Surface effects in hyperspectral infrared measurements from the AIRS instrument of the Aqua satellite

(Experimental Processing of IR Measurements from the AIRS Instrument)

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The importance of incorporating the surface emissivity in the solution of the atmospheric infrared remote sensing inverse problem is explained by:

* **Optically “black” surfaces don’t exist**; emissivity variations cause measurable changes in infrared radiance

* Satellite meteorological **remote sensing instruments have good radiometric sensitivity** with a relative accuracy of .2K. Disregarding the spectral-spatial variations of emissivity in the radiative transfer model (in the atmospheric windows) magnifies the errors by at least a factor of three to five.

* To realize the potential of the satellite measurements, **a radiative transfer model accounting for surface emissivity must be used**.

* Different kinds of surface cover, with different surface optical properties, with extremely high spatial and temporal variations, restrict the use of a priori estimates of the surface effects. The **direct evaluation of emissivity in the inverse solution is a simpler and more effective approach**.
Spatial distribution of Ch 1552 at 1385.02 [1/cm] measurements [K]
Spatial distribution of Ch 1553 at 1385.57 [1/cm] measurements [K]
Spatial distribution of Ch 1554 at 1386.11 [1/cm] measurements [K]
Spatial distribution of Ch 1555 at 1386.66 [1/cm] measurements [K]
Spatial distribution of Ch 1556 at 1387.21 [1/cm] measurements [K]
AIRS radiance changes (in deg K) to atm & sfc changes
Optical properties of cloud particles: imaginary part of refraction index

 Imaginary part of refraction index

SW & LW channel differences are used for cloud identification
\{4 \text{ \(\mu\)m - 11\(\mu\)m}\}, \{4.13 \text{ \(\mu\)m - 12.6\(\mu\)m}\}, and \{4.53 \text{ \(\mu\)m - 13.4\(\mu\)m}\}
Spatial distribution of 944.1 [1/cm] measurements [K]
Spatial distribution of 2555 [1/cm] measurements [K]
Spatial distribution of 2555 – 944.1 [1/cm] measurements [K]
1 - StDev of bb measurement error [K] (RED), 2 - StDev of earth measurements [K] (BLUE); 3 - total atmospheric transmittance
The following issues are addressed:

* to improve the signal to noise ratio, a spatial filtering procedure is developed; spatial smoothing is used in all spectral channels (a rectangular box of variable size defined for each spectral band is used for each field of view);

* to identify the presence of cloud, tests for spatial smoothness (second differential), and spectral smoothness (differences between LW band channels and SW band channels) are used;

* spatial averaging and cloud identification are combined in a joint algorithm for data analysis: averaging ⇔ identification ⇔ averaging on “clear” sub-sample;

* the temporal-spatial structure of errors is discussed, and the shortwave and longwave components of the errors are estimated.
Spectral distribution of spatial smoothing filter
(half-size given in pixel number)
Spatial distribution of Ch 121 at 679.62 [1/cm] measurements [K]
Spatial distribution of Ch 121 at 679.62 [1/cm] measurements [K] filtered
Spatial distribution of Ch 121 at 679.62 [1/cm] measurements [K]

original - filtered
Spatial distribution of Ch 1789 at 1560.24 [1/cm] measurements [K]

original
Spatial distribution of Ch 1789 at 1560.24 [1/cm] measurements [K] filtered
Spatial distribution of Ch 1789 at 1560.24 [1/cm] measurements [K] 
original - filtered
Spatial distribution of Ch 217 at 711.58 [1/cm] measurements [K]: 
original
Spatial distribution of Ch 217 at 711.58 [1/cm] measurements [K]: filtered
Spatial distribution of Ch 217 at 711.58 [1/cm] measurements [K]: original - filtered
StDev of measurement error [K] after filtering derived from the spatial differential (GREEN)
StDev of measurement error [K] after filtering derived from bb measurement error [K] (PINK)
StDev of bb measurement error [K] (BLUE);
\[ \tilde{J}(\theta) = \epsilon(\theta) B[T_s] \tau_s^{\uparrow}(\theta) + \int_{\tau_s^{\uparrow}(\theta)}^1 B[T(p)]d\tau^{\uparrow}(p,\theta) \]

\[ + (1-\epsilon(\theta)) \tau_s^{\uparrow}(\theta) \int_{\tau_0^{\downarrow}(\vartheta^*)}^1 B[T(p)]d\tau^{\downarrow}(p,\vartheta^*) + \xi \]
Solution approach

Radiative transfer in earth-atmosphere system with a reflecting surface is modeled. Surface reflection is described by hemispherical directional effective emissivity for an effective angle of incidence.

Solution parameters include emissivity spectrum, surface temperature, atmospheric moisture and temperature profiles.

Emissivity spectrum variation was parametrically defined (N=11). Atmospheric moisture profile variation was parametrically defined (N=17). Atmospheric temperature profile variation was parametrically defined (N=31). Problem dimensionality N=60.

Non-linear Fredholm equation of first kind is solved using method of least squares (regularized wrt atmospheric parameters) in coordinate descent on basis of a Gauss-Newton numerical schema.

Number of analyzed spectral channels around 2100.
Iterative algorithm of solution

\[ \varepsilon^{(0)} = 0.92 , \quad T_s^{(0)} = \overline{T}_s , \quad T^{(0)}(p) = \overline{T}(p) , \quad W^{(0)}(p) = \overline{W}(p) \]

\[ \varepsilon^{(n+1)} = \arg \min_{\varepsilon} \| \tilde{J} - J[\varepsilon, T_s^{(n)}, T^{(n)}(p), W^{(n)}(p)] \|^2_{D^{-1}} \quad (I) \]

\[ \varepsilon \in [0.6, 0.985] \]

\[ x_s^{(n+1)} = \arg \min_{x_s} \| \tilde{J} - J[\varepsilon^{(n+1)}, T_s^{(n)} + x_s, T^{(n)}(p), W^{(n)}(p)] \|^2_{D^{-1}} \quad (II) \]

\[ T_s^{(n+1)} = T_s^{(n)} + x_s^{(n+1)} \]

\[ \begin{bmatrix} x(p)^{(n+1)} \\ w(p)^{(n+1)} \end{bmatrix} = \arg \min_{\begin{bmatrix} x(p) \\ w(p) \end{bmatrix}} \left\{ \begin{array}{c} \| \tilde{J} - J[\varepsilon^{(n+1)}, T_s^{(n+1)}, T^{(n)}(p) + x(p), W^{(n)}(p) + w(p)] \|^2_{S^{-1}} \\ + \| T^{(n)}(p) + x(p) - \overline{T}(p) \|^2_{R_x^{-1}} + \| W^{(n)}(p) + w(p) - \overline{W}(p) \|^2_{R_w^{-1}} \end{array} \right\} \quad (III) \]

\[ T^{(n+1)}(p) = T^{(n)}(p) + x^{(n+1)}(p) , \quad W^{(n+1)}(p) = W^{(n)}(p) + w^{(n+1)}(p) \]

\[ n := n + 1 \quad \text{for} \quad \| \tilde{J} - J[\varepsilon^{(n+1)}, T_s^{(n+1)}, T^{(n+1)}(p), W^{(n+1)}(p)] \|^2_{S^{-1}} > Sp(D^{-1}S) \]
17 basic functions of moisture vertical profile estimate
11 basic functions of emissivity estimate
total atmospheric transmittance (GREEN)
Radiance response [%] to emissivity variation (.94 - .96)
Example of spatial (latitudinal) cross-section of emissivity estimates over North Africa (Sahara)
Laboratory measurements of surface reflection: SAND
Laboratory measurements of surface reflection: BASALT
Laboratory measurements of surface reflection: GRANITE
Laboratory measurements of surface reflection: SOIL
Spatial distribution of emissivity estimate
Ch 770 at 911.23 [1/cm]
Spatial distribution of emissivity estimate

Ch 977 at 990.34 [1/cm]
Spatial distribution of emissivity estimate

Ch 1246 at 1127.99 [1/cm]
Spatial distribution of emissivity estimate

Ch 1297 at 1234.45 [1/cm]
Spatial distribution of emissivity estimate

Ch 2197 at 2500.6 [1/cm]
Spatial distribution of emissivity estimate
Ch 2333 at 2616.38 [1/cm]
Spatial distribution of surface temperature estimate [K]
Spatial distribution of surface temperature first guess [K]
Spatial distribution of moisture [%] at 300mb estimate & first guess
Spatial distribution of moisture [%] at 300mb

first guess
Spatial distribution of moisture [%] at 500mb
estimate & first guess
Spatial distribution of moisture [%] at 500mb
first guess
Statistics of residuals [K] (a) - over Land, (b) - over Ocean

Average - Black, StDev - Red
Conclusion: Analysis of measurements show that:

The spatial smoothing technique is effective for filtering the SW spatial component of measurement errors; smoothed spatial fields of radiances correspond better to the spatial properties of the desired spatial fields of atmospheric temperature-moisture profiles.

Non-blackbody surface emissivity significantly weakens the radiance signal and has strong influence on lower tropospheric temperature and moisture retrievals

\( \varepsilon_{\text{IR}(\text{sfc})} \) presents strong spectral and spatial variability over land surfaces;

Solutions with \( \varepsilon_{\text{IR}(\text{sfc})} \) consideration are improving the vertical-horizontal spatial structure of atmospheric temperature-moisture estimates.