $v_{i+1} = v_i + dv_i$.
- As with tests of the AIRS to CrIS translation, we get "true L1d" by convolving kcarta radiances with an L1d basis at the desired resolving power.
- AIRS L1c is translated to L1d by deconvolution to the intermediate grid followed by reconvolution to the desired L1d basis, and this is compared with true L1d.
- A statistical correction similar to that used for the AIRS to CrIS translation is then applied

L1c to L1d translation



Mean and standard deviation over the 49 fitting profiles for the L1c to L1d translation minus true L1d, for a resolving power of 1200.

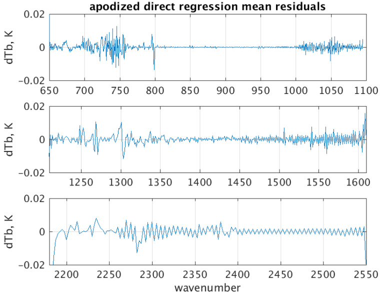


Mean and standard deviation over the 49 fitting profiles for the L1c to L1d translation minus true L1d, for a resolving power of 700.

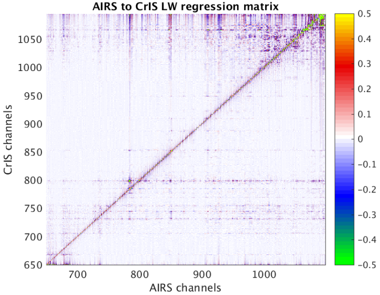
direct regression

- The AIRS to CrIS and AIRS to L1d translations can be represented as a single linear transform, the composition of the deconvolution and reconvolution matrices.
- We can get such a one-step tranform in other ways.
- For example if r_a and r_c are $m \times k$ and $n \times k$ AIRS and CrIS radiance sets, we can find X to minimize $\|Xr_a - r_c\|_2$.
- Typically $k > m$, giving an overdetermined system, and we solve $r_a^t X^t = r_c^t$ for X by regression.
- This differs from the regression corrections used earlier; there regression was used to find linear or quadratic correction coefficients independently for each channel.
- As before we use the 7377 profile set as the dependent and the 49 profile as the independent sets.
- This approach is prone to over-fitting, and the regression matrices show significant off-diagonal correlations.

direct regression



Mean residuals for apodized AIRS to CrIS direct regression.

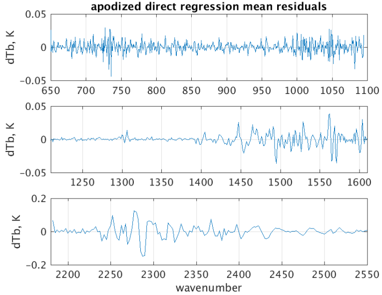


Regression coefficients for the LW direct regression.

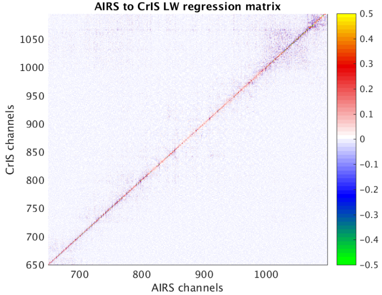
principal component regression

- We can use a form of principal component regression to reduce unwanted correlations.
- Let r_a and r_c be $m \times k$ and $n \times k$ AIRS and CrIS radiance sets.
- Let $r_a = U_a S_a V_a^T$ be a singular value decomposition with singular values in descending order and U_a^i the first i columns of U_a.
- Similarly let $r_c = U_c S_c V_c^T$ be a singular value decomposition with singular values in descending order and U_c^j the first j columns of U_c.
- Let $\hat{r}_a = (U_a^i)^T r_a$ and $\hat{r}_c = (U_c^j)^T r_c$ be r_a and r_c represented with respect to the bases U_a^i and U_c^j.
- Then find X to minimize $\|X\hat{r}_a - \hat{r}_c\|_2$ by solving $\hat{r}_a^T X^T = \hat{r}_c^T$ for X by regression.
- This gives us $R = U_c^j X (U_a^i)^T$, an AIRS to CrIS transform parameterized by the AIRS and CrIS basis sizes i and j.

principal component regression

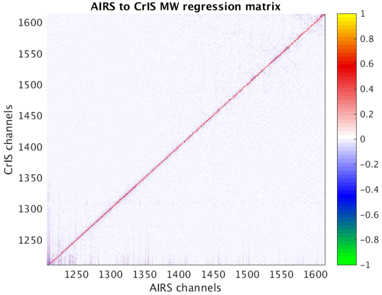


Mean residuals for apodized AIRS to CrIS principal component regression.

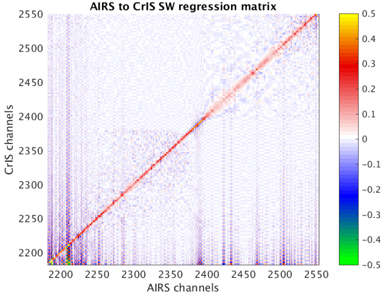


Regression coefficients for the LW principal component regression.

principal component regression



Regression coefficients for the MW principal component regression.



Regression coefficients for the SW principal component regression.

conclusions

- The AIRS deconvolution gives a modest resolution enhancement, at the cost of added artifacts and noise.
- The deconvolution can be used for other translations, such as an idealized grating model.
- AIRS to CrIS translation via deconvolution, reconvolution, and a statistical correction works better than translation via regular or principal component regression.
- Translation via deconvolution works significantly better than conventional interpolation, including interpolation to the intermediate grid followed by convolution to the final target.
- This talk, a more in-depth companion paper, and all the translation and test code discussed here are available online at github:
    - https://github.com/motteler/decon_paper
    - https://github.com/strow/airs_deconv
    - https://github.com/strow/iasi_decon