MONITORING OF THE GREENHOUSE GASES FROM SPACE BY GOSAT

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ABSTRACT:

The global monitoring of the greenhouse gases is necessary to handle the global warming issue and the monitoring from space is very useful for the global monitoring. In order to realize this and repeatable monitoring, the GOSAT program was started. The mission of the GOSAT is to observe CO2 and CH4 column density with relative accuracy of 1 % for CO2 and 2 % for CH4 at 1,000 km square spatial scale and in 3 months average, and provides these data during the Kyoto Protocol's first commitment period which is from 2008 to 2012. It is expected to reduce sub-continental scale CO2 annual flux estimation errors by half using GOSAT.
GOSAT has two main mission instruments to be called TANSO altogether. One of TANSO is the Fourier transform Spectrometer which observes CO2 and CH4 and another one is Cloud and Aerosol Imager whose data are used to compensate the FTS data..
In January of 2009, GOSAT was launched and the initial calibration was completed in July and the initial validation was started.
In February, 2010, the initial validation was completed and the data release to the general users was started on Februay 18,2010.
The data release to the PI, Princepal Investigator, had been performed prior to the data release to the general users.
We are cooperating with NASA/JPL team on the calibration and validation and this collaboration has made notable achievement in the improvement of the analysis accuracy of the CO2 concentation.

1. INTRODUCTION

In 1997, the Kyoto Protocol was adopted at COP 3. Later, in 1999, the GCOM-A1 mission began.
The purpose of GCOM-A1 was to research atmospheric chemistry and to observe the solar occultation method.
In 2002, the Japanese government ratified the Kyoto Protocol. Soon after, societal concern with the global environment and global warming grew sharply. As mentioned in the Kyoto Protocol, succession and acceleration of the development of systematic observation was necessary.
As a result, JAXA and affiliated organizations decided to change the purpose of GCOM-A1 from researching atmospheric chemistry to contributing to the administration of the applicative environment. The name was also changed from GCOM-A1 to GOSAT and in 2005, development of GOSAT began. To achieve this mission objective the observation direction was changed from limb to nadir observation for global observation.
In this paper, the characteristics of the satellite including the mission instruments will be described at first and be followed by the outline of on orbit calibration and data processing, the result of the initial calibration and recent products.

2. GOSAT Satellite Characteristics

2.1 Satellite

GOSAT stands for Greenhouse gases Observing Satellite and its nickname is "IBUKI," which means "breath" in Japanese.
The mission objective of GOSAT is to observe CO2 and CH4 column density with a relative accuracy of 1 percent, that is about 4 ppm for CO2 and 2 percent, that is 34 ppb for CH4 at a spatial scale of 1,000 km by 1,000 km and in 3-month averages. And the mission target is to reduce the estimation error of sub-continental-scale CO2 annual flux by half.
The figure 1 is photograph of the GOSAT flight model taken at the launch site. GOSAT was launched on January 23rd of 2009.
GOSAT is the joint project of JAXA, Ministry of Environment and National Institute for Environmental Studies.
JAXA is responsible for the development of the satellite including mission instruments and on orbit operation, data acquisition and level 1 data processing, and so on. And JAXA takes a role for the calibration. NIES takes a role for the algorithm development, level 2 or higher data processing, validation and so on. Data are distributed from JAXA and NIES.
Ministry of Environment takes a role to develop the a part of the main mission instrument and uses the GOSAT data for their administration.
Table 1 shows the characteristics of the GOSAT.

2.2 Mission Instruments

GOSAT has two mission instruments collectively called TANSO. One of TANSO is the Fourier transform spectrometer (FTS) which observes greenhouse gases and another one is Clound and Aerosol Imager (CAI) whose data are used to compensate FTS data..
Figure 2 and 3 shows the picture of FTS and CAI and table 2 and 3 shows the specifications of the FTS and CAI respectively.

Fig. 1

GOSAT flight model taken at the launch site

Table 1 The characteristics of GOSAT

Size	Main body	3.7m x 1.8m x 2.0m (Wing Span 13.7 m)
Mass	1,750 kg	
Power	3.8 kW (EOL)	
Design Life Time	5 years	
Orbit	sun synchronous orbit	
	Local time	13:00 +/- 0:15
	Altitude	666 km
	Inclination	98 deg
	Recurrent Period	3 days
Launch	Vehicle	H-IIA
	Schedule	23rd January, 2009

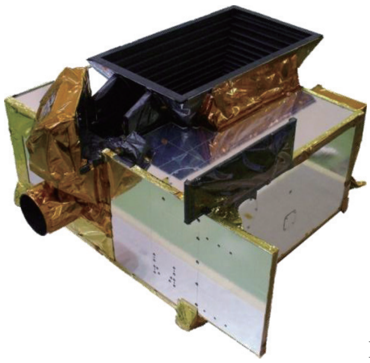

Fig. 2 TANSO-FTS

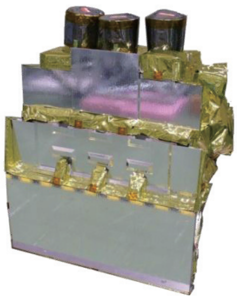

Fig. 3 TANSO-CAI

Table 2 The specification of TANSO-FTS

Ground Pointing Mechanism and Fore optics				
Configu-ration	2-axes pointing mirror (fully redundant) for ground pointing, calibration and IMC			
Pointing	cross track : +/- 35 degrees along track : +/-20 degrees			
FOV	IFOV(footprint) : 10.5 km FOV : 790km			
Fourier Transform Spectrometer				
Speed	4, 2, 1.1 seconds/1 interferogram			
Spectral ch	1P, 1S	2P, 2S	3P, 3S	4
Obs. band (μm)	0.75-0.78	1.56-1.72	1.92-2.08	5.5-14.3
resolution (cm-1)	0.2	0.2	0.2	0.2
detector	Si	InGaAs	InGaAs	PC-MCT
calibration	Solar Irradiance, Deep Space, Moon, Diode Laser(ILS)			Black Body, Deep Space

The line of sight of the FTS is steered by 2-axes pointing mirror in the range between plus and minus 35 degrees in the cross-track direction and plus and minus 20 degrees in the along-track direction.

Table 3 The specification of TANSO-CAI

band No.	observation band (nm)	IFOV (km)	FOV (km)	No. of Pixels (in cross track)
1	372-387	0.5	1,000	2,000
2	667-680	0.5	1,000	2,000
3	866-877	0.5	1,000	2,000
4	1560-1640	1.5	750	500

Driving this 2-axes mirror FTS observes at intervals. Usually FTS observes five points in the cross track direction from left to right and right to left, alternately such as the image on the left of the figure 4. The white dots of figure 4 show the observation points. FTS is capable of increasing the number of observation points up to nine in the cross-track direction.
GOSAT can observe specific points requested by users in addition to the grid points. When GOSAT observes the specific points, the nominal grid points in the corresponding area are replaced with the specific points such as the image on the right of the figure 4. The observation mode also transitions from grid observation mode to specific point observation and back to grid observation mode.
The reflectance of the sea surface is low, so GOSAT observes sun glint over the ocean. When sun glint is observed, this specific observation mode is used.

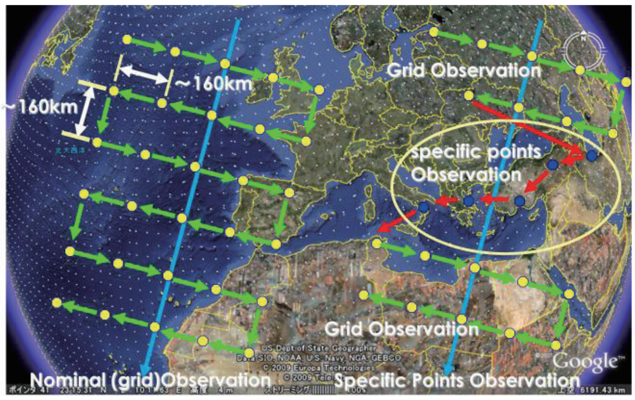

Fig. 4 observation pattern of TANSO-FTS

FTS has the monitor camera and this camera's optical axis is adjusted coaxially with the line of sight of FTS, therefore this camera can take the image of the ground where FTS observes. And the images can provide the information that there is cloud or not in the FOV of TANSO-FTS, the line of sight of FTS points a scheduled area or not and so on.
The FOV of this camera is over 30km.

GOSAT observes 24 hours a day.
But half of the revolution is daytime and another half is nighttime, so the SWIR bands work half time of each revolution.

3. Calibration

As shown in the table 2, TANSO-FTS has a few calibration methods. The figure 5 shows the image of on orbit operation.
In the figure 5 right side is daytime and SWIR bands observe in the region indicated blue dot line. And the red dot line shows the extent of the TIR bands observe.
In the region indicated by red solid line the ground is nighttime but the satellite can see the Sun. So the solar irradiance calibration is performed in this area.
GOSAT perform the lunar calibration once a year.
When the lunar calibration is performed, GOSAT stop the

rotation around the pitch axis at the descending node and fix the atitude and when GOSAT come around above Antarctica the line of sight of the FTS and CAI will be pointed to the moon.
After the moon calibration the altitude is keeped until the descending node and start to rotate around the pitch axis again.
The blackbody and deep space calibration are performed at regular intervals.
But during the blackbody and deep space calibrations are performed, TANSO-FTS cannot observe.
Therefore the positions where blackbody and deep space calibrations are performed are changed every revolution.

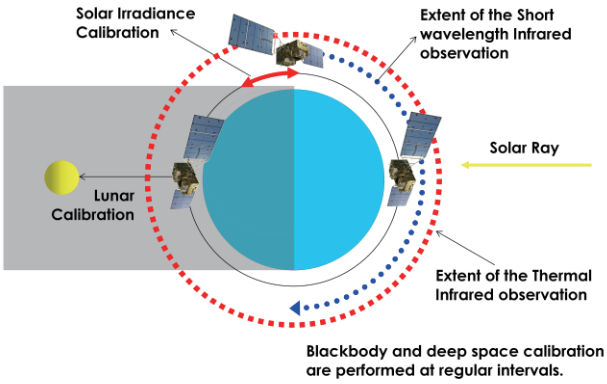

Fig. 5 On orbit operation

4. Data processing

The GOSAT data is expected to be used not only for research of global warming but also for actual use, so the data distribution latency is very important. Therefore the observation data are downloaded to the ground station in svalbard of Norway every 2 revolutions. Figure 6 shows the data processing flow.
Additionally, GOSAT data are downloaded to Hatoyama station in Japan almost every 12 hours.
The downloaded data, namely interferogram, are transferred to Tsukuba Space Center in Japan and processed to the spectra.
And these spectra are transferred to the National Institute for Environmental Studies and performed level 2 and higher level processing and the column density and the global distribution map for CO2 and CH4 are produced.
And after that, Level 4 processing will be performed and estimated the net flux.

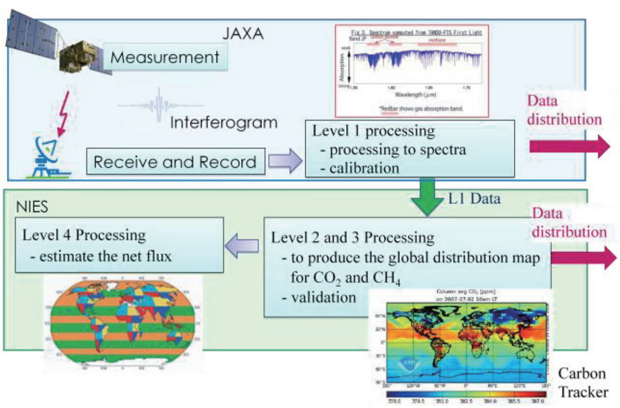

Fig. 6 Data Processing Flow

5. Initial Calibration

In the initial calibration, we evaluated the following three items concerning FTS performances.
Radiometric, spectral characteristics and geometric evaluation.
And concerning the one of CAI, two items were evaluated.
Radiometric evaluation of the FTS was performed in two method. One is solar irradiance calibration using solar diffuser mounted on the TANSO-FTS and another one is vicarious calibration using ground reflectance data base.
Spectral characteristics evaluation was performed about the wave number accuracy and the instrument function.
Geometric evaluation was performed about pointing accuracy.
The radiometric evaluation of CAI was performed by the vicarious calibration. Over the land the ground reflectance data base was used and over the ocean the relative calibration between channels was performed.
The geometric evaluation of CAI was performed about two items, absolute geometric accuracy and band-to-band registration.

5.1 FTS Radiometric Calibration

For radiometric calibration the solar diffuser mounted on the TANSO-FTS was used. The both faces of this solar diffuser are usable and usually one fixed face is used for solar irradiance calibration every revolution. And the solar diffuser is turned around every month and another face is exposed to the solar ray for the solar irradiance calibration.
Figure 7 shows the ratio of the radiance of the solar diffuser to the Kurucz model and reverse side of the solar diffuser.
It's found the trend toward the degradation in band 1.
It's estimated that the factor of the degradation of the band 1 data is the degradation of the reflectance of the solar diffuser from the bottom graph of figure 7.
But this degradation is too large and the trajectory has continued to degrade through last one month. On the other hand, the ratio of the solar diffuser irradiance to Kurucz solar irradiance model has not changed through last one month. This means that the reflectance of the reverse side of the solar diffuser increased and this is very hard to believe. This issue is now under review.

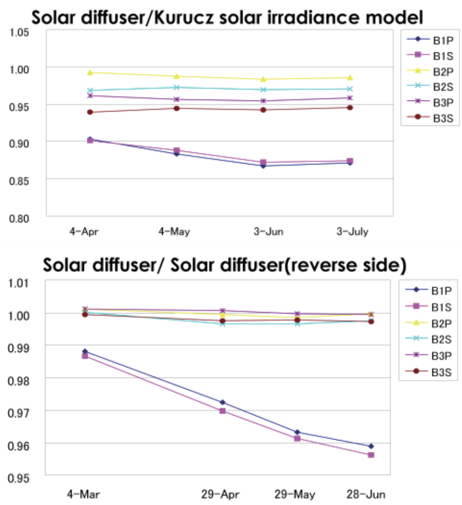

Fig. 7 Ratio of the radiance of the solar diffuser with reference

As the another calibration method the vicarious calibration was performed using the reflectance data of the Sahara. The areas where the ground reflectance was stable were selected as the evaluation points and the radiance of these points were calculated using ground reflectance data base and compared with the GOSAT observation data.
In both cases of solar irradiance and vicarious calibration, we used the Kurucz solar irradiance model as a reference.
Table 4 shows the result of radiometric calibration.

These values are FTS calibration coefficient which were derived from the reference data over the observation radiance.
There was no significant difference between two methods, and relative radiometric accuracy is under 3% except for band 1.

Table 4 The result of radiometric calibration
(calibration coefficient)

Band	1P	1S	2P	2S	3P	3S
Solar Irradiance Calibration	1.093	1.089	1.008	1.026	1.012	1.031
Vicarious Calibration	1.129	1.121	1.031	1.030	1.010	1.003

Normally we use the existing ground data base for the vicarious calibration.But last year we had taken the ground data such as the surface albedo, humidity and temperature using sonde at Railroad valley in Nevada in cooperation with JPL team.
And the difference between the GOSAT data and simulated data was 9% in band 1.It’s considered that the major error sources are solar irradiance data, TANSO instrument response degradation IFOV averaged albedo extrapolation and BRDF correction.We are now under consideration about these error sources.And in this June, we had performed the vicarious calibration at Railroad valley again in cooperation with JPL team. The result is now under investigating.

5.2 FTS Spectral Characteristics Calibration

The wave number accuracy was evaluated as one of the spectral characteristics calibration. The Fraunhofer lines were used for band 1 to 3 and atmospheric absorption lines were used for band 1 to 4 to evaluate the wave number accuracy.
We compared these lines in the observation data with the Kurucz solar irradiance data base or HITRAN data base.
From these evaluation, it has become clear that the wave number has the offset due to the alignment shift of the sampling laser and this shift is on going now and going to converge at about 0.4 cm-1.
Figure 8 shows the difference of the wave number from the Kurucz data base of all bands from April to June of 2009. The shift of Band 1 is large. The study revealed the alignment shift of the sampling laser and it considered that the shift of the wave number arised from the alignment shift of the sampling laser.
So we calculated the amount of the alignment shift of the sampling laser from the amount of the wave number shift.
The results of this calculation are shown in the figure 9.
The amount of the shift has matched up to the alignment shift of sampling laser calculated by other method.
From these evaluation, it has become clear that the wave number has the offset due to the alignment shift of the sampling laser. This shift in on going now and going to converge at about 0.4 cm-1.

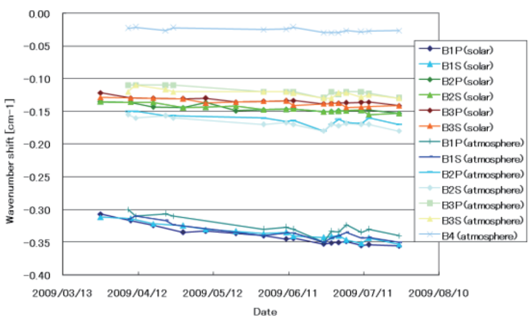

Fig. 8 Difference of the wave number from Kurucz database

Fig. 9 Laser wave length calculated from the wave number shift

We have evaluated the instrument function in band 2 P and S polarization every month as another one of the spectral characteristics evaluation. The figure 10 shows the instrument function of Band 2P. In this figure the result of PFT and measured data on orbit were overwritten.
The FWHM of the instrument function normalized at 0-peak were used to evaluate and it was confirmed that there was no fluctuation of the spectrum and FWHM from the PFT.

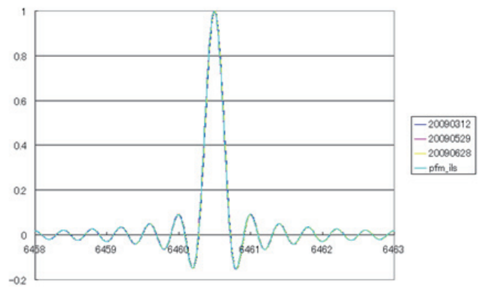

Fig. 10 Instrument function of band 2P

It was indicated that the instrument function model made by the PFT data should be re-evaluated through the data processing and evaluation of the data.
So we used the EM of TANSO-FTS to re-evaluate the instrument function model and it was confirmed that we needed the refinement of the IFOV figure and evaluation of the effect of the intensity distribution in the flux of light used in the PFT on the instrument function.
Therefore we are now evaluating the IFOV figure in consideration of the aberration of optics and the effect of the intensity distribution in the flux of light used in PFT by two methods, one is the same method as the PFT which use the Tunable Diode Laser and diffuser. And it was confirmed that the intensity distribution is not uniform and we are investigating the effect of this ununiformity. Another method uses the integral sphere and a collimater. The instrument function measured by this method almost agreed to the model calucluation.

5.3 Geometric Calibration

We evaluated the pointing accuracy as the geometric calibration. To confirm the direction of the line of sight of FTS, the images taken by the monitor camera in the FTS were used As a result, it was confirmed that the rms error is about 0.4 km and 0.2 km in the cross-track and along-track direction respectively.
These are results in the case of nadir looking. The figure 11 shows the results of the evaluation of the pointing accuracy at the all observation points.
The upper and lower graph shows the pointing error in the cross track and along track direction respectively.
As these graphs show the error angle become large at the first observation point of five one and the error angle is about 900m.

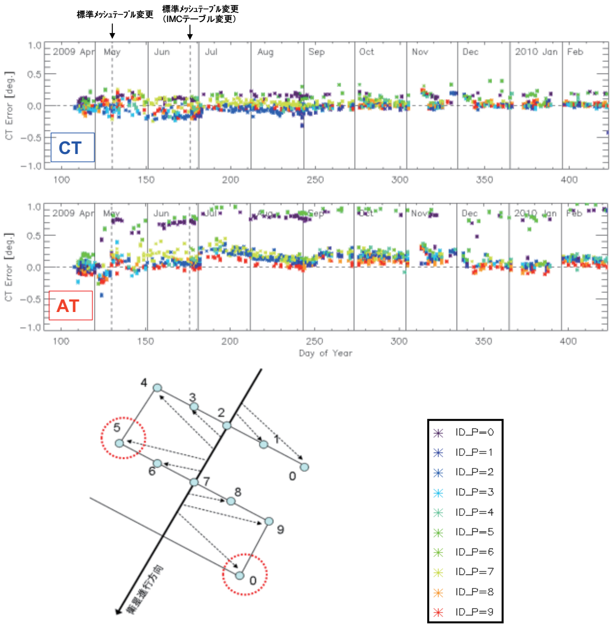

Fig. 11 Pointing Accuracy

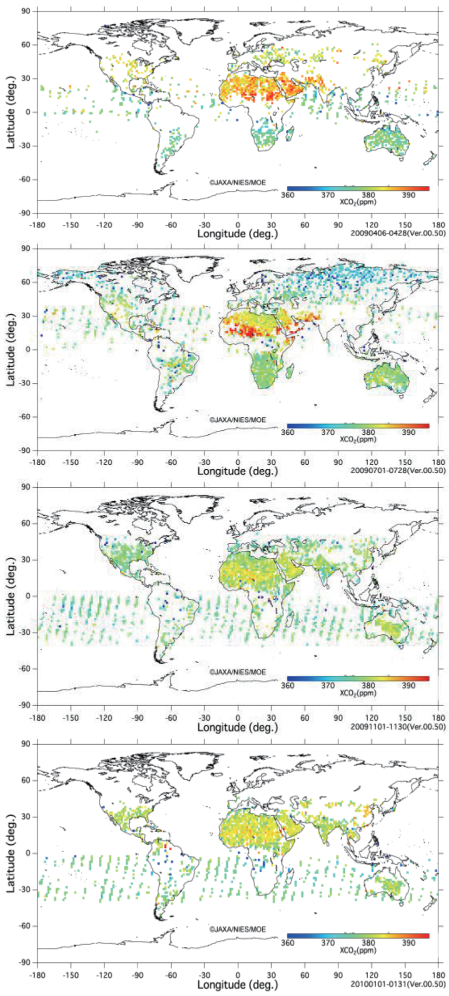

Fig. 12 Seasonal CO2 column averaged dry air mole fraction (from top April, July, November and January)

6. Recent Products

The initial validation was completed at end of January of 2010 and it was achieved that the relative accuracy is 1 % for CO2 and 2 % for CH4. But now GOSAT data have several number of biases and the result of the retrieval becomes large when there are particles such as the sand over the desert. We are now investigating the method to reduce this bias and to eliminate the influence of particles in the atmosphere.

6.1 FTS Products

GOSAT began observation in April of 2009 and since then a year's worth of data has been accumulated. Figure 12 and 13 shows the seasonal column averaged dry air mole fraction of carbon dioxide and methane, respectively.

The high concentration in Africa in these figures are an error due to the sand over the desert. And in the areas where the SNR of the observation data is low, the data are not processed because the results have many errors and in areas covered by cloud it is impossible to calculate the concentration. In areas where the elevation angle of the Sun is less than 20 degrees, the data are not processed because the calculation result has many errors, so there are no data in the high latitude area in northern hemisphere in winter. We can see the low concentration in summer in the northern hemisphere due to the photonic synthesis of vegetation.

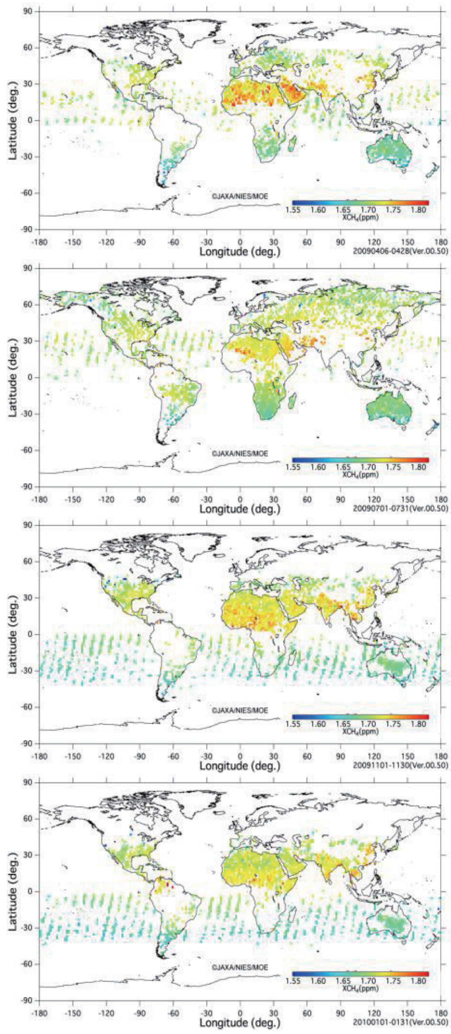

Fig. 13 Seasonal CH4 column averaged dry air mole fraction (from top April, July, November and January)

6.2 CAI Products

The CAI observes aerosol to counterbalance the FTS data.
To fulfill this function CAI has the observation bands in ultraviolet, red, near infrared and shortwave infrared.
In April of 2010, a volcano erupted in Iceland.
The CAI took a picture of the spreading ash plume.
The figure 14 shows the false color images taken by CAI that the intensity of the ultraviolet, red and near infrared band is represented in blue, green and red respectively, and the yellow part shows the spreading ash plume.
The upper and lower image was taken on 15th and 16th of April respectively.

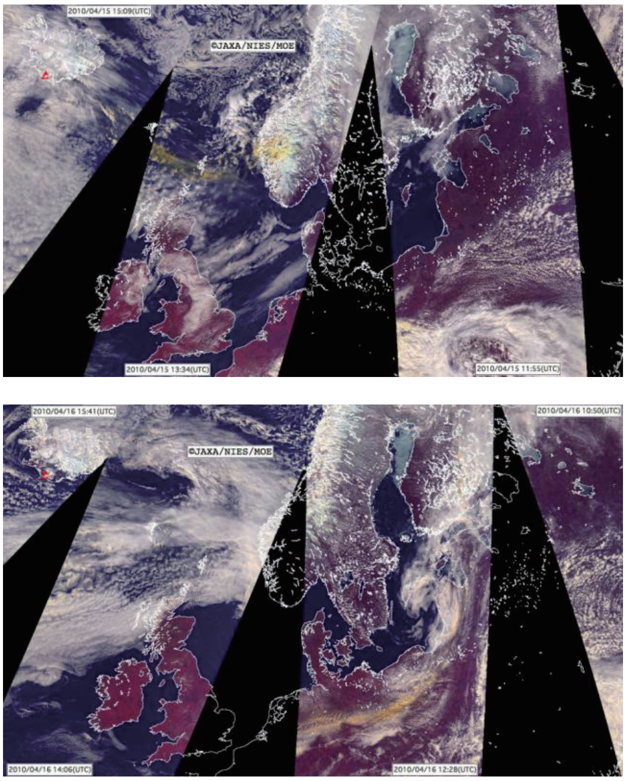

Fig. 14 the false color images of the ash plime from volcano

7. Cooperation with ACOS tema

We cooperated with the ACOS (Atmospheric Carbon Dioxide Observations from Space) team in regard to the calibration and validation.
In June of 2009 and 2010 the GOSAT and ACOS teams jointly performed vicarious calibration at Railroad Valley.
All GOSAT Level 1B data, that is, spectral data, are sent to ACOS team, that is JPL evely day, and the ACOS team processes a part of L1B data to Level 2 data. The figure 15 shows the CO2 column-averaged dry air mole fraction of each season processed by the ACOS team.
The high concentration in the high latitude region in the northern hemisphere is an error due to the low SNR. In the area where the the elevation angle of the Sun is less than 20 degrees the data are not processed in the same manner that the Japanese data are. Therefore, data in the high latitude regionof November and January distribution maps were not processed.

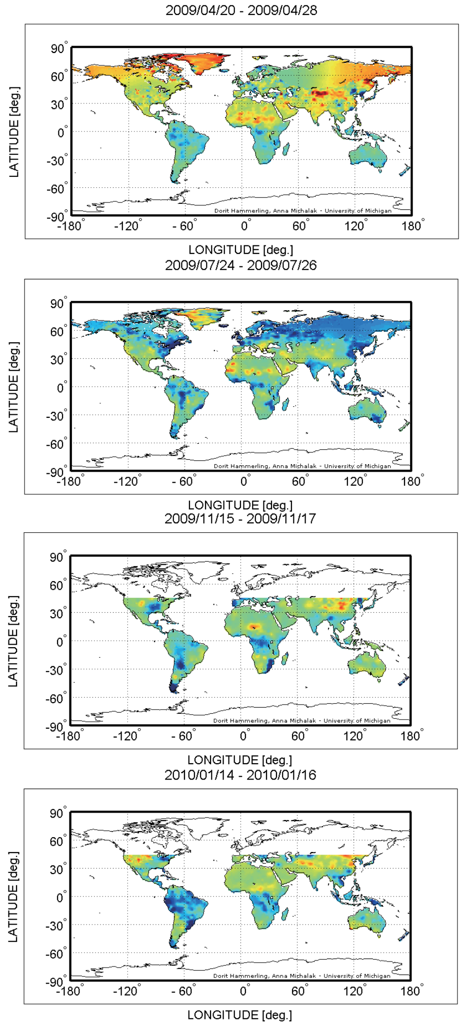

Fig. 15 the column averaged dry air mole fraction of CO2 (from top April, July, November and January)

8. Conclusion

On 23rd of January of 2009, GOSAT was launched and until now a year's worth of data has been accumulated.
The initial calibration and validation were completed and it was achieved that the relative accuracy is 1 % for CO2 and 2 % for CH4. The cooperation with the ACOS tema contributed the improvement of the accuracy.
A few anomalies of the behavior of the pointing mirror such as the misalignment were found, but these anomalies don't make a difference to the observation data.
GOSAT data have several number of biases and the method to reduce this bias is under research.
When there are particles such as the sand over the desert, the result of the retrieval becomes large and we are now studying the method to eliminate the influence of these particles.
From now on the monthly data will be compared with the one of the same month of last year.
We would like to expect the utilization of the satellite data for the administration of the Earth environment.