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A priori estimation for spectral shift of atmospheric carbon dioxide satellite measurement

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ABSTRACT

Atmospheric carbon dioxide (CO_2) satellite measurements need high spectral resolution and high signal-to-noise (SNR) to achieve high precision of 1% or better. However, measurements with high spectral resolution are suffered to spectral shift and channel mismatch is inevitable, which will causes CO_2 retrieval error. For spectral shift correction, a priori information of wavenumber offset is important. We build the spectral shift model with correction factors composed of wavenumber squeeze and offset, designed the method of estimating the a priori information of wavenumber offset through convolution kernel, and developed the retrieval method of correction factors based on a priori information. The ability of estimating wavenumber offset a priori is most stable for 0.27 cm^{-1} convolution kernel, which can accurately find the reference line from GOSAT 1 September 2013 global measurements with SNR larger than 100 and without cloud contamination. Based on a priori information, correction factors retrieval precision is better, and RMS is reduced nearly by 85% for twelve days of global GOSAT measurements, implying better agreement between the simulated spectra and GOSAT. This technique can be applied to other high spectral resolution measurements, such as OCO-2, TanSat, GMI and so on.

1. Introduction

Atmospheric carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas. For atmospheric CO_2 varies with time and space, satellite measurement provides a powerful tool to monitor its global concentration distribution, which is expected with a precision of 1% column-averaged CO_2 dry air mole fraction XCO_2 or better for regional averages and monthly means to enhance our existing knowledge [1–3].

In order to reach so high retrieval precision, high spectral resolution and high signal-to-noise ratio (SNR) are required for satellite measurement, and near-infrared (NIR) spectral range is chosen. During the past decade, there are three satellites providing long time series of atmospheric CO_2 information, the Scanning Imaging absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) [4], the Greenhouse gases Observing SATellite (GOSAT) [5] and the Orbiting Carbon Observatory (OCO)-2 [6]. Compared with SCIAMACHY, the achievable precision of GOSAT and OCO-2 is validated to be better, because the spectral resolution becomes finer [7–9].

Measurement with high spectral resolution or even hyper-spectral resolution is beneficial to supply more information about the retrieval gas. Based on this superiority, the major retrieval methods developed currently are retrieving CO_2 profiles

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using all the channels [10,11], supposing that the wavenumber of measurement is precise, so each channel of measurement corresponds to simulation strictly. However, due to insufficient of spectral calibration, degradation of the instrument and the effect of Doppler shift and so on, there are some cases that the channels are always mismatch due to spectral shift of the measurement, which happened both in GOSAT and OCO-2 [3]. A careful spectral shift correction has to be made before retrieval, for large retrieval error will occurred if ignoring this channel wavenumber mismatch.

There has been some work on correcting the spectral shift of high resolution measurements. For GOSAT, correction factors are estimated firstly for each sub-band, through maximizing the cross-correlation between the observed and reference spectra. Then the dispersions to the correction factors are retrieved [12]. For OCO-2, a simple instrument Doppler correction is performed, then a priori wavelength offset is estimated through the standard mark point, finally the offset is retrieved simultaneously with CO_2 [3]. All these emphasis that a priori wavenumber offset is important and need to be estimated before retrieval. However, in order to get the a priori information, GOSAT needs complex lookup table construction, and OCO-2 needs manual intervention to locate the standard mark point, they all not effective and automated enough when dealing with numerous satellite measurements. Our objective is to develop an effective technique for a priori wavenumber offset estimation and spectral correction based on this.

In this paper, we discuss the spectral correction method for CO_2 satellite measurements based on effective a priori estimation. Section 2 gives an introduction to the concepts of spectral shift model and correction factors, and describes the spectral correction technique. Section 3 describes the selection of convolution kernel and analyzes its efficiency through GOSAT global measurements. We compare the corrected spectrum to original spectrum in Section 4. In Section 5, we derive some conclusions from our research and discuss the practical advantages of this technique.

2. Method

2.1. Model of spectral shift

According to the spectral calibration method on the ground, the relationship between wavenumber axis and channel axis can be illustrated through:

$$\nu(j) = a_1 j + a_0 \quad (j = 1, 2, \ldots, N) \tag{1}$$

Where ν represents the wavenumber, j represents channel number, N represents total number of channels, a represents the polynomial coefficient and the sub-index 0–1 represents the order of polynomial. In common, 1th order is enough, especially for GOSAT, which wavenumber is completely linear, a_1 and a_0 are 1.995E-1 and 6.154E3 separately.

The spectral shift occurred due to instrumental and orbit environmental effect:

$$\nu'(j) = \left(a_1 + \beta\right) j + (a_0 + \alpha) \tag{2}$$

Where ν' represents the corrected wavenumber, β represents wavenumber squeeze and α represents wavenumber offset. So the shift of the wavenumber is$\beta j + \alpha$, and no shift occurred when α and βequal to 0.

2.2. Correction factors retrieval

An effective way to model the measured spectrum Y_j defined for a set of j = 1,2,. . .,M spectral channels is to consider the following way:

$$Y(j) = F(j, x) \tag{3}$$

where x containing α and βdenotes the spectral correction factors to be retrieved, and $F(j, x)$denotes the simulation spectral value at ν'. Satellite measurement provides the wavenumber and radiance of each channel, if wavenumber of the channel changed, corresponding radiance value of this channel will also change, but is not easy to accurately get. Considered this problem, we perform the spectral shift correction on simulation, which is calculated by SCIATRAN with spacing grid improved largely to 0.01 cm^{-1} or even finer, so we can get corresponding radiance of the adjusted wavenumber through interpolation.

To get x we apply an optimal nonlinear weighted least-squares fit to minimize the following objective function [13]:

$$\chi^2(x) = \sum_{j=1}^{N} \left(Y(j) - F_{adj}(j, x)\right)^2 \tag{4}$$

where subscript adj denotes the adjustment of the base line of simulation to match the measurement, for large radiance bias may makes the converge failed. We solve x through updating $\mathbf{dx_{i+1}}$, using Levenberg-Marquardt method to improve iteration speed and stability:

$$dx_{i+1} = -\frac{\chi^2(x_i)}{\gamma \cdot \nabla_x \chi^2(x_i)} \tag{5}$$