Cross-track Infrared Sounder Spectral Gap Filling toward Improving Inter-calibration Accuracy

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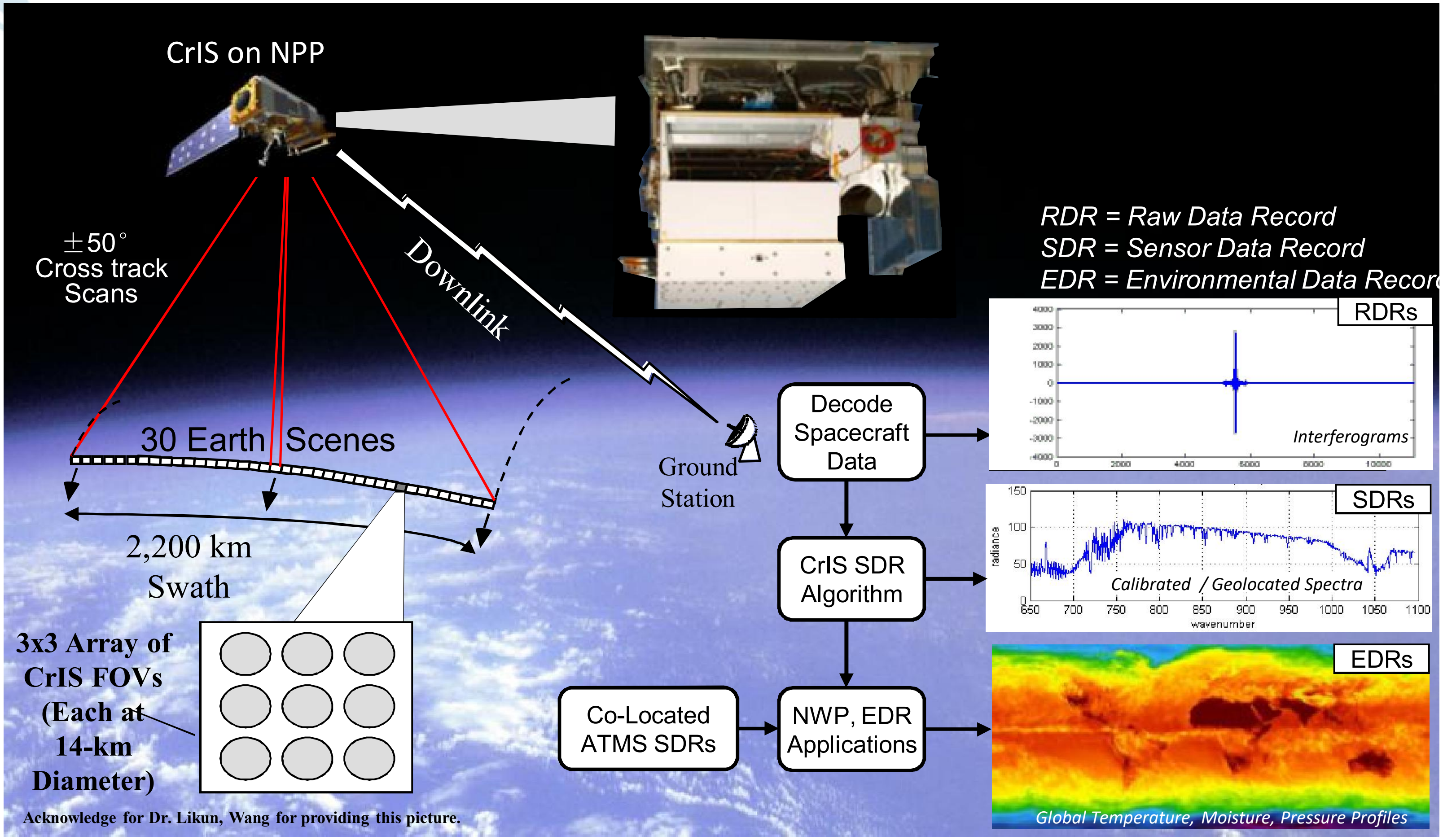
Background

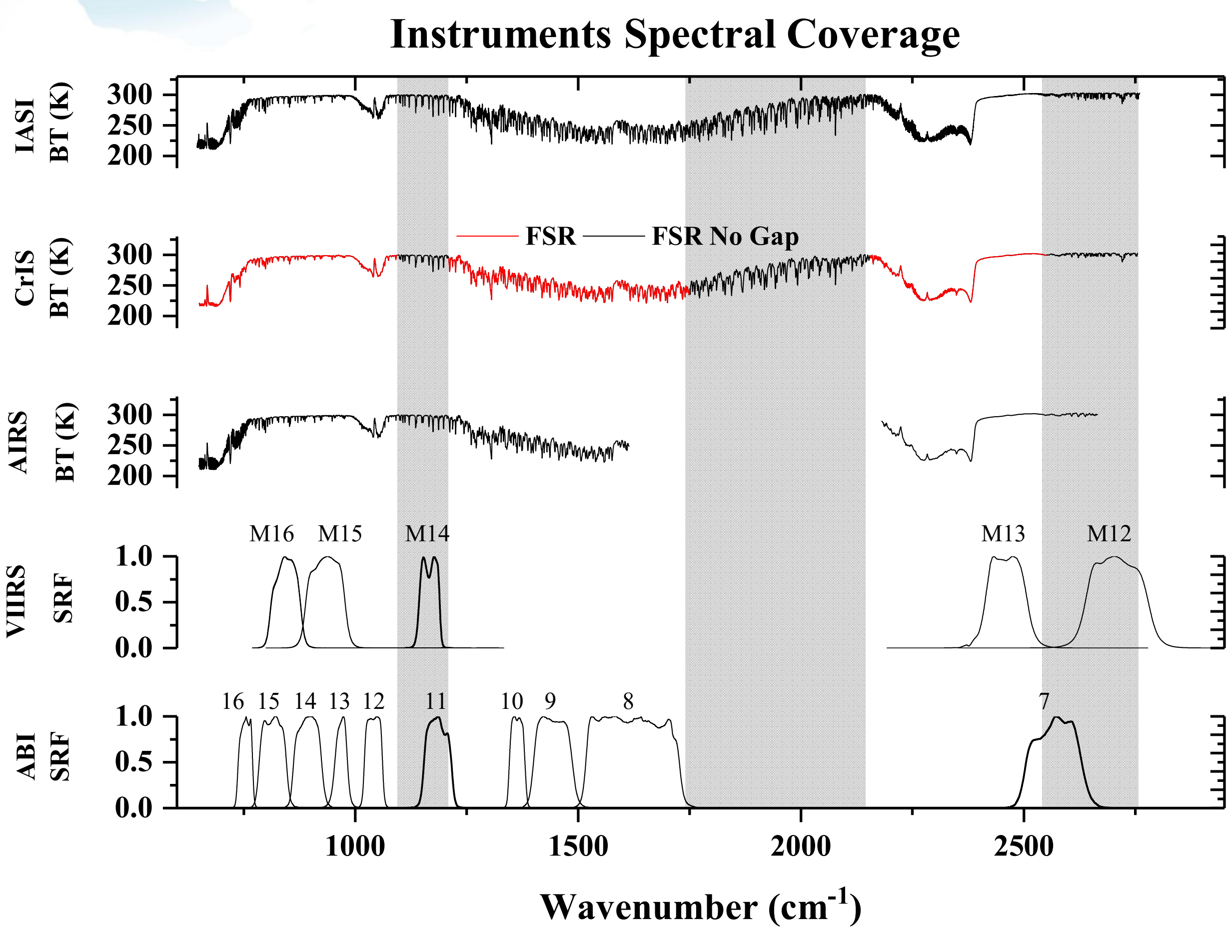
❖***<u>CrIS (Cross-track Infrared Sounder)</u>*** is a hyperspectral infrared sounder mainly for providing atmospheric temperature and moisture profiles to improve weather forecast.



It is a Michelson interferometer with ***<u>2211 (Full Resolution, 0.625 cm^{-1})</u>*** channels over three wavelength ranges: LW infrared (650-1095 cm^{-1}), MW infrared (1210-1750 cm^{-1}), and SW infrared (2155-2550 cm^{-1}).

Background

Due to its excellent performance (***high radiometric and spectra accuracy with low noise***), CrIS radiance is also used as an ***infrared reference*** to check calibration accuracy of broadband sensors, such as AVHRR/ABI on GOES, VIIRS on NPP.



CrIS AS A REFERENCE

$$R_{simulated-broadband} = \frac{\int_{v1}^{v2} R_{CrIS}(v)\cdot S(v)\cdot dv}{\int_{v1}^{v2} S(v)\cdot dv}$$

Spectral Gaps

impact the accuracy of inter-comparison between CrIS and other sensors !!!

NOAA STAR SNO prediction website: https://ncc.nesdis.noaa.gov/SNOPredictions

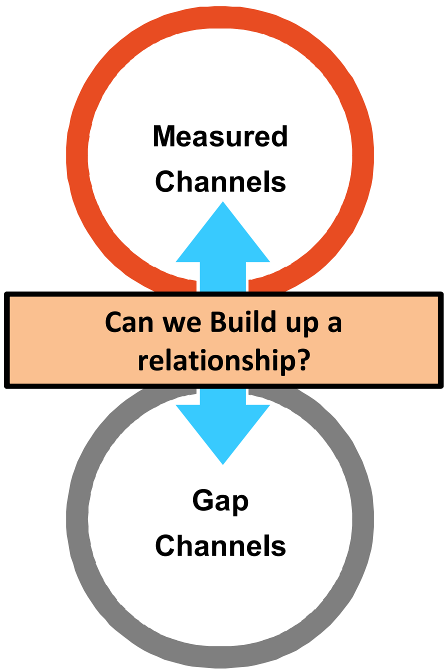
Outline

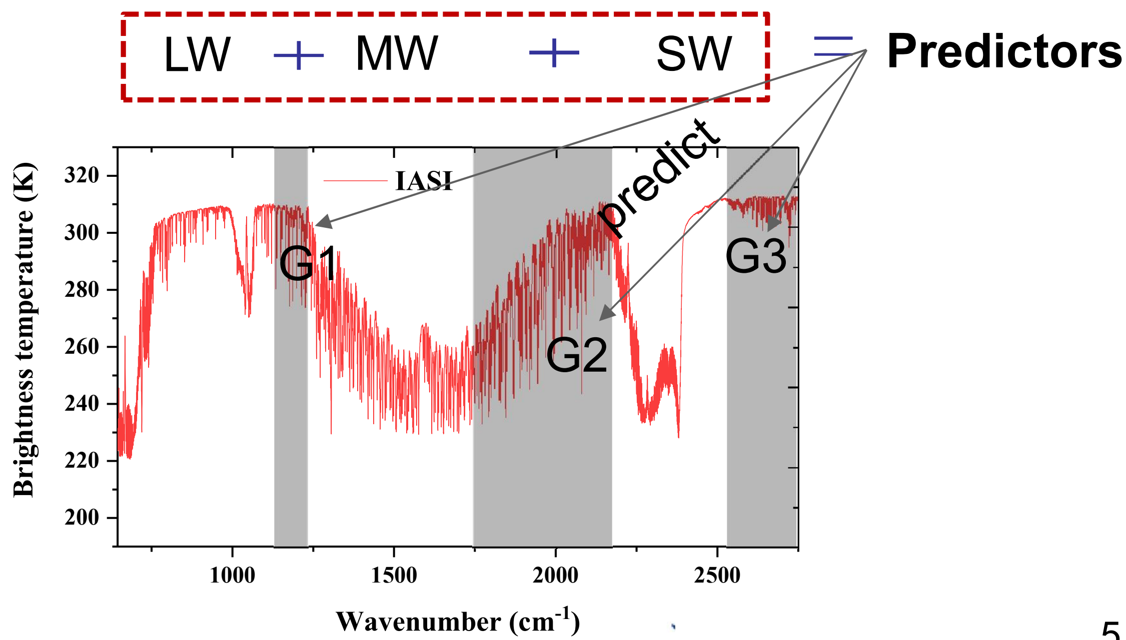
- **Methodology of the CrIS gap channels prediction**
  - **Training dataset generation**
  - **Principal Component Regression based spectral gap prediction**
- **Prediction results validation**
  - **Theoretical accuracy analysis**
  - **Inter-comparison with hyper-spectral infrared sounders**
- **Application**
  - **CrIS – VIIRS inter-comparison on M14**
  - **CrIS – ABI inter-comparison on channel 7, 8 and 11**
- **Conclusions and future work**

Methodology

The theoretical basis of this method is that

- the top of atmosphere (TOA) wavenumber dependent radiances are highly correlated with each other. (the CrIS gap channels spectral information possibly has already existed in the measured channels)





Methodology

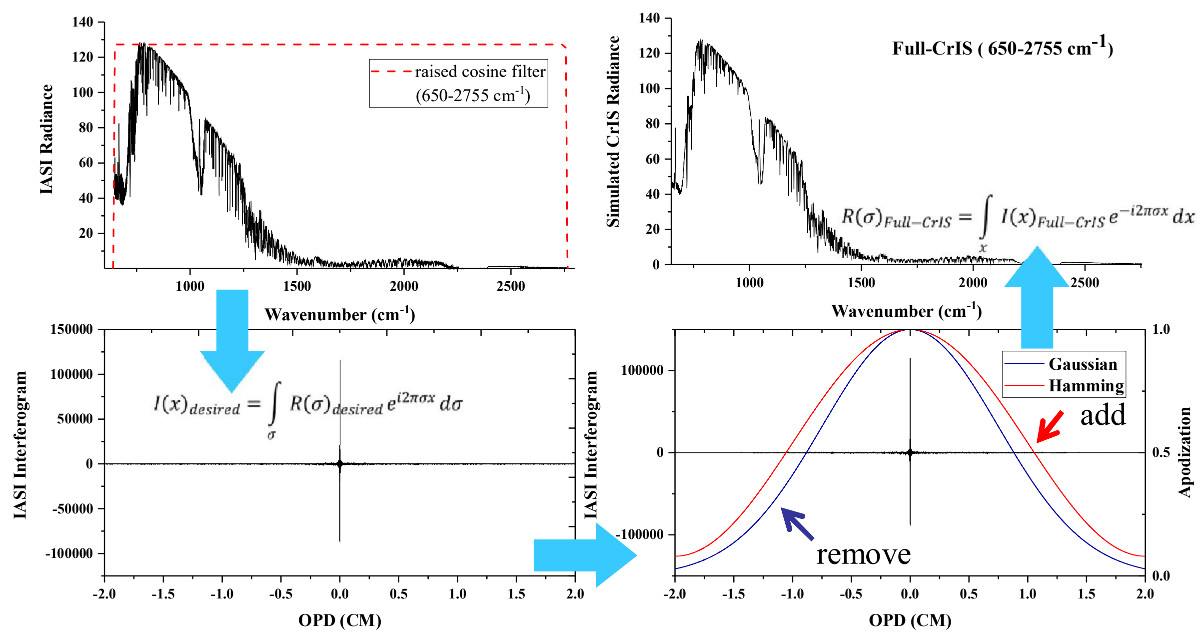
Training dataset generation

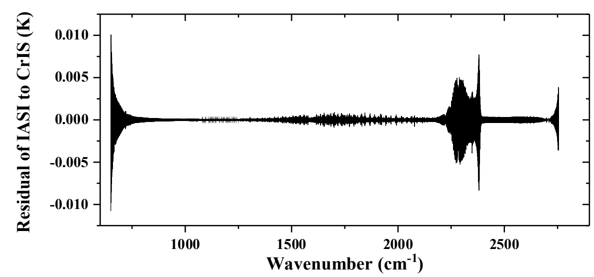
To establish this relationship, a **Full-CrIS** training dataset spectra which includes both measured and gap channels needs to be built up at first.

•The Full-CrIS training dataset was simulated from spectra measured by **Infrared Atmospheric Sounder Interferometer (IASI)**.

- ❑ **IASI with 8461 spectral channels sampled every 0.25 cm^{-1}, covering 'ALL' the CrIS spectral information**
- ❑ **The conversion residual from IASI to CrIS spectrum is very small (basically less 0.01 K)**

Several steps are performed to convert the IASI spectra to Full-CrIS





Finally, four days IASI/B spectra selected from different seasons to represent different atmospheric and surface conditions are simulated into Full-CrIS and used as the training dataset in this study.

Methodology

Principal Component Regression (PCR) based spectral gap prediction

Suppose the gap channel radiances can be predicted by using

$$R\_Gap(\sigma) = \sum_{i=0}^{k} R\_MEA(i) \cdot \boxed{P(\sigma, i) + \beta(\sigma)}$$

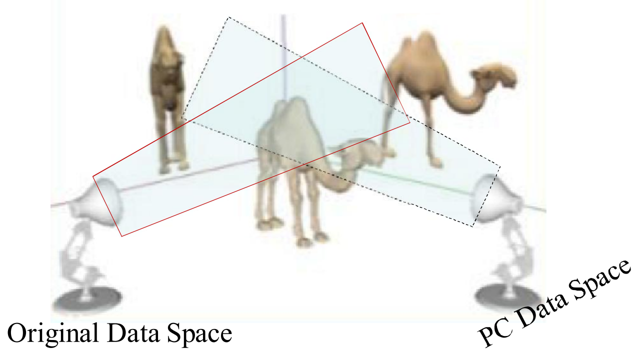
This part can not be directly derive!

Gap channel radiance — Measured channel radiances — Prediction Coefficients

However, it is hard to straightforward derive above **Prediction Coefficients** by using a fitting method.
This is because the wavenumber dependent radiances are highly correlated with each other (**Multi-collinear**).

Principle Component Analysis (PCA)

PCA is orthogonal transformation technic



The original picture is from Justin, Rusalem, IASI conference 2016

PCA

- ❑ Reduce the dimension of the dataset
- ❑ Conserve a maximum of the effective information
- ❑ Denoising the random noise of the dataset
- ❑ Decorrelation of the interdependent variables

Therefore, a Principle Components based Regression (PCR) method is used in this study to derive the prediction coefficients.

Methodology

Principal Component Regression (PCR) based spectral gap prediction

If the CrIS gap channel radiance $y \in \{y_1, y_2, \cdots, y_m, m = 1158\}$ can be predicted by the measured channel radiances $x \in \{x_1, x_2, \cdots, x_n, n = 2211\}$ using Eq.1,

$$y_i = \beta_{0,i} + \beta_{1,i} \cdot x_1 + \beta_{2,i} \cdot x_2 + \cdots \beta_{j,i} \cdot x_j + \cdots + \beta_{n,i} \cdot x_n + u_i \qquad (1)$$

where $\beta_{\mathrm{j,i}}$ is the prediction coefficients, u_i is the residual, j is the jth measured channel radiance and i is the ith gap channel. Then, in order to derive the above the coefficients β and u, all the gap channel radiances with a total of t observations can be written in the matrix form,

$$Y = D_X \times B + U \qquad (2)$$

where Y is an $m \times t$ matrix containing the CrIS gap channel radiances (m channels and t samples, D_X is the design matrix with a dimension $(n + 1) \times t$ with the first column elements set to 1 and the rest of columns containing the CrIS measured channel radiances X with a dimension $n \times t$, B is the prediction coefficient matrix with a dimension $m \times (n + 1)$, and U is the $m \times n$ residual matrix representing the matrix manipulation.

The prediction coefficient matrix B then can be calculated through Eq.3 with the **Full-CrIS** training dataset,

$$B = \left(D_X{}^T \times D_X\right)^{-1} \times D_X{}^T \times Y \qquad (3)$$

where T and the superscript -1 represent the transpose and inverse, respectively.

Methodology

Principal Component Regression (PCR) based spectral gap prediction

To solve the multi-collinear problem, a principal component transformation is performed on X to de-correlate the measured channel radiances into orthogonal **principal component scores pcs_X** before deriving the coefficients.

by replacing X in the design matrix with pcs_X, the relationship between the principal component scores of the measured channel radiances and the gap channel radiances now can be properly established through Eq.4 with the training dataset,

$$B_{pcs} = \left(D_{pcs_X}{}^T \times D_{pcs_X}\right)^{-1} \times D_{pcs_X}{}^T \times Y \qquad (4)$$

where the B_{pcs} is the principle components based gap channel prediction coefficient matrix.

Parameter Optimization

- Since most of the Earth spectral variances are mainly distributed in the first few principal components, **only the leading k_X principal component scores are used as the predictors**.
- To improve the fitting accuracy, **the noise decreased gap channel radiances Y_{dec}** are calculated firstly. Here, the Y_{dec} are reconstructed from their leading k_Y principal component scores.

Eventually, based on the optimized predictors and response variables, the prediction coefficient matrix B_{pcs} can be successfully regressed with training dataset by using (5),

$$B_{pcs} = \left(D'_{pcs_X}{}^T \times D'_{pcs_X}\right)^{-1} \times D'_{pcs_X}{}^T \times Y_{dec} \qquad (5)$$

the symbol $'$ indicate the truncated matrix or its result is truncated

Methodology

Principal Component Regression (PCR) based spectral gap prediction

At last, the CrIS gap channel radiances in Y_{CrIS} are predicted from the real CrIS data X_{CrIS} through (6),

$$Y_{CrIS} = \left[(X_{CrIS} - \bar{X}) \times {N_X}^{-1} \times {E_X}^T\right]' \times P_{pcs} + {C_{pcs}}^T \qquad (6)$$

where N_X and $\bar{X}$ are the instrument noises and mean radiances derived from the **Full-CrIS** training dataset respectively; C_{pcs} is the constant row of the B_{pcs} and P_{pcs} is the coefficient rows of the B_{pcs}.

By combining all the above matrices together, Eq.6 finally becomes

$$Y_{CrIS} = X_{CrIS} \times P + C \qquad (7)$$

- *P* is the CrIS gap channel prediction coefficients
- *C* is the corresponding gap channel constant

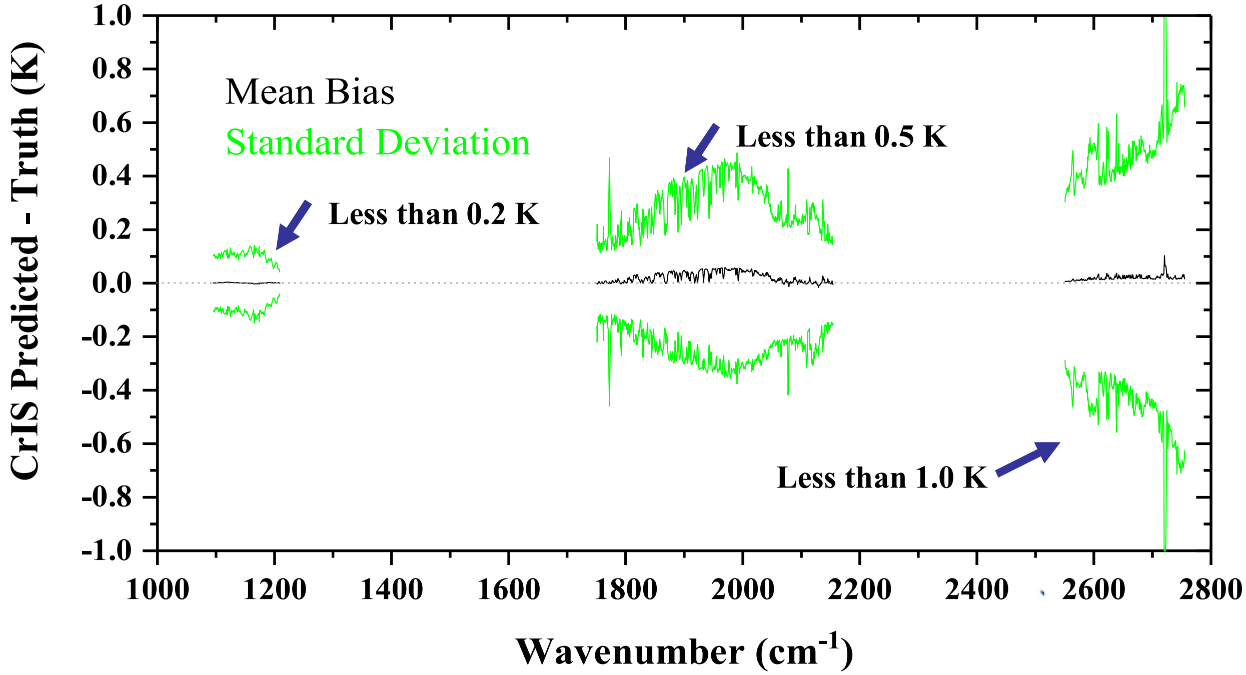
PS : The uncertainties caused by the difference of instrument noises between **real CrIS** and **Full-CrIS** should be neglected. This is because the CrIS instrument noises is overall similar to that of the Full-CrIS and the noises left in the predictors are basically very small after the PC rotation.

Prediction results validation

Theoretical accuracy analysis

The evaluation of the prediction results is not easy since we do not have real measured data in these CrIS gap channels.

- ❖ One-day IASI/B data which are different from the training dataset, are selected and converted into Full-CrIS spectra.
- ❖ The measured channels of the Full-CrIS are used as predictors, while the gap channels of the Full-CrIS are used as the truth to check the prediction accuracy.



Prediction results validation

CrIS – AIRS

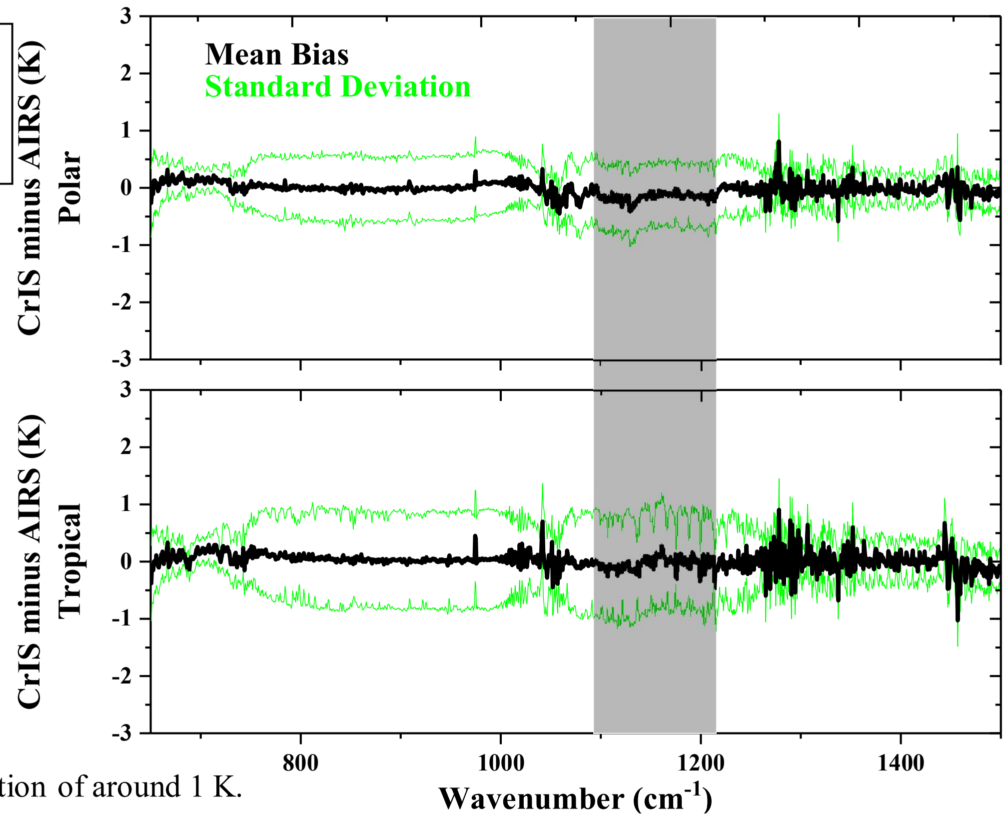
<u>SNO selection:</u> **FOV distance** : less than 6.85 km ; **Time difference**: less than 2 (polar) and 15 minutes (tropical);
View angle difference: abs(cos(zen1)-cos(zen2)) < 0.01 ; **VIIRS M16** : std(M16) / mean(M16) <0.05; **NADIR**: FOR 15 and 16

SNO (Simultaneous Nadir Overpass) for AIRS:

2016-11-10, 2016-11-13, 2016-11-16, 2016-11-18

AIRS – CrIS conversion: AIRS is a grating spectrometer, while CrIS is a interferometer. (UMBC, Howard E. Motteler 2016)

- deconvolve AIRS L1C (2465 channels) data to 0.1 cm-1 resolution spectrum;
- convert it to desired CrIS band by using the same IASI-CrIS conversion method .



<u>SNO difference in LW gap channels:</u>
Their BT differences are close to zero with a standard deviation of around 1 K.

As shown, the predicted CrIS gap spectra agree well with those observed by AIRS.
The BT differences over the predicted channels are similar to those of the measured channels.

Prediction results validation

CrIS – IASI

SNO selection: **FOV distance** : less than 6.5 km ; **Time difference**: less than 2 minutes ; **NADIR**: FOR 15 and 16

View angle difference: abs(cos(zen1)-cos(zen2)) < 0.01 ; **VIIRS M16** : std(M16) / mean(M16) <0.05

SNO for IASI-A:

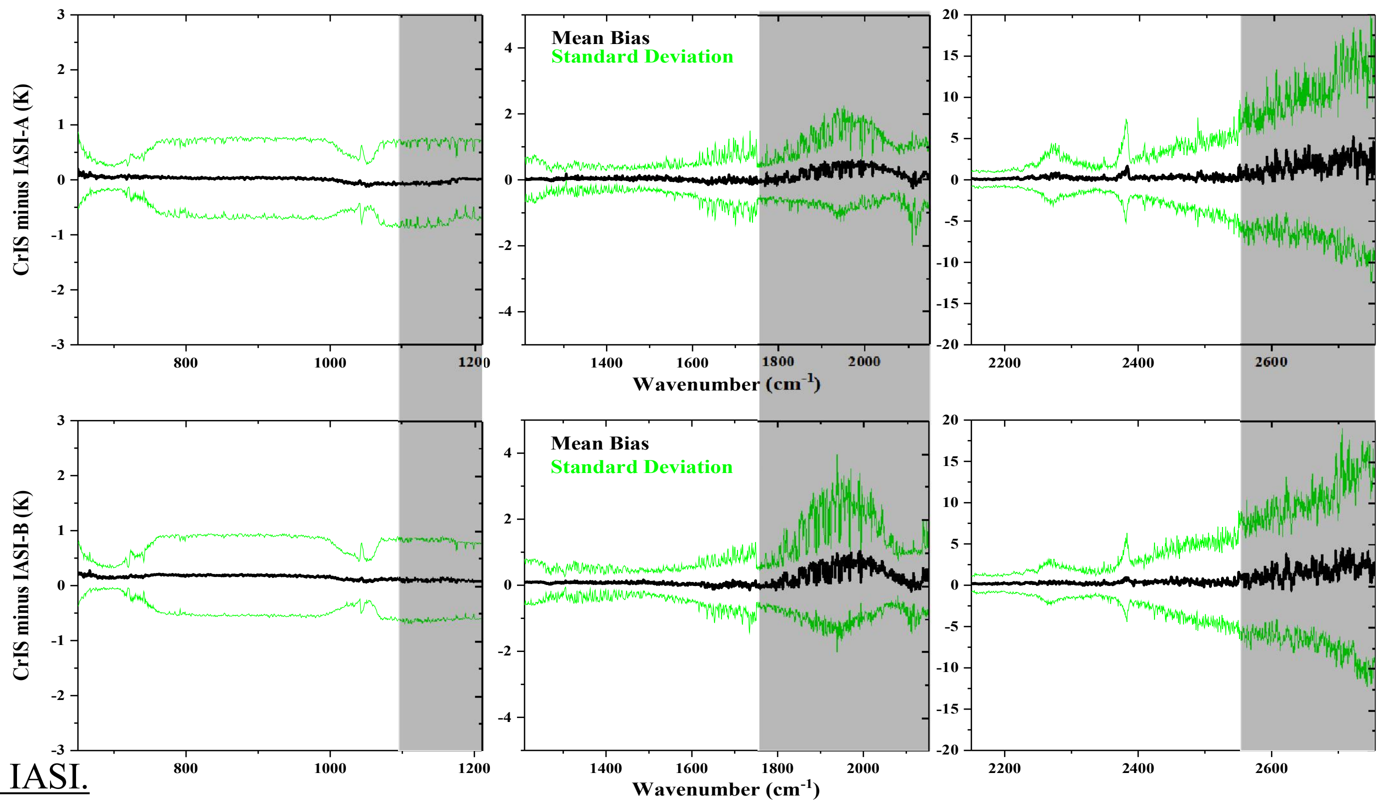
2016-08-13, 2016-08-14,

2016-10-03, 2016-10-04

SNO for IASI-B:

2016-09-09, 2016-09-10,

2016-10-30, 2016-10-31



Good Agreements
are observed between CrIS and IASI.

- Their spectral differences in LW are similar to that of AIRS-CrIS inter-comparison.
- Due to the SW radiances are much lower than LW given the same BT, the BT uncertainties are increase with the increase of wavenumber.
- In general, the predicted CrIS gap spectra agree well with those measured channels through the comparison with IASI, suggesting they may have potential ability to be used in inter-calibration.

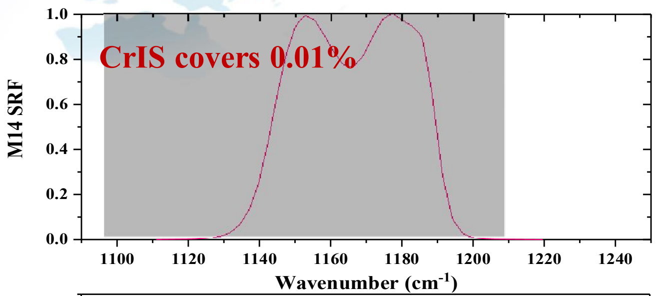
Application

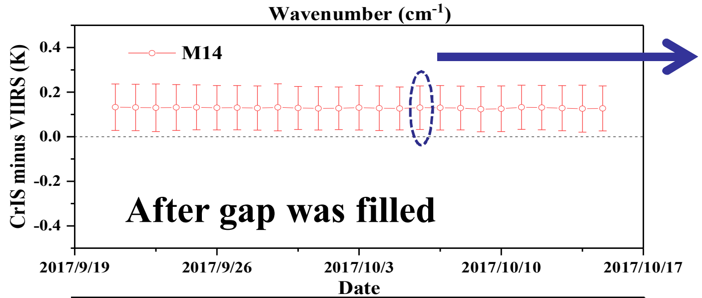
CrIS - VIIRS

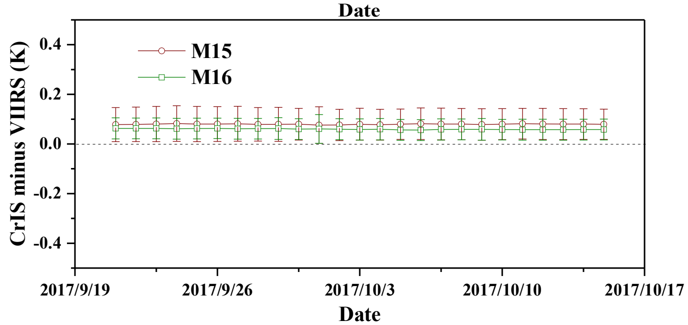
SNO selection: The CrIS and VIIRS are paired together by using a fast collocation method proposed by Wang et al. (2016).

Only uniform scenes are selected: VIIRS M16 : std(M16) / mean(M16) <0.01 ; VIIRS within CrIS are averaged.

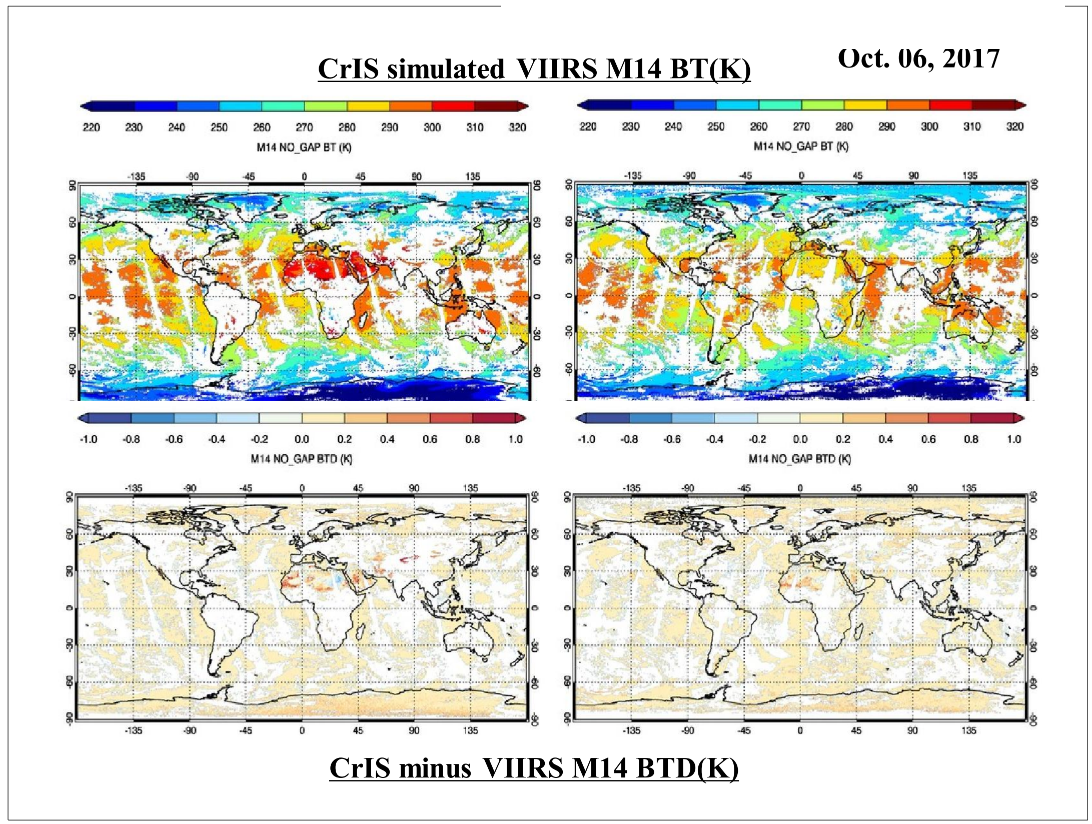
Spectral response functions of VIIRS M14







Global distribution



Gap-filling method works very well and stable in the M14 LW window channel, even though the bias and standard deviation are a little higher than M15 an M16.

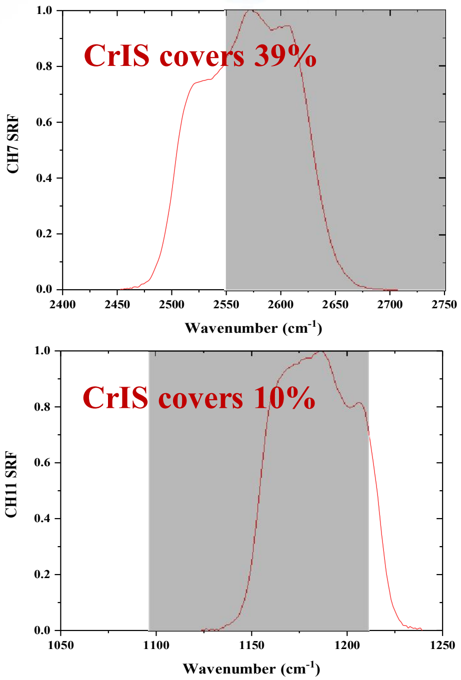
Application

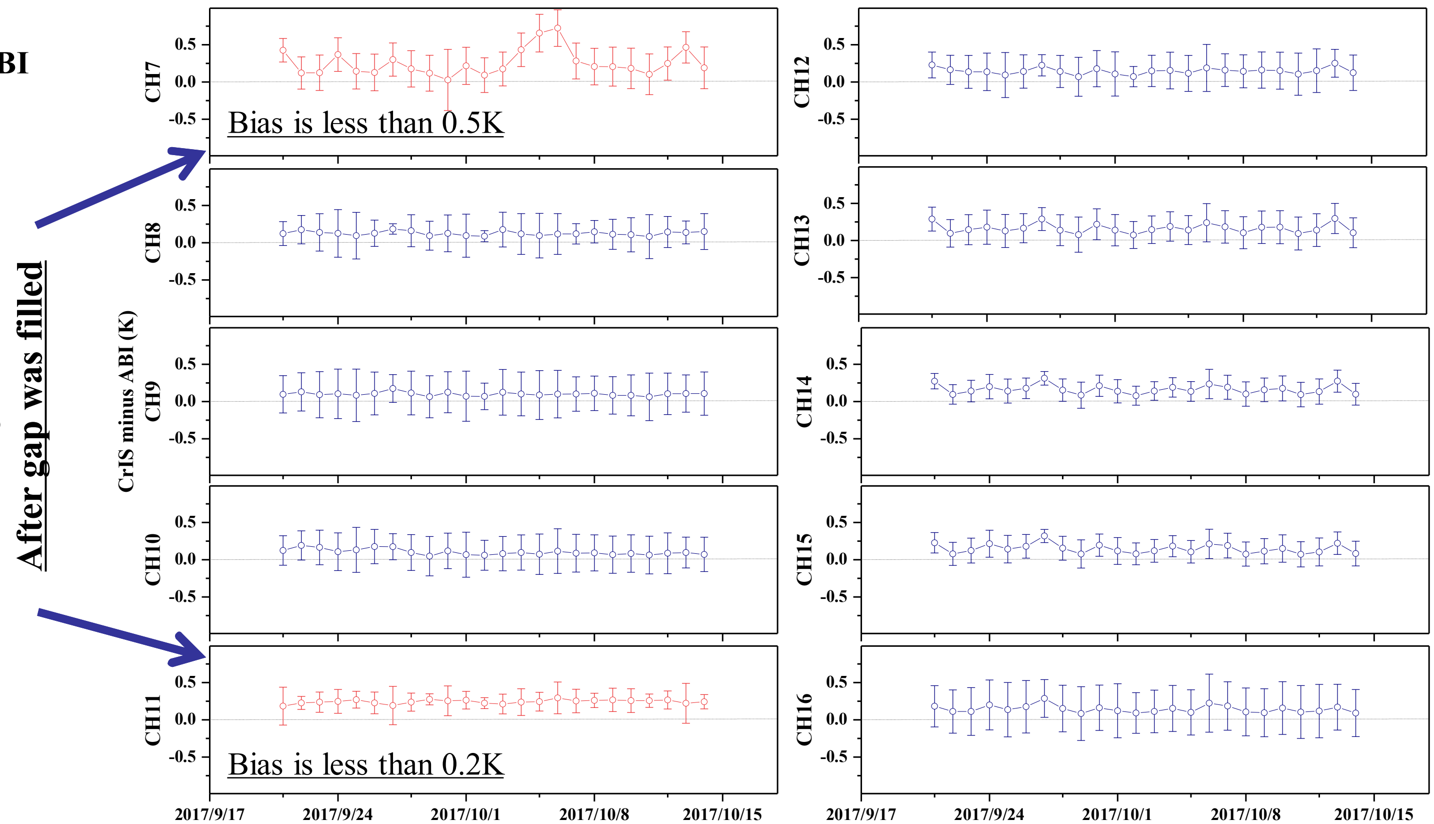
CrIS - ABI

SNO selection: **FOV distance**: less than 7 km ; **Time difference**: less than 10 minutes ; **Nadir:** FOR 14, 15, 16 and 17

View angle difference: abs(cos(zen1)/cos(zen2)-1) less than 0.02; **ABI CH14 :** std(M16) / mean(M16) <0.01 ; ABI within CrIS are averaged

Spectral response functions of ABI channel 7 and 11



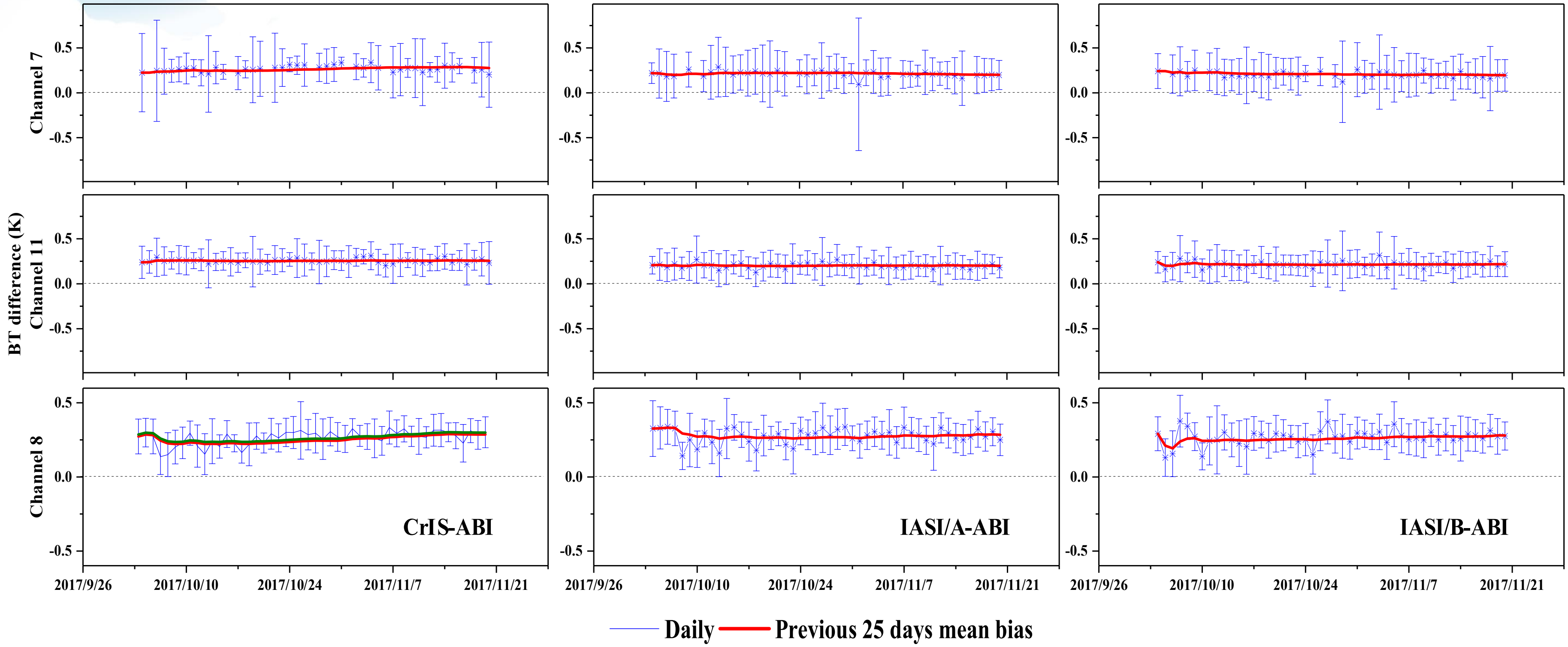


The comparison between CrIS and ABI over the gap spectral regions also shows considerable results, **especially for channel 11**. Their differences in the channel 7 and 11 are basically similar to those observed over other infrared channels.

Application

CrIS – ABI & IASI-ABI

<u>**SNO selection**</u>**: FOV distance** : less than 7 km for CrIS & less than 6.5 for IASI; **Time difference**: less than 10 minutes ; **View angle difference**: abs(cos(zen1)/cos(zen2)-1) less than 0.02; **ABI CH14 :** std(M16) / mean(M16) <0.01 ; ABI within CrIS are averaged; **Nadir:** FOR 14, 15, 16 and 17 for CrIS & 13,14,15,16,17,18 for IASI



- Both the mean bias and standard deviation are in the same uncertainty level with those observed from IASI/A and B.
- This actually indicates that the prediction uncertainty is far below than the inter-comparison uncertainty when the CrIS convolved with the broadband channels.
- their mean bias also slightly decreased over the water vapor channel 8 after the little gap was filled by the proposed method, as the green line (before the gap was filled)

Conclusions and future work

- ❖ **A new prediction algorithm was developed to fill up the CrIS gap channels** from 650 – 2755 cm-1 and also can be applied to other instruments with spectral gap.
- ❖ The proposed gap channel **prediction method shows good performance** and great potential in the inter-calibration studies, especially for the "Big Gap" spectral region over VIIRS-M14 and ABI-CH11.
- ❖ The gap filling up coefficients are ready and easily for people to use and test now.
  - ❖ ftp://ftp.orbit.nesdis.noaa.gov/pub/smcd/spb/lwang/cris-gap-coeff/
- ❖ **Spectral gaps will be continually existed in the future hyperspectral sounders, such as, JPSS-1/2, FY-3/4?, …,** which makes the gap filling task become essentially important now.

Future work

- ❑ The training dataset need to be improved in next step.
- ❑ The inter-comparison performance of the predicted CrIS gap channels with other geostationary sensors, such as, AHI and the Advanced Geosynchronous Radiation Imager (AGRI) on board the recently launched FengYun-4 satellite, need to be further investigated in future studies.

Thanks

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