On-orbit characterization of TanSat instrument line shape using observed solar spectra

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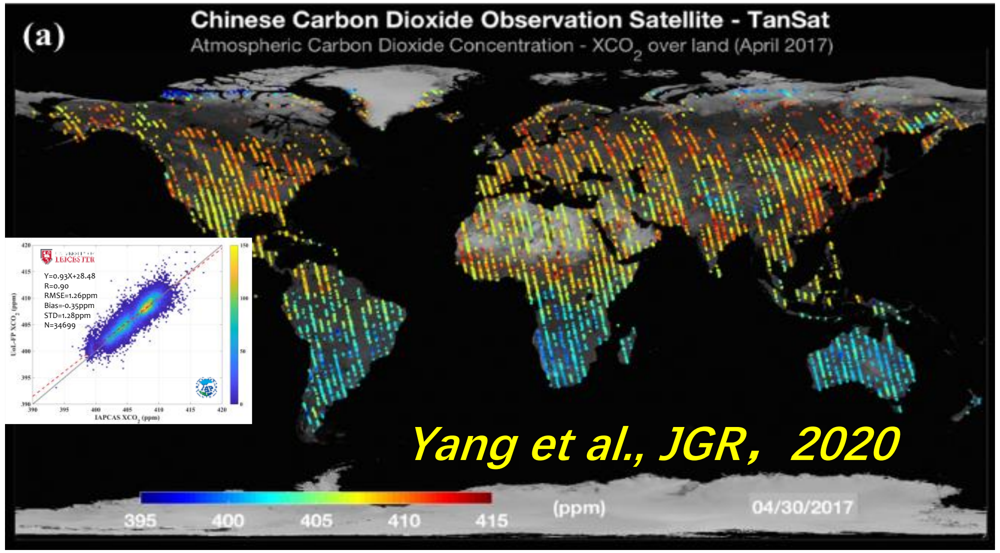
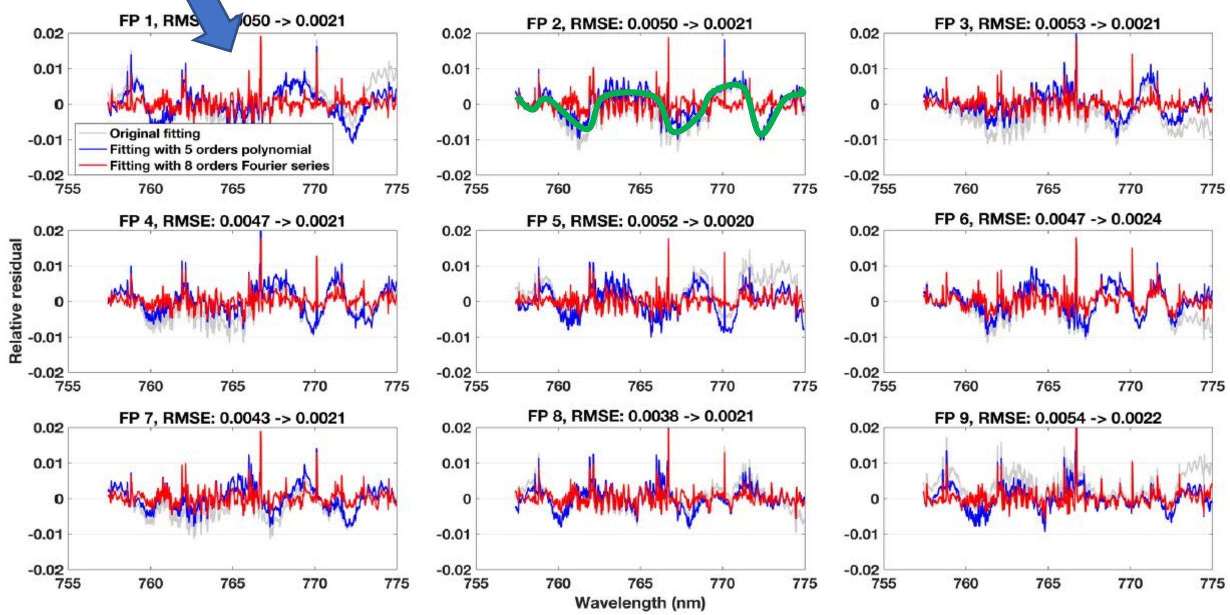
1. Motivation

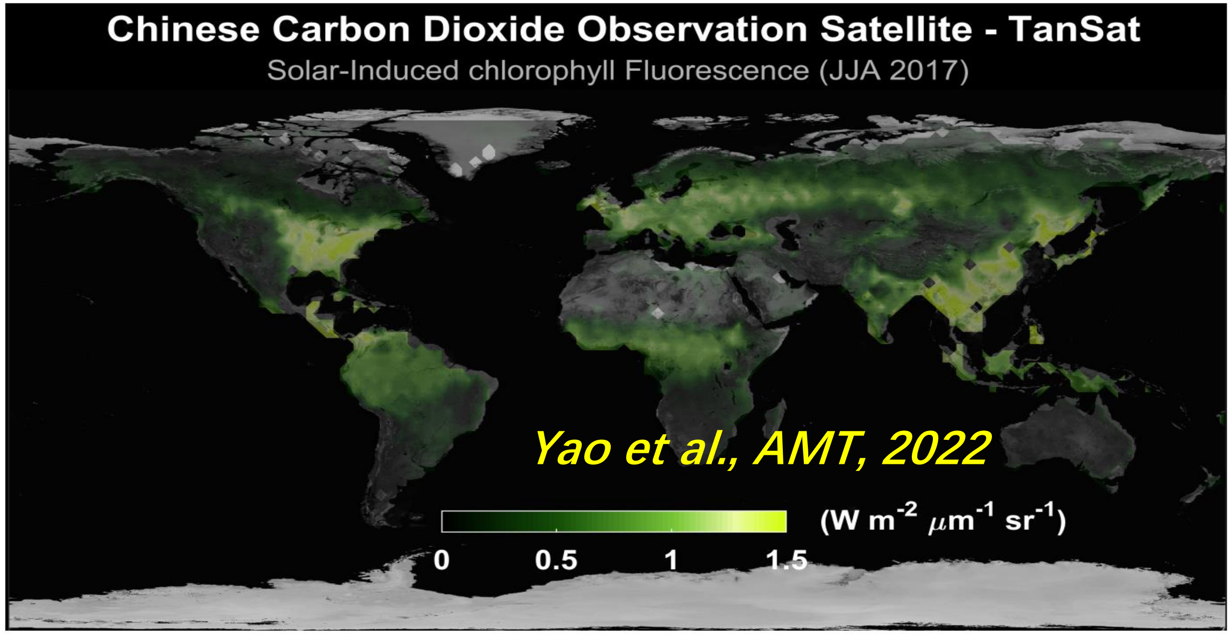
a. Wave-like pattern was corrected, spikes remains at solar lines

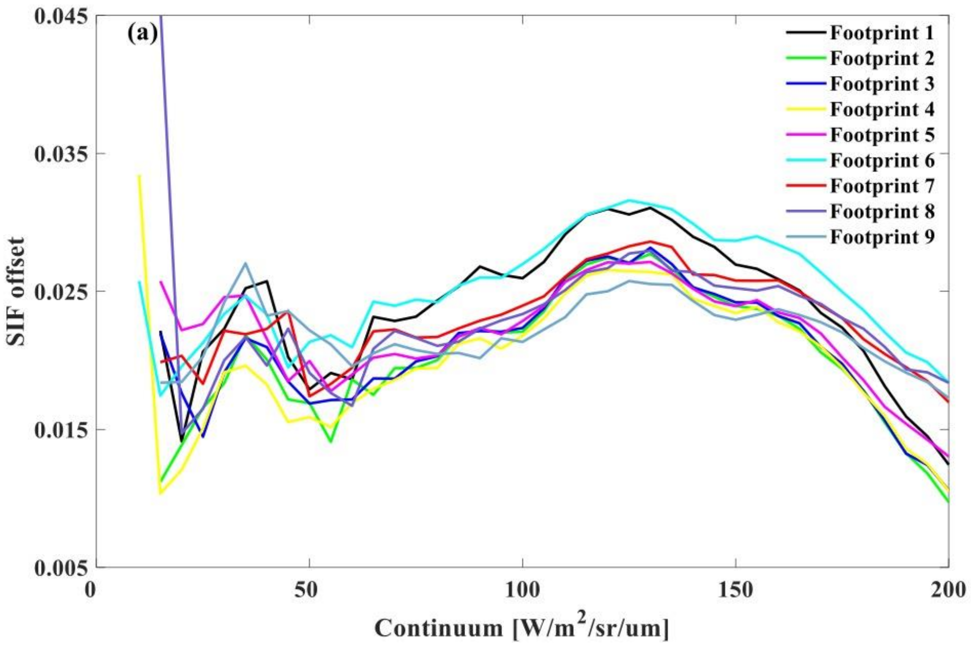




- **Yang et al., (2020) developed a spectrum correction method to reduce the retrieval errors by the online fitting of an 8th-order Fourier series. spikes remains at solar lines by using the preflight ILS.**
- **This correction provides a significant improvement to the O2 A band retrieval, also improve cloud screening and XCO2 retrieval.**
- **These structures behave as a shift of wave-like patterns on different footprints. May be relates to etalon effect.**

b. The TanSat SIF product (757 nm), offset correction





- **Offset correction derived in vegetation-free areas is applied to correct the bias that depends on the SIF energy level, footprint, and time.**

- **An offset in vegetation-free areas indicates potential instrumental artifacts, such as stray light, in the retrieval.**

2. The TanSat Sun calibration measurements

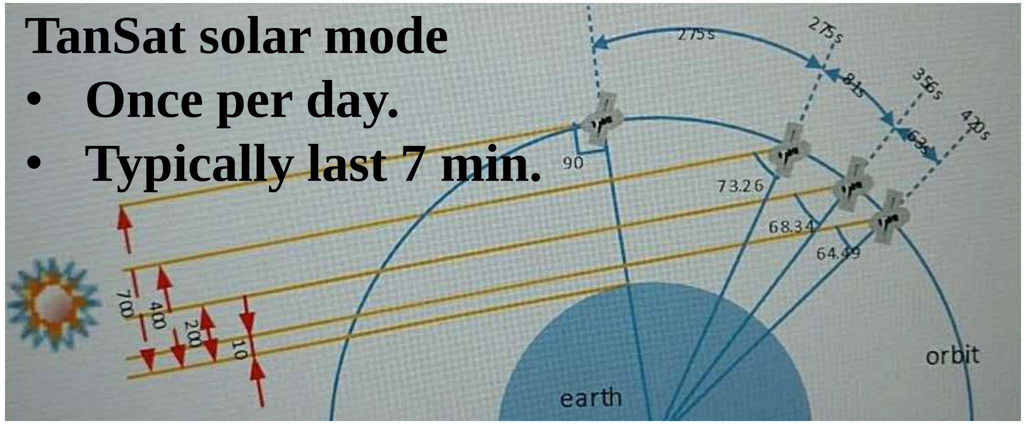
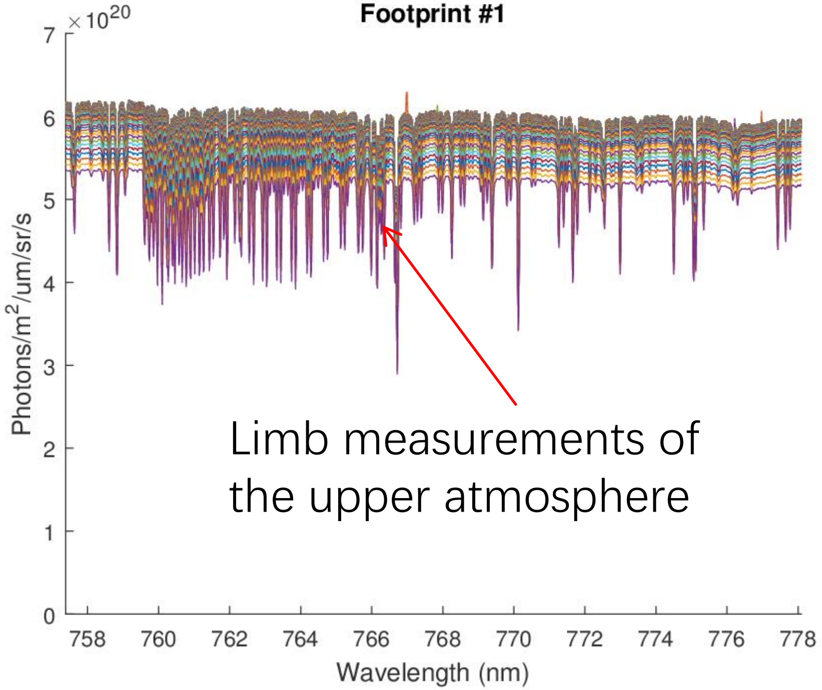
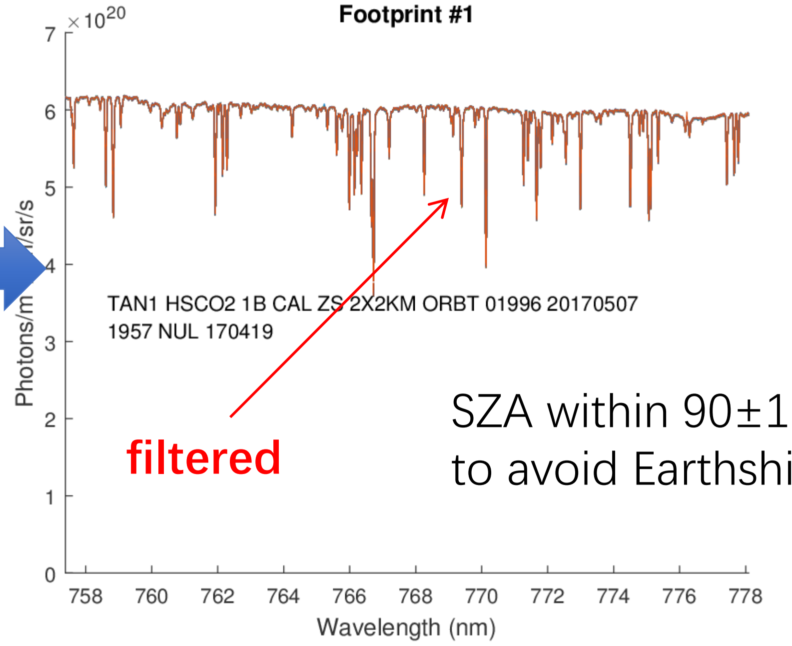


Table 1. Summary of HRHS-GS performance requirements.

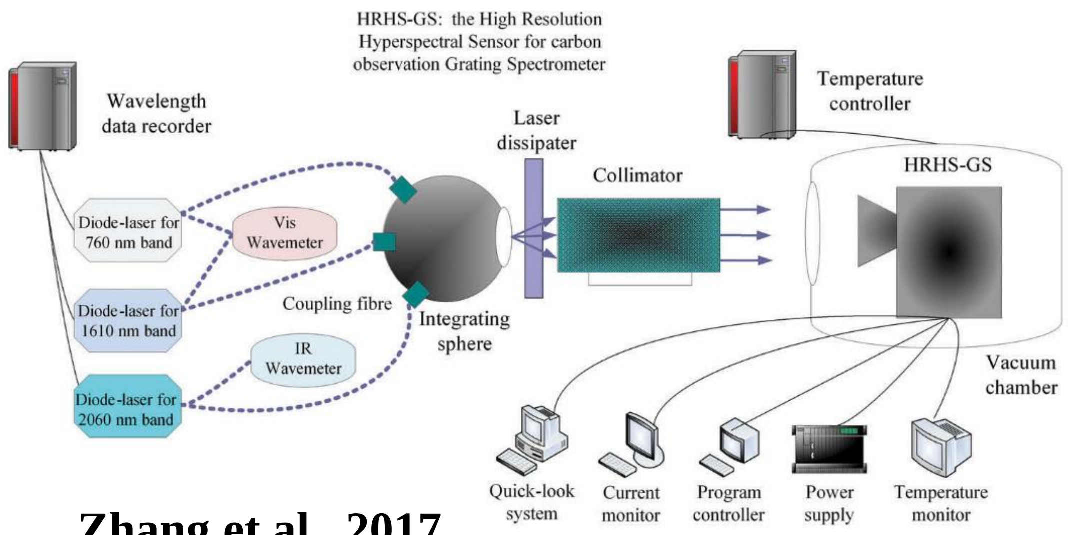
Parameter	Band 1 (O_2 A-Band)	Band 2 (weak CO_2 Band)	Band 3 (strong CO_2 Band)
Spectral range (nm)	758–778	1594–1624	2041–2081
Spectral resolution $\Delta\lambda$ (nm)	0.033–0.047	0.12–0.15	0.16–0.2
SNR	≥360:1 @5.8×10^{19} photons sec^{-1} m^{-2} sr^{-1} μm^{-1})	≥240:1 @2.1×10^{19} photons sec^{-1} m^{-2} sr^{-1} μm^{-1})	≥180:1 @1.1×10^{19} photons sec^{-1} m^{-2} sr^{-1} μm^{-1})
Integration time	0.293 s		
Observation modes	Nadir; Target; Sun-glint; Occultation		
Ground sample distance (@700 km)	1 km×2 km		
Swath (km)	≥20		



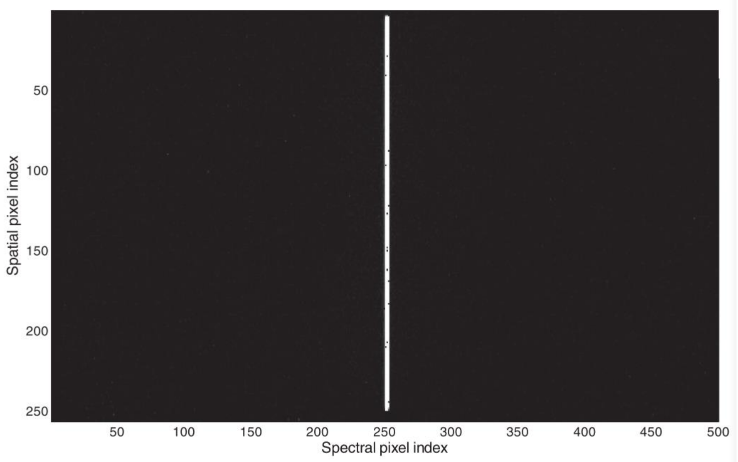


SZA within 90±1.5 (170 frames) are used to avoid Earthshine contamination

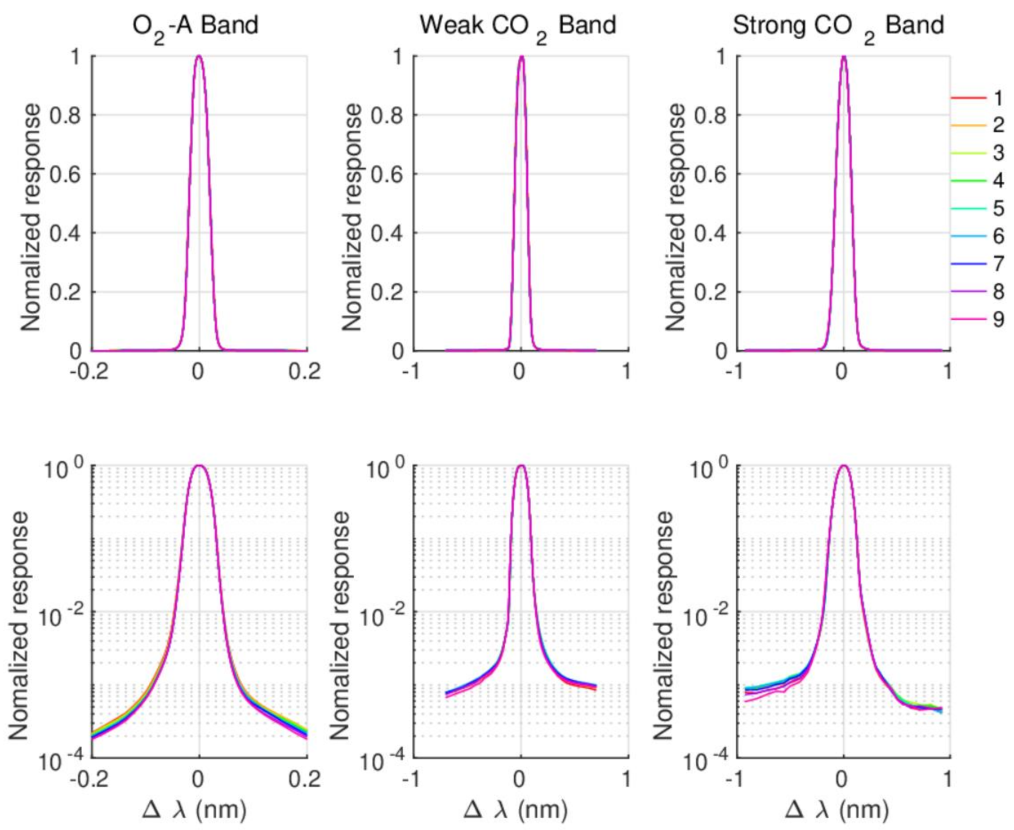
The TanSat Instrument Line Shape



Zhang et al., 2017

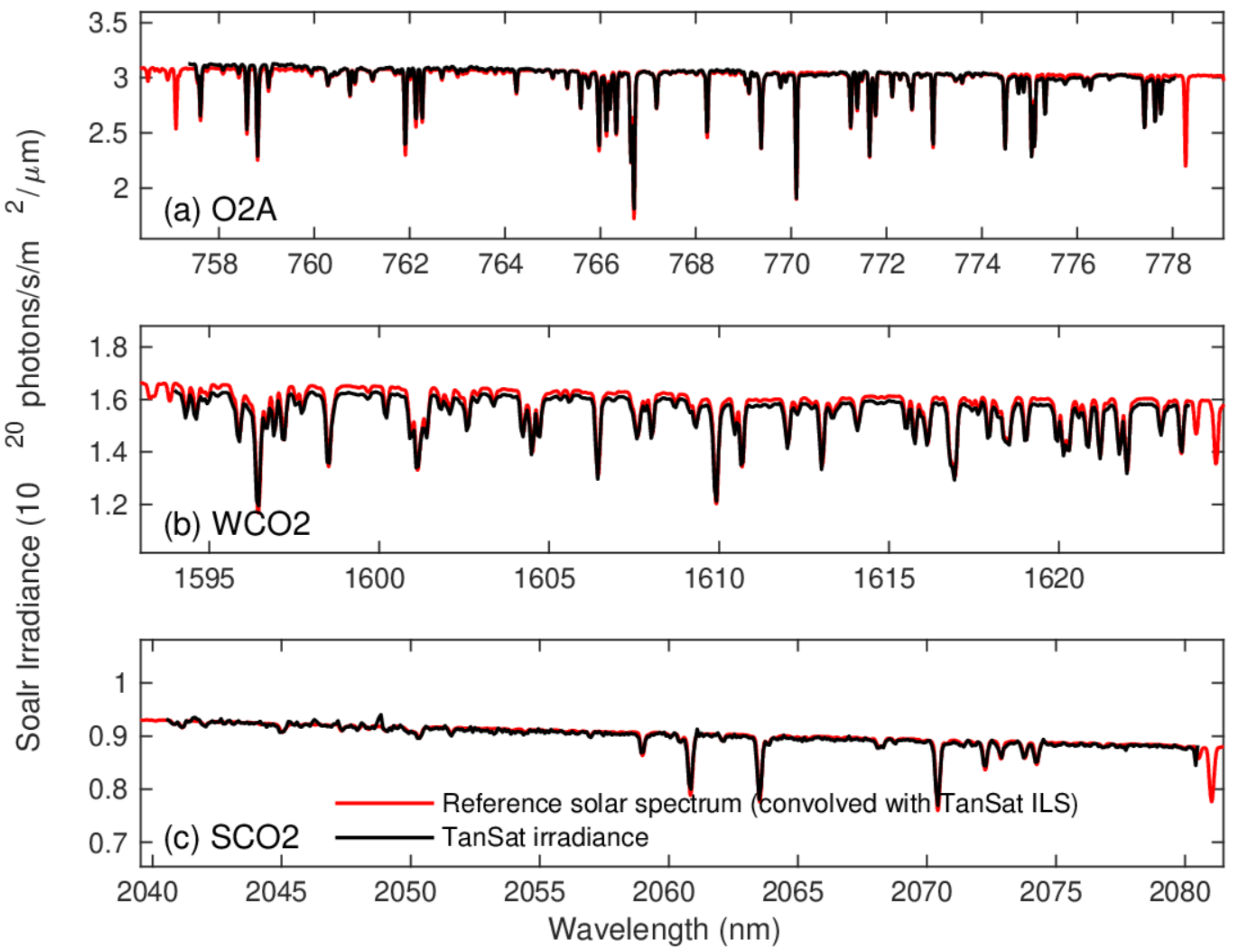


An image of the slit of the 1610 nm band spectrometer. (Li et al., 2017)



Tabular ILS functions for each band are given in the level 1B data

nonlinear least squares fitting $I_0^{sim}(\lambda) = I_0^{ref} \otimes ILS(\lambda - \delta\lambda) \times ScalePoly,$



1. version 2016 of the disk-integrated Solar pseudo-transmittance spectrum

2. version 2020 solar line list

Toon, G.C. et al., 2021

3. TSIS-1 Hybrid spectrum

Coddington et al., 2021

The 2020 version of the solar line list does not improve the fitting. Using TSIS spectrum only slightly improves the fitting residual in O2A band

3. ILS functions

super Gaussian + Pearson type-VII

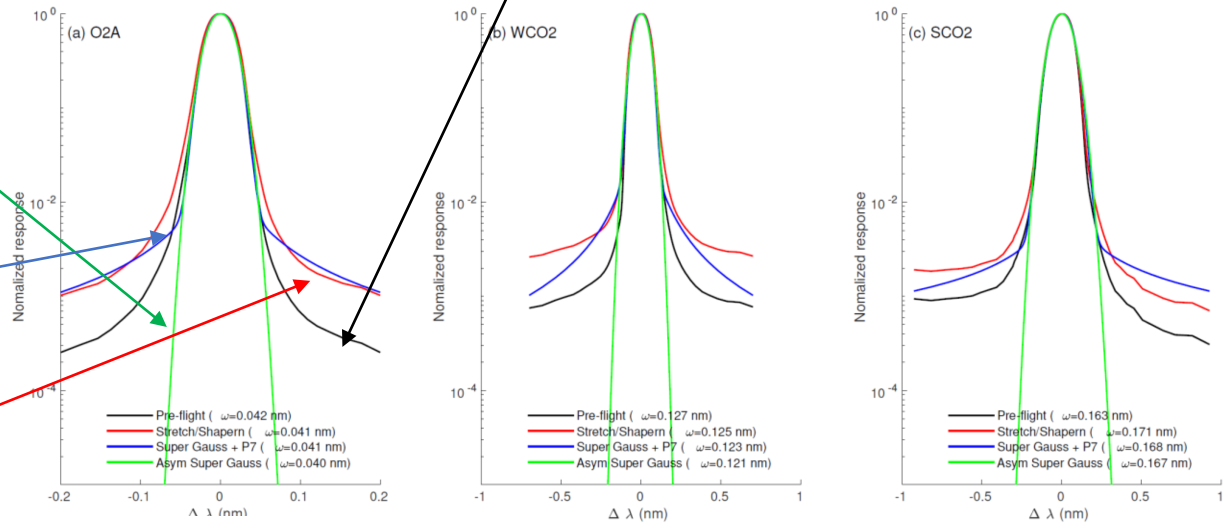
Modified from TROPOMI (van Hees et al., 2017)

Preflight Tabular ILS

peak $$SG = \frac{k}{2\omega\Gamma(1/k)} exp\left(-\left|\frac{x}{\omega(1 + a \times sgn(x))}\right|^k\right),$$

tail $$P7 = \frac{\Gamma(m)}{\sqrt{\pi}\gamma\Gamma(m - 0.5)}\left(1 + \frac{x^2}{\gamma^2}\right)^{-m},$$

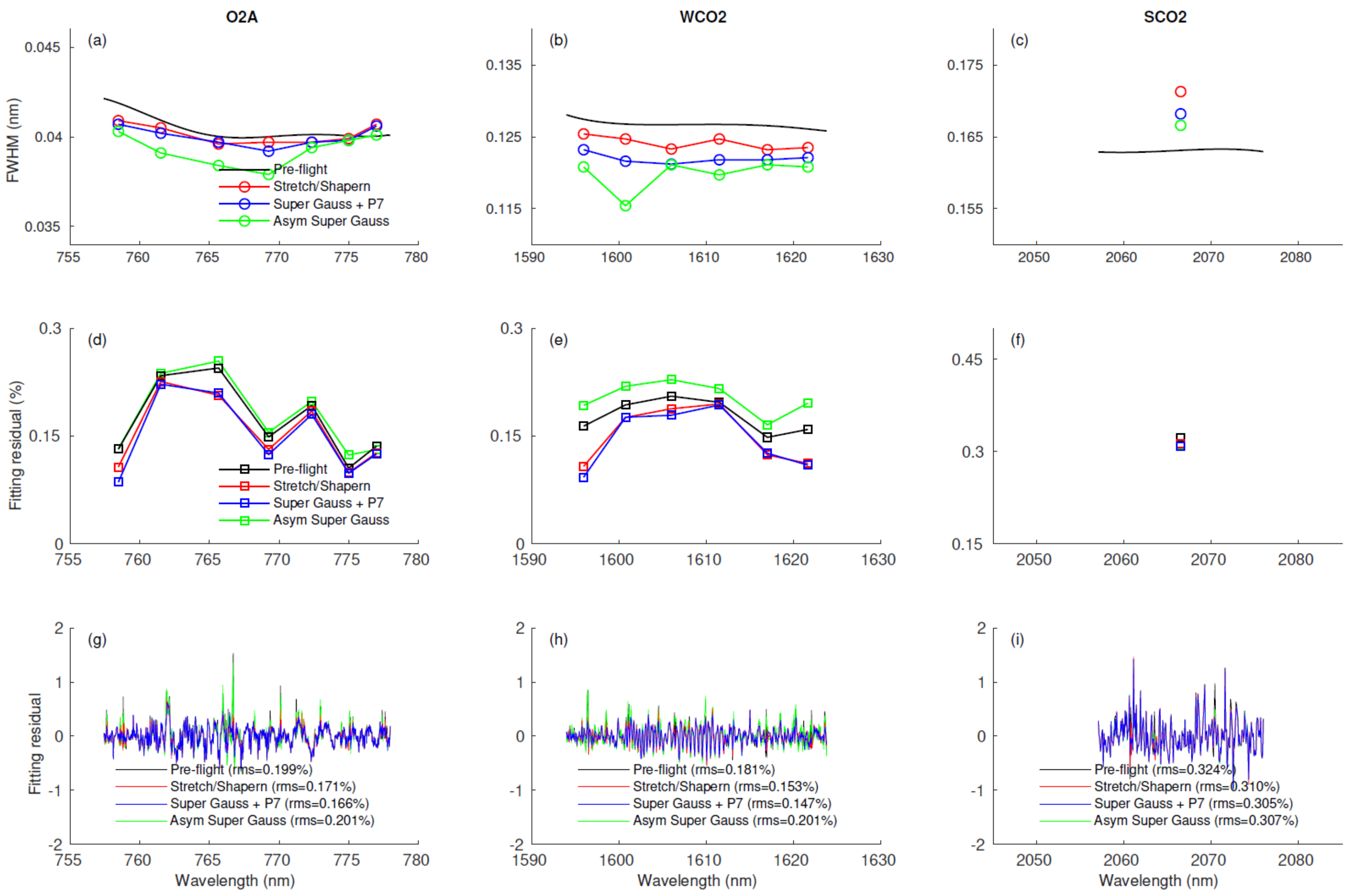
$$S(x, \omega, k, a, m, \gamma, \eta) = (1 - \eta)SG(x, \omega, k, a) + \eta P7(m, \gamma),$$



stretch/sharpen $$S(x, \gamma, \alpha) = \left(S_{pre}\left(\frac{x}{\gamma}\right)\right)^{\alpha},$$

(Day et al., 2011, Sun et al., 2017)

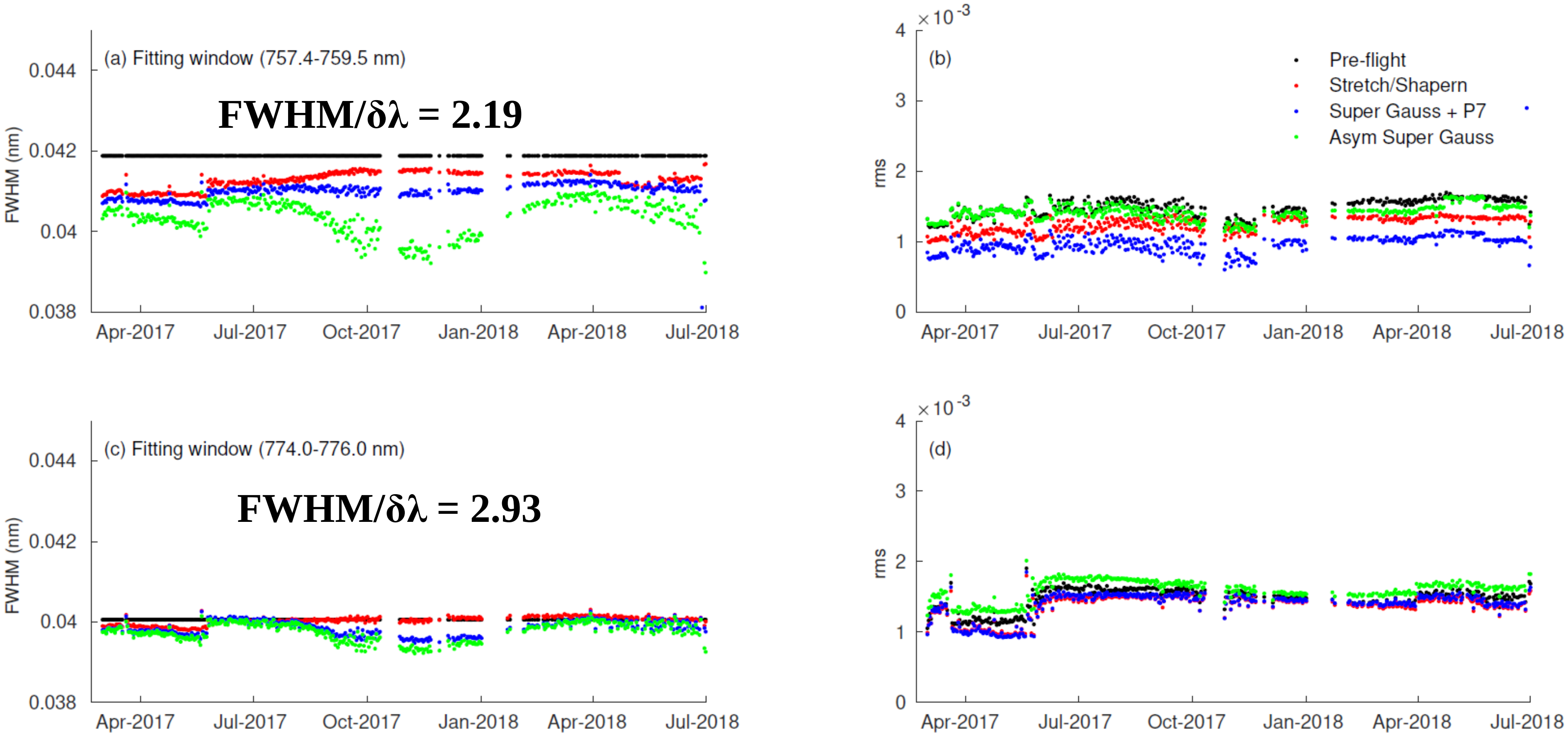
4. Spectral variation in ILS



footprint 1 on March 1, 2017

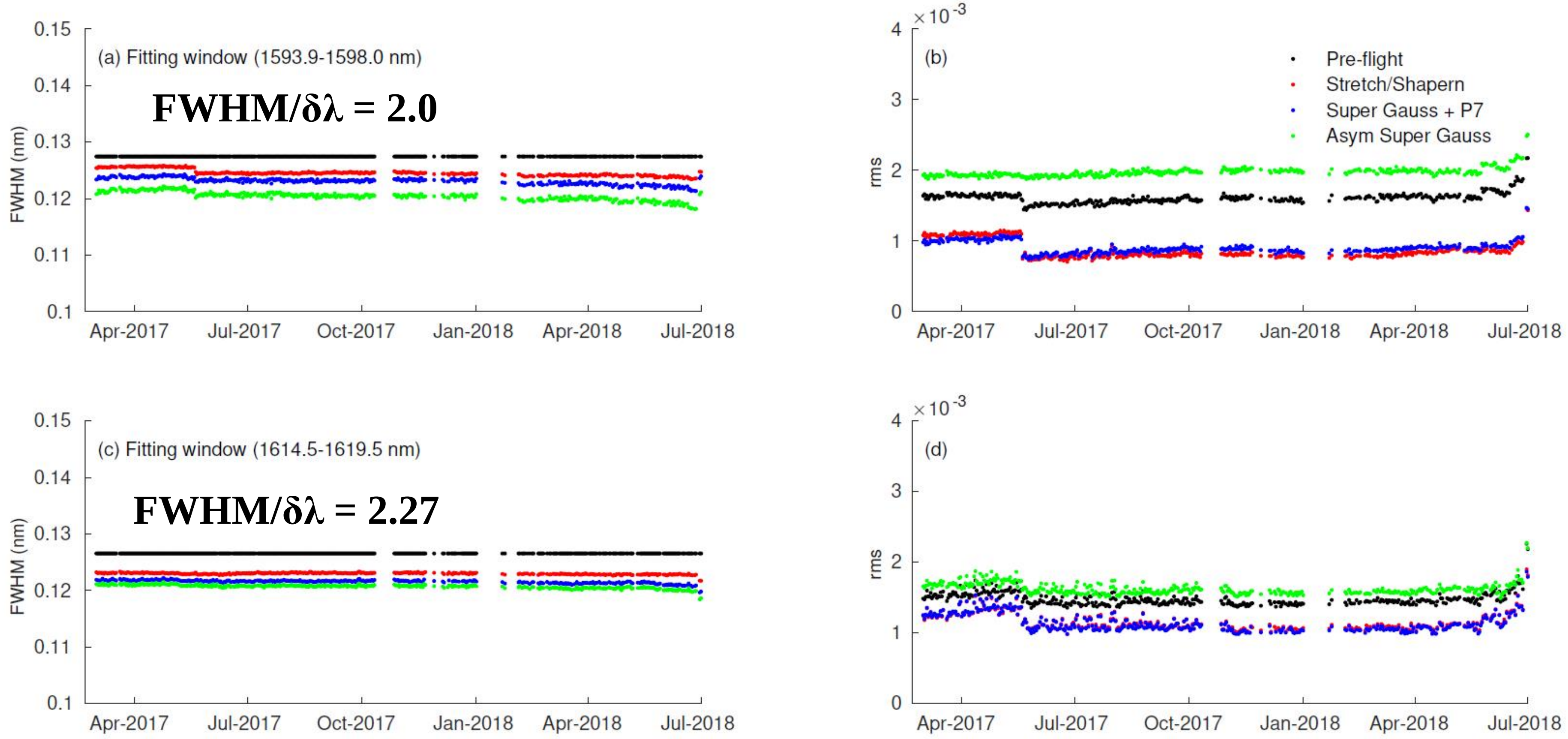
- The derived FWHMs are generally smaller than those of the preflight ones, particularly in the WCO2 band.
- Using the asymmetric super Gaussian behave differently due to the shape mismatch.
- Noticeable improvement (50%) in the fitting residuals in both the O2A and WCO2 bands using stretch/sharpen and super Gaussian+P7 function
- Improvements at specific solar lines, the oscillating structure remains.

Temporal variation in on-orbit TanSat ILS O2A band



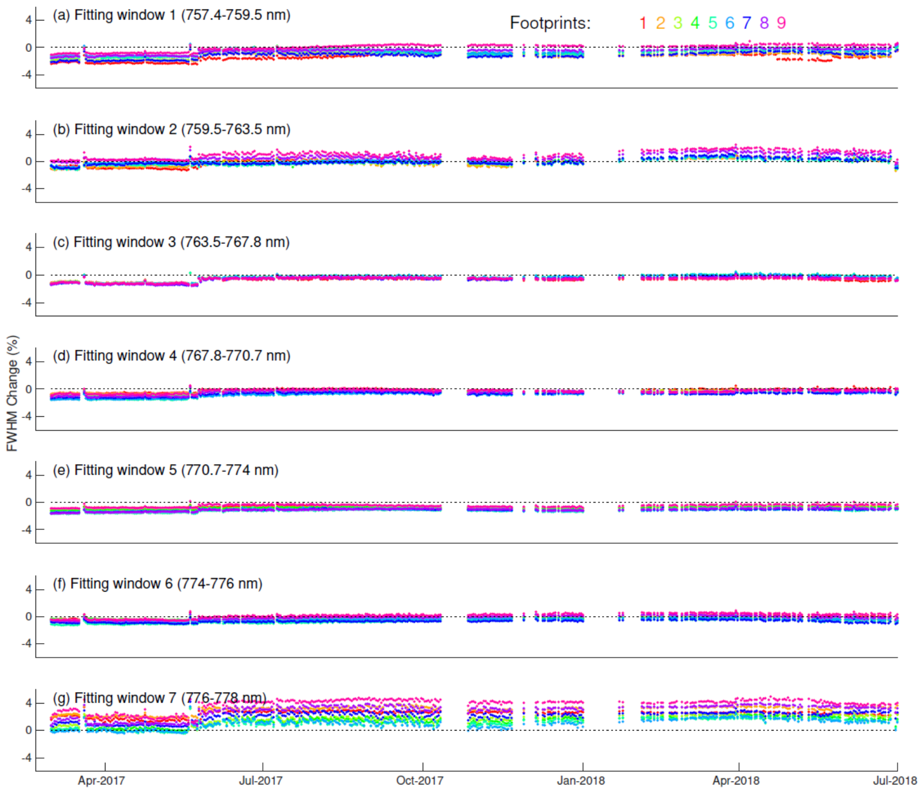
- Sun et al., 2017 demonstrated the large temporal variation in FWHM using asymmetric super Gaussian function is due to the insufficient spectral sampling.
- These time-dependent biases are much smaller for the super Gaussian+P7 function and the stretch/sharpen function

Temporal variation in WCO2 band

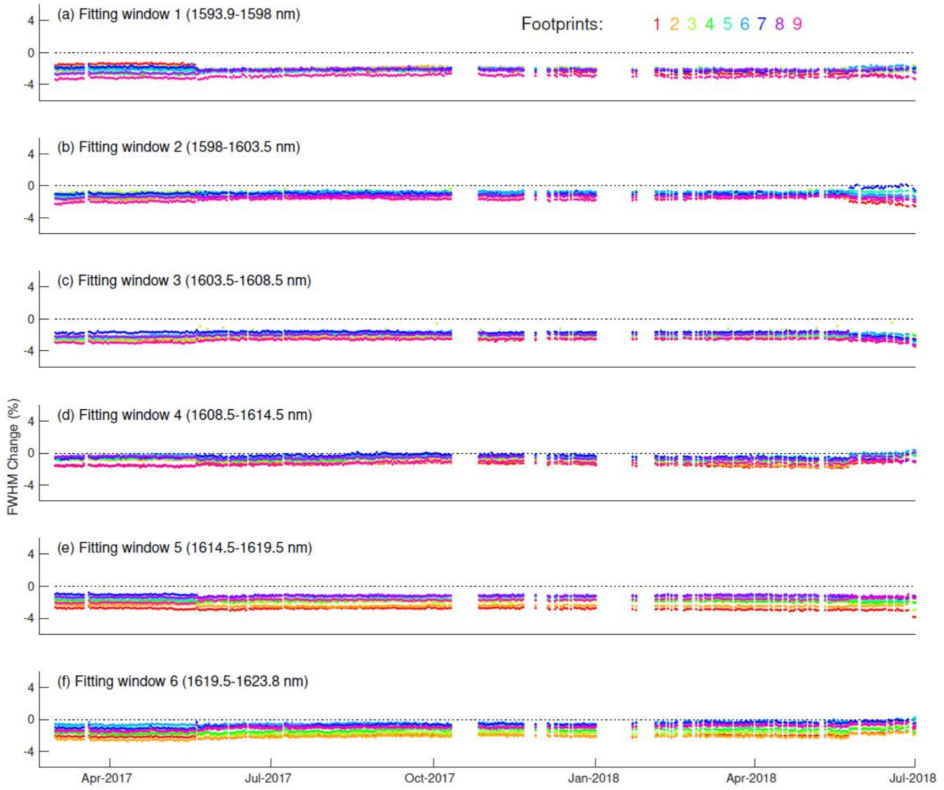


- **No periodical biases for any ILS functions were found, probably because the much lower spectral resolution (0.125 nm) mitigates the effect of ILS edges on Solar lines**
- **The average fitting residuals show less variation overtime. The derived ILS functions improve the fitting residual compared with the preflight ILS in O2A and WCO2 bands over time**

O2A band



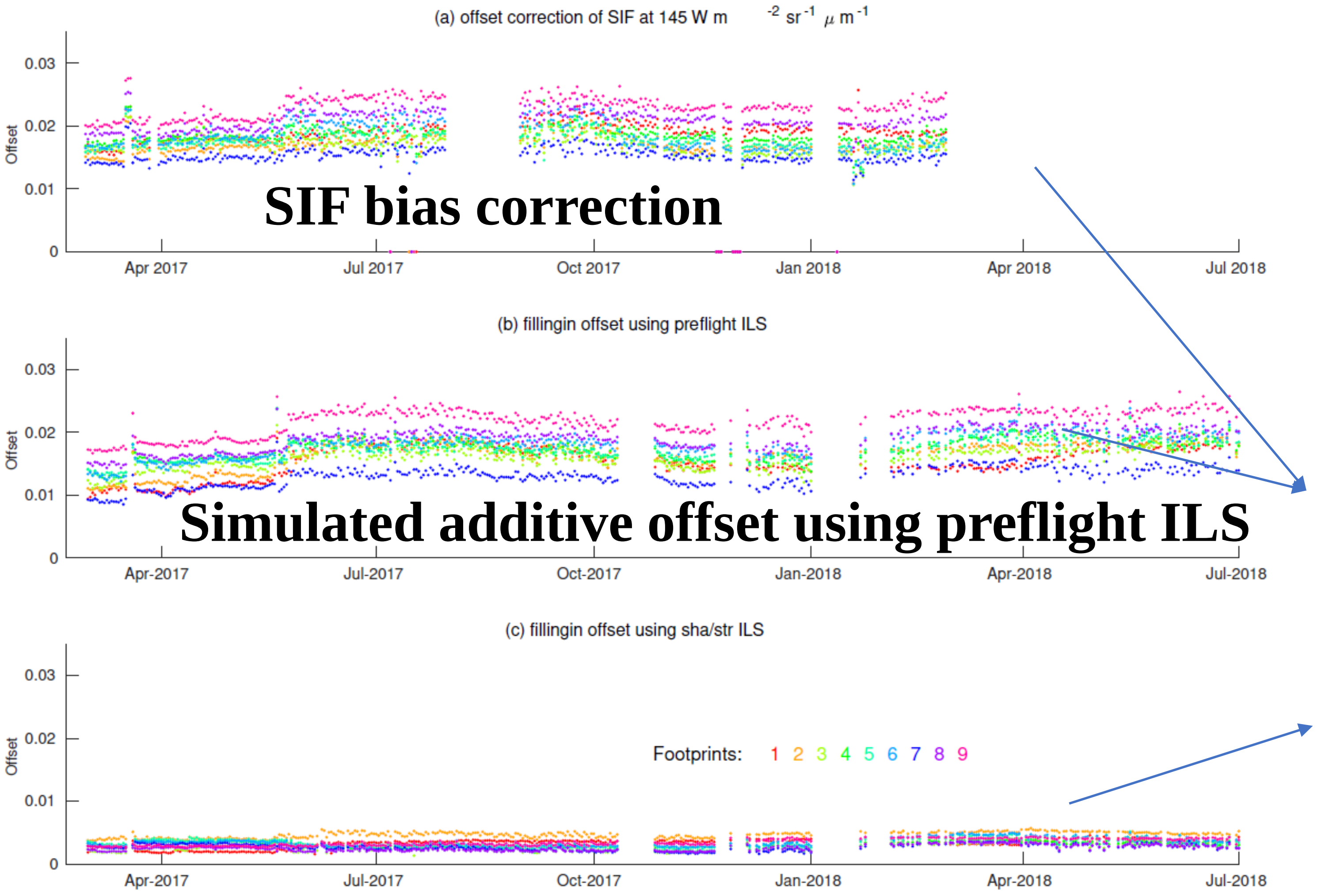
WCO2 band



Variation in relative difference between FWHM derived using stretch/sharpen function and preflight FWHM in fitting windows

For WCO2 band the relative differences are up to –3.5%. These differences depends on the footprint and wavelength.

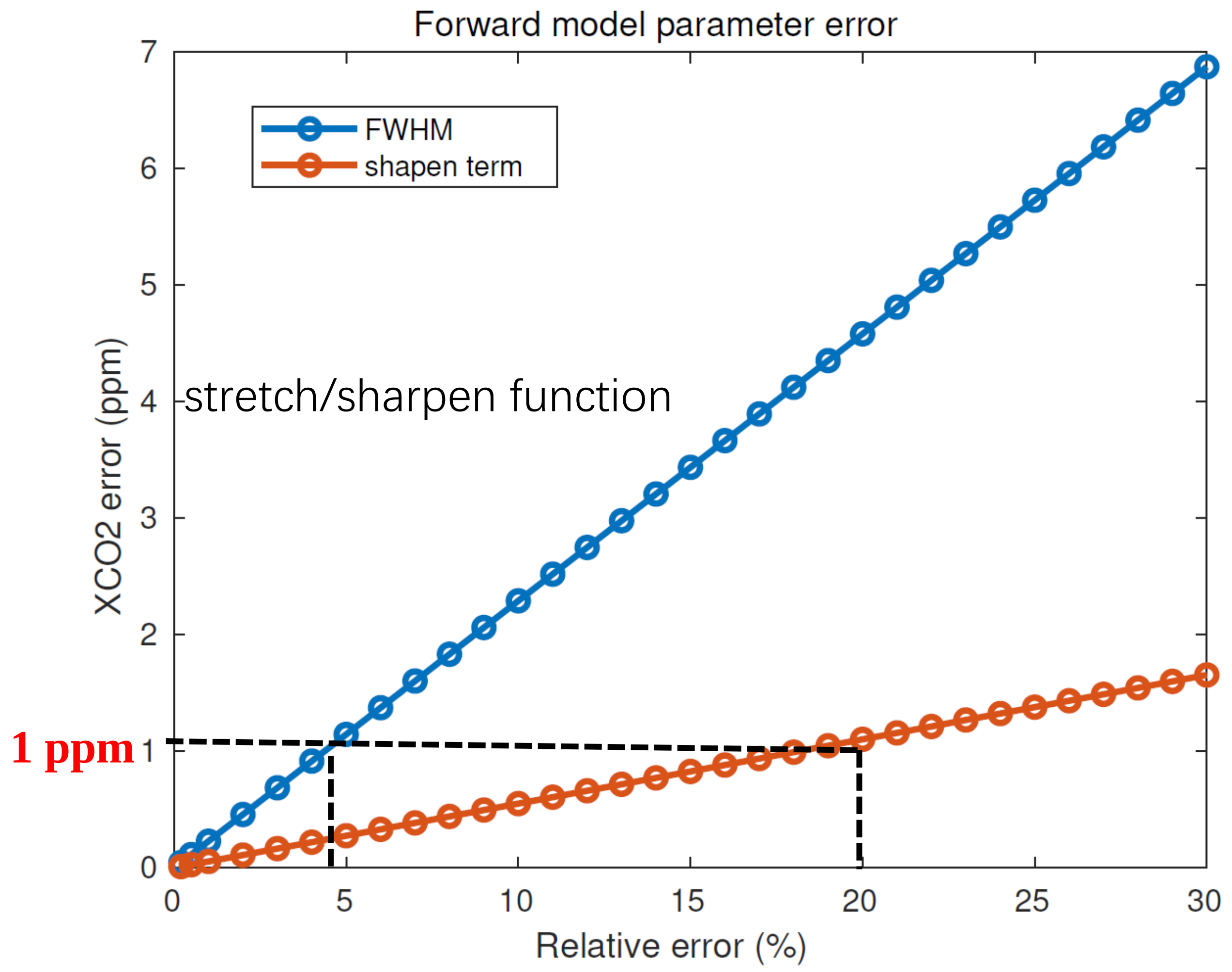
5a. Effects of ILS on SIF and XCO2 retrieval



Simulated additive offset using derived ILS

- **The broadening wings of ILS in the O2A and the WCO2 bands of TanSat indicate uncorrected stray light effect**
- **ILS correction may be needed to reduce the dependence of SIF on bias correction.**
- **These solar simulated offsets in solar spectra show similar temporal patterns to the SIF correction factors.**
- **The time- and footprint-dependent solar filling-in offsets are substantially reduced by using the retrieved ILS (stretch/sharpen function)**
- **the sharpen term in the WCO2 band varies from about 0.8 to 0.9**

5b. Effects of ILS on XCO2 retrieval

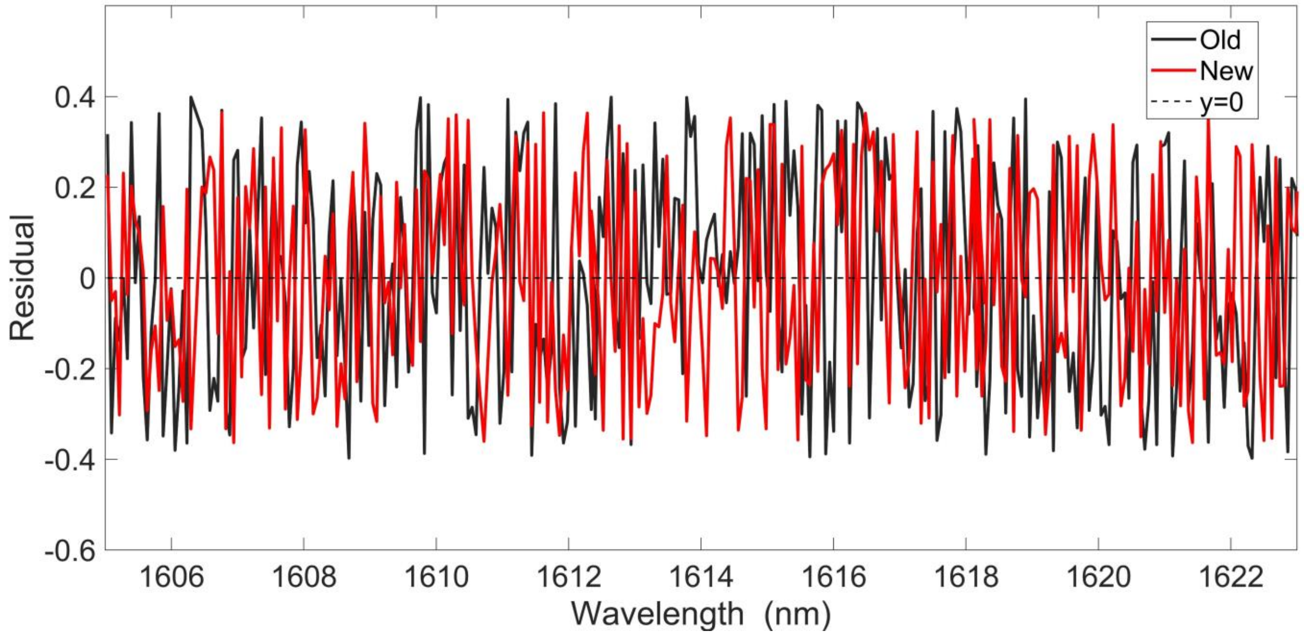


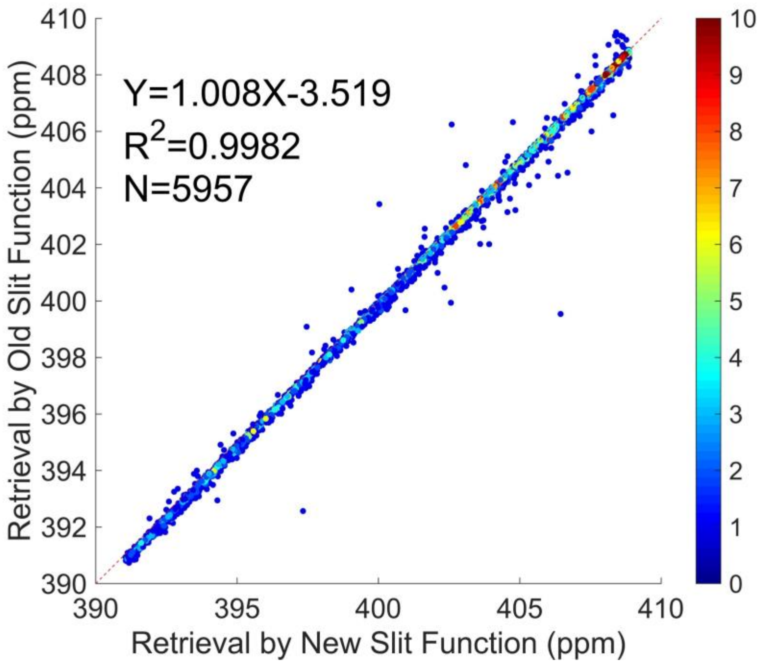
linear error analysis using synthetic TanSat spectra

- **The ILS width should be known to be within about 4% for 1 ppm accuracy requirement**
- **The effect of wings is considerable when large uncertainty exists (~20% vs 1 ppm)**
- **The interference error due to ILS is negligible.**
- **It is possible to constrain the ILS without jeopardizing XCO2**

5b. Effects of ILS on XCO2 retrieval

A preliminary test for XCO2 retrieval for one orbit on July 1st ,2017.





- **Using the corrected ILS reduced fitting residual by 8-10% in the WCO2 band**
- **the average differences of XCO2 retrievals between using corrected and pre-flight ILS is 0.15 ppm.**

Conclusions

- To improve the accuracy of XCO2 retrieval, the ILS must be accurately determined
- The on-orbit ILS of TanSat by fitting measured solar irradiance from 2017 to 2018 with a well-calibrated high-spectral-resolution solar reference spectrum. Various advanced analytical functions are used to represent the ILS
- Using supers Gaussian+P7 and the stretch/sharpen functions substantially reduced the fitting residual in O2 A-band and weak CO2 band
- the difference between the derived ILS width and on-ground preflight ILS was be up to –3.5% in the weak CO2 band
- The large amplitude of the ILS wings depending on the wavelength, footprint, and bands, indicated possible uncorrected stray light.
- 4% uncertainty in the full width of half maximum (FWHM) or 20% uncertainty in the ILS wings can induce an error of up to 1 ppm in the XCO2 retrieval. (Please refer to Cai et al., Remote Sensing 2022 for more details)

Thank you for your attention