The Correction of Disturbed Near Infrared Spectra to be Observed by Space-borne Fourier Transform Spectrometer of GOSAT

Tadao Aoki*1, Tatsuya Yokota*1, Koji Nobuta*2 and Akira Kotani*2

Abstract

The Fourier Transform Spectrometer (FTS) is a powerful tool for measuring weak radiations with high spectral resolution, by virtue of its multiplex advantage. However, to fully appreciate this advantage, we have to be patient during a time for the acquisition of an interferogram that is to be converted to a spectrum of the band concerned. In case of the FTS of GOSAT (Greenhouse gases Observing Satellite), it takes four seconds for obtaining an interferogram of Earth-reflected solar radiations. To observe the reflected solar radiation from the Earth from moving satellite in space, we encounter a difficulty that during the acquisition of the interferogram, the optical characteristics of instantaneous filed of view (IFOV) could change. One of the causes of IFOV radiance fluctuation is the fluctuation of line-of-sight of the spectrometer, which is induced by the image motion compensation (IMC) of scanning mirror. Simulations showed that such disturbances could generate serious errors in CO₂ retrieval. A method has been shown by Aoki et al. (2006)** to correct this type of disturbances in the interferograms. The disturbance to IFOV radiance could also be induced by other causes. In this paper, we examine the effects of pulse-like glittering caused by the reflection from roof of houses, cars or others, and show the same correction method to the interferogram as that adopted in IMC correction well works.

Keywords : GOSAT, FTS, CO₂ retrieval, data processing, interferogram, disturbances

1. Introduction

For predicting the future global warming, it is important to understand the mechanism of the annual variation of greenhouse gases. Such this study is partly hampered by lack of the precise knowledge of global distribution of sink and source of greenhouse gases. Since the global survey by direct observations of sinks and sources is unlikely due to the cost problem and accuracies, methods have been proposed for estimating the structure of sinks and sources from the combination of in situ measurements and satellite observation of the greenhouse gases. For designing a satellite observing system, requirement for the accuracy of density measurement of gases is a key parameter.

A simulation study has been conducted to estimate the accuracy that is required for satellite measurements in order to retrieve the surface structure of the sinks and sources of carbon dioxide with the reliability comparable to that obtainable from in situ measurements at the surface. The simulation showed that the accuracy of satellite measurements for the mean CO₂ column amount is required to be 2.5 ppmv in order to attain the same retrieval accuracy of surface structure of sinks and sources as that obtainable from in situ observations at the ground. When the satellite data are available only over the ocean this value becomes about 1.5 ppmv. These figures of required accuracy for satellite measurements may be used as the references for designing the GOSAT observation system, although it is a tough target in view of the present status of remote-sounding technology from space.

The GOSAT-FTS (the nickname is “TANSO”) has three bands in the near infrared regions at 0.76 μm O₂ A-band, and 1.6 and 2.0 μm bands. With the help of the image motion compensation (IMC), FTS looks at the “same” position on the ground. To be accurate, however, during the acquisition of interferograms, the IMC mirror could vibrate, in high frequency, around some average position within a small range of angle, resulting in the high frequency fluctuation of input radiances.

If the accuracy requirement for the CO₂ retrieval of GOSAT, for one point, is set to 1%, it requires the high-accuracy radiance measurements of the order of 0.36% due to the optical depth-transmittance relationship. As a result, the disturbances to the interferogram should be suppressed as small as possible. In the present paper, we examine the possible effect IMC fluctuation to the interferograms by using

---

(Received September 26, 2007. Accepted February 25, 2008)

*1 National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

*2 Fujitsu FIP Corporation, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
surface albedo data obtained by the ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) at various regions in the world. It will be shown the possible retrieval errors of CO₂ for such disturbed interferograms could far exceed above level of CO₂ retrieval error.

In the remote measurement of atmospheric gases from ground-based FTS using the Sun as the light source, it may be possible to avoid the cases where disturbances to the light source due to the cloud or other atmospheric phenomena are present if we carefully observe the cloud and the atmosphere. The fluctuation of light source due to Sun-tracker fluctuation is generally corrected by a hardware system, in which the heliostat motor driver is controlled with a circuit for closed-loop tracking correction based on signals of the CCD image of Sun.

For measuring the atmospheric constituents from ground-based FTS, Gutman et al. (1990) made a series of observations at various zenith angle of the Sun, and made a Langley plot of the optical depth. The bad data, where the so-called subvisible cirrus cloud could be contaminated in the field of view, were identified as those that largely deviate from the mean line. Shao et al. (2006) developed a method to identify the anomaly of interferograms caused by atmospheric phenomena, and by using this technique they rejected the bad data for the analysis of atmospheric gases with open-path FTS.

However, if we can not have sufficient number of observation data for assorting good data and bad data, as adopted by above papers, the disturbances caused by, e.g., cloud or atmospheric phenomena are treated as the noise and data are analyzed including these noise. Actually, it may not always be easy to recognize the presence of these kinds of disturbances from observing the atmosphere and cloud, especially when they are weak. Mitchell et al. (2001) summarized various possible disturbances for observing the surface from airborne FTS. These disturbances include those accompanied with the platform-induced motion, FTS push-broom operation, FTS staring operation and cloud and external motion source.

For space-borne FTS observation, similar disturbances as those of airborne FTS are expected. Aoki et al. (2006) proposed a method to remove the effect of the fluctuation in light source of FTS using the characteristics of frequency of disturbances that is generally much smaller than the frequency of the light source concerned. The signal of the low frequency disturbances appears as the Fourier-transformed spectrum of the interferogram in the low frequency region near to zero wave number. Another method that is also based on the characteristics of difference between the frequency of disturbances and that of light source has been developed by Keppel-Aleks et al. (2007). In this method, they used a simple numerical filtering for smoothing out the effect of low-frequency disturbances on the interferogram.

In the present paper, we examine the effects of pulse-like disturbances to the interferograms and CO₂ retrieval errors and apply the method of Aoki et al. (2006). Such the disturbances are induced, e.g., by pulse-like glittering of observed light caused by the reflection of Sun light from roofs of houses, cars or others. It will be shown that the same correction method to the interferogram as that proposed to the IMC correction well works.

2. A brief description of the GOSAT observation system

The mission of the GOSAT is to globally measure the column amount of carbon dioxide and methane, and to assess the sink and source of carbon dioxide. The main sensor is the FTS but an imager (CAI) is also flown on the satellite to obtain cloud and aerosols information. The column amounts of gases are retrieved from high-resolution absorption spectra of solar radiation reflected from the earth. Four bands of high resolution spectra are obtained by the FTS in the near infrared regions. They are 0.76, 1.6, 2.0, and 14.2 μm bands, as summarized in Table 1. For each band, except for the band 4, there are two detectors to measure two components (horizontal and vertical) of linear polarization of the input signal. As a result, we have 7 sets of spectral data at each observation point.

Scanning time for an interferogram of FTS is less than 4 seconds. It depends on the observation mode. During the scanning with the moving mirror, the IFOV is fixed to the same position by using the IMC mechanism of scanning mirror. Cross track scanning is possible, to scatter the observation points for broad area. Pointing to a specific geographical position can be done by commands from ground station. The inclination of satellite orbit is 98 degrees, the satellite descends
in daytime and crosses the equator at 13:00 of local time, and the height of orbit is 666 km. The diameter of IFOV is about 10.5 km in nadir.

Although the information of vertical profiles of gaseous density is slightly contained in the reflected solar radiation, as is shown in Aoki et al. (2006), normal products of GOSAT are only the column amounts of CO₂ and CH₄. The accuracy target of CO₂ column amount is to exceed 1% in clear sky condition. The retrievals in the condition of thin cirrus coverage will also be tried.

3. Effects of the IMC fluctuation

Since the information of gaseous densities contained only in the very narrow range around the absorption line center, it is desirable to acquire the absorption line spectra with a very high spectral resolution comparable to the line width or more. It is also desirable from the view point of avoiding the contamination of other gaseous lines or Fraunhofer lines of solar spectra. The observation with FTS may practically be only the way to make measurements of high spectral resolution for broad wavelength range simultaneously from space. One of difficulties of measuring high resolution spectra from a moving satellite in space is that during the acquisition of the interferogram, optical characteristics of the IFOV could change due to, e.g., the fluctuation of line-of-sight of the spectrometer, the change of reflection angle, or other causes. Such disturbances modulate the interferogram and lead to the erroneous retrieval of atmospheric gases.

In case of GOSAT-FTS, the disturbance could be generated by the IMC mechanism of the scan mirror. Although the IMC is used to stare the same point of the Earth surface, the IFOV still tremble within a small range of angle during the staring. An example of IMC angle fluctuation of Bread Board Model (BBM) of GOSAT-FTS is shown in Fig. 1. In this figure, at the time = 0 second, the IMC mirror is looking at a place, and suddenly changes to look at another place where we want to stare, and reaches there within about 0.3 second. After this time, the direction of the mirror is roughly fixed, but it is still fluctuating in small range of angle. The maximum deviation of along track angle is the order of 0.02 degree as can be seen in Fig. 1. This value corresponds to the geographical deviation of about 200 m at the surface since the satellite is at the height 666 km. An example of expansion of a part of this figure is shown in Fig. 2.

Such this variation of IFOV positioning could generate a noise to the interferogram since the surface albedo changes depending on the IFOV position. We have simulated this effect on the accuracies of CO₂ retrieval, using real data of surface albedo obtained from the image sensor, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), whose surface resolution is 30 m. An example of surface image of the visible band taken by this sensor is shown in Fig. 3 around Tokyo Bay, Japan. From the 1.6 µm band of the ASTER, we can map the surface albedo that the 1.6 µm band of the FTS would observe. This is shown in Fig. 4.

It takes four seconds in maximum to acquire a set of the interferogram. During this acquisition, the position of the IFOV might tremble as shown in Figs. 1 and 2, and the mean surface albedo averaged over IFOV also fluctuates to some extent. Using ASTER data, we made a simulation calculation of the interferogram that is to be obtained with the 1.6 µm band of FTS whose IFOV size is about 10.5 km. Fig. 5 shows the standard deviation (we denote this value as SD in the following) of mean surface albedo when it trembles as shown in Fig. 1. By comparing Fig. 5 with Figs. 3 and 4, it is found that the standard deviation of mean surface albedo becomes large over the regions which include the boundary between the sea and the land. Fig. 6 is the histogram of the standard deviation of albedo shown in Fig. 5. Fig. 7 is the accumulated histogram of the standard deviation.
of albedo shown in Fig. 6.

White circles in Fig. 2 shows the simulation calculation of the excess error of CO₂ retrieval against the standard deviation of mean surface albedo averaged over IFOV. Here, the excess error is defined by the excess of the error of CO₂ retrieval in the presence of IMC trembling over the error of CO₂ retrieval for the case of no IMC trembling. For both cases, the same measurement noises corresponding to the SN ratio of ** are added to the spectra. In this case of SN ratio, the averaged error of CO₂ retrieval under the condition of no IMC trembling is **. The corresponding value of the standard deviation of albedo is about **.

In Figs. 0 and 1, we showed this value by vertical dotted lines. Another dotted line in these figures shows the value of ** of this value. We consider only the data less than this value is acceptable for using in the CO₂ retrievals.

Similar accumulated histograms are also shown in Figs. 3-12 for other areas in the world. It can be seen that the desert is good area for the retrieval since the variation of surface albedo is very small. Contrary, the area that includes land and water surfaces mixed is not good. The results of these figures seem to suggest that a fairly large part of the world has a large standard deviation of surface albedo and thus not good in retrieval condition.

4. Correction method for the noise contaminated interferogram

Let us write the interferogram which is modulated by the disturbance in the form

\[ S(z) + D = (S^o(z) + D)(1 + \beta(z)), \]

where \( S(z) \) is the AC component of the electric output of the interferogram at the mirror distance \( z \), \( D \) is the DC component, \( S^o \) is the true AC component of the interferogram that is not modulated with disturbance, and \( \beta(z) \) is the fractional component of the disturbances.

By the inverse Fourier transform of the observed interferogram \( S(z) \), we obtain a spectrum \( R(v) \) for the whole wave number range. Using the convolution theorem, the inverse Fourier transform \( (F_t^{-1}) \) of \( S(z) \) can be written as

\[ R(v) = F_t^{-1}[S(z)] = R^o(v) + R^o(v) * R_\beta(v) + DR_\beta(v), \]

where \( * \) shows the convolution operator, \( R^o(v) \) is the spectrum to be obtained from \( S^o \), and \( R_\beta(v) \) is the spectrum to be obtained from \( \beta(z) \).

An example of simulated spectrum \( R(v) \) is shown in Fig. 13 for the case of 1.6 μm band, which suffered the disturbance shown in Fig. 1. \( R^o(v) \) is the spectrum confined in the wave number range of the band pass filter 5800–6400 cm⁻¹. We can see the pseudo spectrum of large amplitude appearing in the low frequency region, which mainly comes from the third term of Eq. (2). Write \( R(v) \) of lower frequency region outside the band pass filter as \( R_L(v) \) and by approximating \( R_L(v) \) as

\[ R_L(v) \equiv DR_\beta(v) \]

we obtain \( \hat{\beta}(z) \) as

---

Fig. 3 Visible picture around Tokyo bay from ASTER observation.
Fig. 4  The albedo distribution around Tokyo bay observed by ASTER for 1.6 μm band.

Fig. 5  The standard deviation (in %) of mean surface albedo averaged over IFOV when it trembles as shown in Fig. 1.

Fig. 6  The histogram of the standard deviation of albedo shown in Fig. 5.

Fig. 7  The accumulated histogram of the standard deviation of albedo shown in Fig. 6 over Tokyo area.
Fig. 8 The excess error of CO₂ retrieval (=error of CO₂ retrieval in the presence of IMC trembling- error of CO₂ retrieval without IMC trembling) against the standard deviation of mean surface albedo averaged over IFOV (white circles). Solid circles show the CO₂ retrieval errors to be obtained for the cases with noise correction is made.

Fig. 11 As in Fig. 7 except for tundra in Canada.

Fig. 12 As in Fig. 7 except for Los Angeles.

Fig. 13 An example of full range spectrum obtained from the interferogram which is modulated by the disturbance.
where $F_t$ is the operator of forward Fourier transform.

By correcting Eq. (1) with using $\beta(z)$ as,

$$S^v(z) + D = \frac{S(z) + D}{1 + \beta(z)},$$

we obtained true interferogram, and by again operating the inverse Fourier transform to this corrected interferogram, we finally obtain the true spectrum $R^v(\nu)$. In Fig. 8, we show the CO$_2$ retrieval errors by solid circles after these corrections are made. We can see the effect of the correction is drastic.

### 5. Effects of pulse-like disturbances

The fluctuation of input radiances could also occur caused by the flickering of leaves, glasses and water surface, induced by the surface wind. The reflection angle changes during the data acquisition according to the satellite motion along the track. All of these disturbances modulate the interferogram, and result in a deformation of the true spectrum.

If there is a small mirror on the Earth surface and if it reflects the sun light toward the satellite (see Fig. 14 as an example), the effects on the observed signal could become significant since reflected light is confined in a small solid angle of about $6.8 \times 10^{-5} \text{ radian}$. Suppose the mean surface albedo in the IFOV of size 10.5 km is 20%, and add a mirror of size 4 × 4 m to the IFOV that reflects all the sun light toward the satellite. The effective albedo of this IFOV will now increase from 40 to about 22%. Since the angular diameter of the sun is only 0.53 degrees, this situation of strong surface albedo only continues for a very short period during satellite moving on the orbit. It would be just like a pulse as shown in Fig. 15 as an example. The interferogram is deformed as shown in Fig. 16 due to this disturbance. Both the position and the width of the pulse could be different depending on the angle between the sun and the satellite. In the present simulation, we considered three cases of pulse duration 0.764, 0.382 and 0.191 sec, and three cases of pulse start time, 0.7, 1.4 and 1.9 sec, after the interferogram acquisition starts. All of these combinations make nine cases of simulations. Fig. 17 is an example of the spectrum calculated from the interferogram disturbed with one of nine
pulse-like disturbances. A very strong spectral line appears at about zero wave number region. Fig. 18 is the expansion of a part of spectrum around zero wave number regions.

White circles in Fig. 19 are simulated retrieval error of CO$_2$ for these nine cases. It is found the errors due to these types of disturbance could become seriously large. However, applying the correction method shown in previous section, these errors could drastically be reduced to negligible levels as shown by solid diamonds in Fig. 19.

6. Summary and discussion

The GOSAT makes high spectral-resolution observation of solar radiation reflected from the earth. Observation is made with FTS at 0.76, 1.6, 2.0, and 14 $\mu$m wavelength bands. It takes four seconds, in maximum, to acquire an interferogram.

During this time, IMC mechanism of scanning mirror works to stare the same position of IFOV on the Earth. However, the performance of IMC is not complete and could make IFOV position fluctuate with amplitude of about a few hundreds meters. When the distribution of surface albedo is inhomogeneous, the interferogram suffers disturbance, and resultant spectrum, and thus, the resultant retrieved CO$_2$ amount becomes in error. The simulation of retrieval using ASTER data for albedo distribution showed that in many parts of world error could become a few percent or more. By the correction method for the interferogram as shown in section 4, these errors could reduce to 0.05% or less.

In the present work, we applied this method of correction to pulse-like disturbances and showed that CO$_2$ retrieval errors could be reduced from about 1–10% to less than 0.02%.

References


8) T. Yokota, H. Oguma, I. Morino, A. Higurashi and G. Inoue: Test measurements by a BBM of the nadir-looking SWIR FTS aboard GOSAT to monitor CO$_2$ column density from

[著者紹介]
●青木 忠生（アオキ チョウゾウ）
1943年生。1969年東北大学大学院理学研究科博士課程中退。東北大学理学部助手（大気分光学の研究）。1978年気象庁気象衛星センター技官（極軌道気象衛星データ処理システムの開発）。1985年気象庁気象研究所（大気放射、リモートセンシングの研究）。2004年（独）国立環境研究所、地球環境研究センター、フェロー（GOSATデータ処理システムの開発）。AGU、AMS、日本気象学会、日本リモートセンシング学会。1991年度日本気象学会賞。E-mail: aoki.tadao@nies.go.jp

●横田 進也（ヨコタ シュウヤ）
1956年3月生。1981年 東京大学大学院工学系研究科修士課程（計数工学専攻）修了。同年、環境庁国立公園研究所（現、国立環境研究所）に入所。1987年に工学博士（東京大学）。1989年より2005年までオゾン観測センサILAS及びILAS-IIプロジェクトに従事。データ処理アルゴリズムの開発研究及び定常処理システムの開発運用管理を担当。2003年より温室効果ガス観測技術衛星（GOSAT）プロジェクトを担当。2006年4月、地球環境研究センター衛星観測研究室長。国際GOSATプロジェクトリーダーとなり、現在に至る。当学会、計測自動制御学会、情報処理学会、IEEE-GRSSなどの会員。E-mail: yokoa@nies.go.jp

●信田 浩司（ノブタ コウジ）
1969年生。1999年名古屋大学大学院理学研究科博士後期課程修了。博士（理学）。2000年富士通エフ・アイ・ビー株式会社入社。環境観測技術衛星ADEOS-II搭載センサILAS-IIおよび温室効果ガス観測技術衛星GOSATのデータ処理システム開発に従事。E-mail: nobuta.koji@nies.go.jp

●小谷 明（コタニ アキラ）
1979年11月生。2002年名古屋大学理学部地球惑星科学学科、2004年東京大学大学院理学系研究科地球惑星科学専攻修士課程修了。2004年富士通エフ・アイ・ビー（株）入社。地震動のシミュレーション・解析、衛星分光学データによる気象観測データ処理アルゴリズムの開発・改良、衛星データの処理運用システムの開発・構築等に従事。日本地震学会。E-mail: kotani.akira@nies.go.jp