Thermal And Near infrared Sensor for carbon Observation (TANSO)
On board
the Greenhouse gases Observing SATellite (GOSAT)

Research Announcement

Appendix A

Outlines of GOSAT and TANSO Sensor

GOSAT (Greenhouse gases Observing SATellite) carries an observing instrument called Thermal And Near infrared Sensor for carbon Observation (TANSO), which is composed of a Fourier Transform Spectrometer (TANSO-FTS) and a Cloud and Aerosol Imager (TANSO-CAI)

A.1 Outline of GOSAT

GOSAT is scheduled to be launched into space by JAXA's H-IIA rocket in early 2009 and will acquire data on the global distribution of carbon dioxide (CO_2) and methane (CH_4) (column abundance and altitude distribution) for at least five years. Two observation sensors, TANSO-FTS and TANSO-CAI, are placed in the earth-facing (+Z) plane of the satellite and operated by a three-axis attitude control system in such a way that the sensors keep looking toward the geocentric direction. GOSAT secures power supply needed for the operation of itself and the sensors on board with two sets of solar paddle to be deployed facing towards the sun, records and playbacks the mission data acquired by the sensors on the Mission Data Processor (MDP) subsystem, and transmits the data down to the ground stations.

Figure A.1-1, Table A.1-1 and Table A.1-2 show an overview of GOSAT in orbit, its major specifications and orbital parameters, respectively. Figure A.1-2 represents nominal orbits of GOSAT.

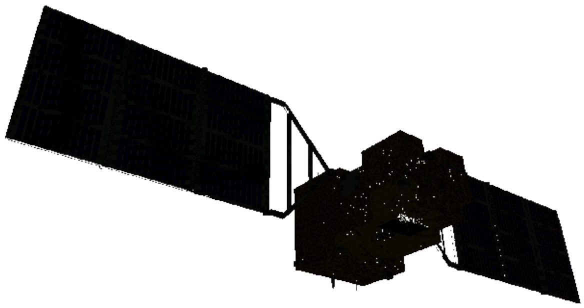

Figure A.1-1 Overview of GOSAT in orbit

Table A.1-1 Major Specifications of GOSAT

Specification items	Description
Size	Main body: H3.7m(X) × W1.8m(Y) × D2.0m(Z) (except for its extrusions) Wing span: 13.7m
Mass	1,750 kg
Power	3.8 kw (EOL)
Life time	5 years
Launch schedule	January 23, 2009

Table A.1-2 Orbital Parameters of GOSAT

Parameters	Description
Orbit type	Sun-synchronous, quasi-recurrent
Altitude against the earth	666 km at Equator
Inclination angle	98.06 deg
Orbits/day	14 + 2/3 revolutions/day
Orbits/recurrence	44 revolutions/3 days
Descending node time	13 hours ±15 minutes

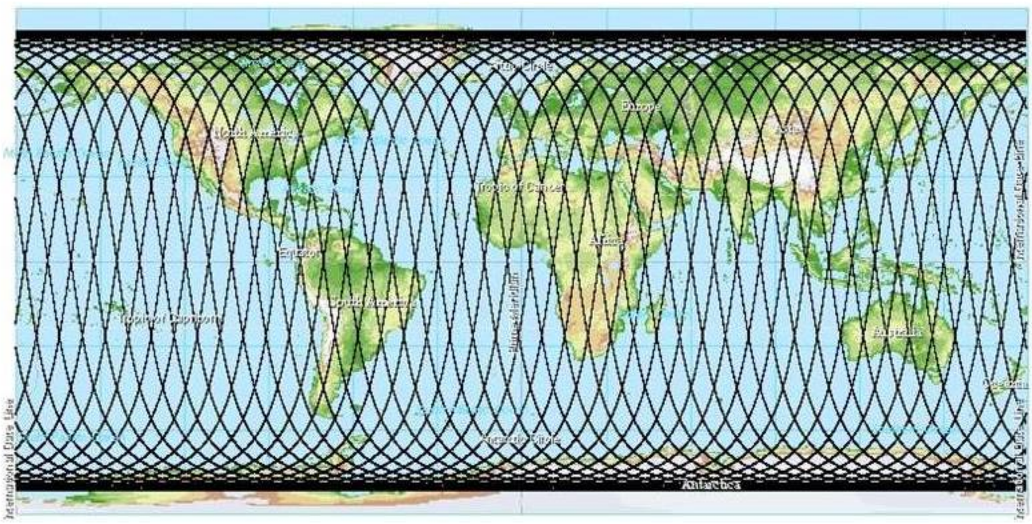

Figure A.1-2 GOSAT's nominal orbits

A.2 Outline of GOSAT/TANSO-FTS

A.2.1 Outline of TANSO-FTS

Table A.2-1 below provides an outline of TANSO-FTS.

Table A.2-1 Outline of TANSO-FTS

Observation method	Earth-looking observation
Method of measurement	Spectral measurement of atmospheric absorption by the Fourier transform interferometer
Functions	1. Observes the atmosphere in visible, short wavelength infrared and thermal infrared bands looking toward the earth center. 2. Carries out observation over the land on lattice points. 3. Observes the same footprint during one interferogram measurement while the satellite is moving. 4. Multiple observations are carried out for a same footprint to improve SNR. 5. Observes at a fixed angle (or fixed distance) interval in cross-track direction during the lattice observations. 6. Returns to the same footprint after three days. 7. Observes sea area where sunglint is expected, using the two-axis (AT/CT) mechanism. 8. Conducts a combination of observations in lattice point, sunglint and specific point modes. 9. Performs the following in-orbit calibrations: (1) Solar irradiance calibration in the visible and short wavelength infrared bands and blackbody calibration in the thermal infrared band (2) Deep-space calibration in the visible-, short wavelength- and thermal-infrared bands (3) Annual lunar calibration on the sensitivity by pointing the satellite and the two sensors to the moon

TANSO-FTS is composed of the following three units:

(1) TANSO-FTS Optical Unit

(2) TANSO-FTS Control Unit

(3) TANSO-FTS Electrical Circuit Unit

Figure A.2-1 shows a block diagram of TANSO-FTS. Considering that the mission of this Project is to get useful results, redundancy is employed in the design of sensors wherever possible. Figure A.2-2 shows an overview and the internal structure of the optical unit of the sensor.

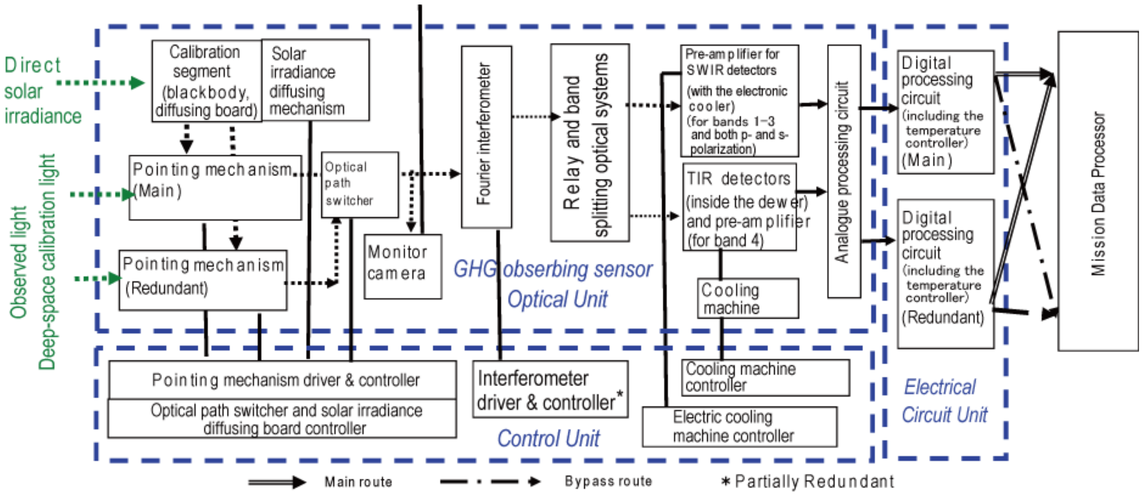

Figure A.2-1 Block Diagram of TANSO-FTS

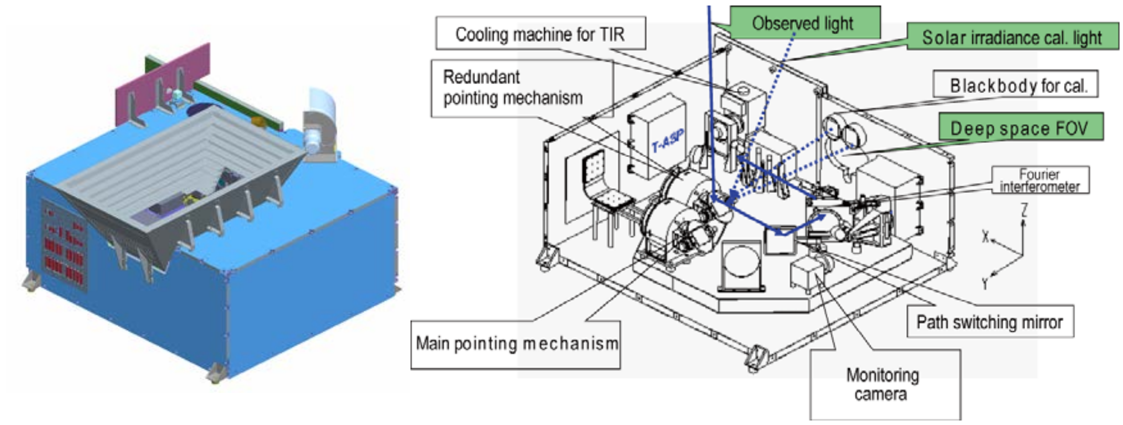

Figure A.2-2 Overview and Internal Layout of the Optical Unit of TANSO-FTS.

A.2.2 Specifications of TANSO-FTS

(1) Fourier interferometer mechanism

Table A.2-2 summarizes the specifications of the Fourier interferometer mechanism and outlines the scanning method.

Table A.2-2 Outline of the specifications of the Fourier interferometer and its scanning method

Spectroscopy	Fourier interferometer
No. of ports	2 (single-pass)
Scanning method	Two corner cubes are attached to the ends of the V-shaped swing arm. The arm swings to scan with the supported flexible blades acting as the axis. (See Figure A.2-4.)
Data acquisition method	Scanning on both sides and data acquisition on one way
Beam splitter	ZnSe (without coating)
Sampling	Sampling by laser diodes
Signal processing	Interferogram data are transmitted down to the earth.

Figure A.2-3 illustrates the structure of the scanning mechanism. The scanning speed stability required is 1% or lower. The interferometer acquires interferogram on both sides of the zero (optical) path difference (ZPD) location.

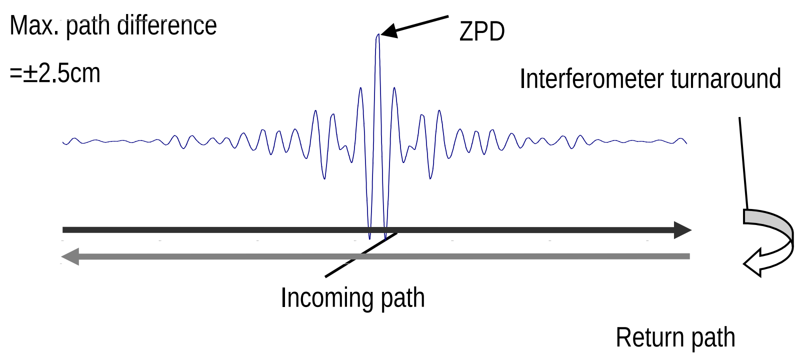

Figure A.2-3 Scanning by the Fourier interferometer

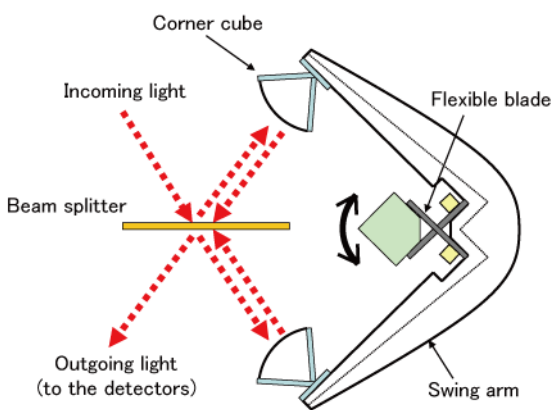

Figure A.2-4 Layout of the double corner cubes, swing arm and flexible blades

(2)Band configuration

TANSO-FTS has detectors for four bands, all of which have the same field of view (FOV). Table A.2-3 tabulates the wave number range, spectral resolution, and other parameters for each band.

Table A.2-3 Wave number range and spectral resolution of the four bands used by FTS

Band	Band 1	Band 2	Band 3	Band 4
Band name	Visible	SWIR	SWIR	TIR
Polarimetric observation	Yes	Yes	Yes	No
Wave number Range (Note 1)	12900 - 13200 cm^{-1}	5800 - 6400 cm^{-1} (Note 5)	4800 - 5200cm^{-1}	700 - 1800 cm^{-1}
Out-of-band characteristics (Note 2)	Transmittance of 0.1% or less in the ranges of <12700cm^{-1} >13400cm^{-1}	Transmittance of 0.1% or less in the ranges of <5000cm^{-1} >6800cm^{-1}	Transmittance of 0.1% or less in the ranges of <4500cm^{-1} >5500cm^{-1}	Transmittance of 0.1% or less in the ranges of <600cm^{-1} >3800cm^{-1}
Spectral resolution (Note 3)	0.2 cm^{-1}	0.2 cm^{-1}	0.2 cm^{-1}	0.2 cm^{-1}
FWHM of the instrument function (Note 4)	0.6 cm^{-1} or less	0.27 cm^{-1} or less	0.27 cm^{-1} or less	0.27cm^{-1} or less
Targets of the measurement	(O_2) →information on air pressure & cirrus cloud	CO_2, CH_4, H_2O	CO_2, CH_4, H_2O, information on cirrus cloud	CO_2, CH_4, H_2O, etc.

Note 1: 80% or above of the maximum efficiency can be achieved within the wave number ranges of Bands 1, 2 and 3. As for Band 4, 60% or above of the maximum efficiency can be achieved in the designated wave number range by converting the sensitivity of the detector into the quantum efficiency. The efficiency here means the product of the efficiency of the optical unit, the quantum efficiency of the detector, and the response of the amplifier.

Note 2: In the wave number range corresponding to the signal turn-around in the Fourier transform, less than 0.01% is assumed.

Note 3: The spectral resolution is defined as (1 / (2 * Max. path difference)).

Note 4: The full width at half maximum (FWHM) of the instrument function is defined as the FWHM when radiation from a monochromatic light source is introduced in the full FOV and the measured data are inverse-Fourier-transformed without apodization.

Note 5: In Band 2, the transmittance must be 0.1 or higher when the laser wavelength is 1.55μm (6460 cm^{-1}), which is for measuring the instrument function in orbit.

(3) Methods of optics, band splitting and polarimetric observation

Table A.2-4 lists the summary of specifications for TANSO-FTS in terms of optics, spectroscopy and polarization, whereas Figure A.2-5 provides an overview of the optical system.

Table A.2-4 Summary of specifications for optics, band splitting and polarization

Optics	Effective aperture	ϕ 68 mm (Bands 1-3), ϕ 60 mm (Band 4)
	F value	F=2 (F value for the optics-detector system to be installed between the FTS sensor and the detector.)
	Optical system	Reflective optical system. However, a refractive optical system is used in the case of focusing on the detectors for Bands 1-3.
	Aperture control	As for Bands 1-3, the corner cubes provide a control of the aperture. While the aperture diameter is 68 mm, the movement of light flux in association with FTS's scanning remains within 1 mm in the direction perpendicular to the optical path. For Band 4, an aperture control is introduced inside the optical system of the detector so as to suppress background light.
	FOV control	The FOV is determined with the slit common to all bands, after the light is modulated by the Fourier interferometer and concentrated. (15.8 mrad: corresponds to 10.5 km when projected on the earth's surface.)
Band splitting	Band splitting	After FOV being narrowed through the slit and the light collimated, the light is splitted through the dichroic filter one after another starting with Band 1.
	Removal of out-of-band light	A narrow band pass filter is set up at the optical system of the detector for each of Bands 1-3.

Polarization	Polarization	For Bands 1-3, the polarization beam splitter is installed in the optical system of the detector for simultaneous observation of two polarizations.

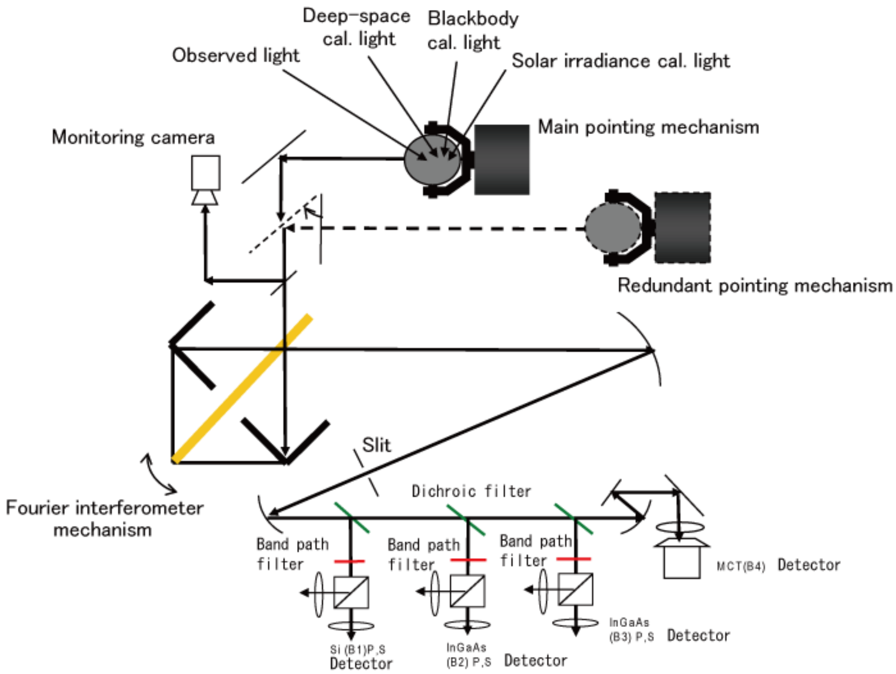

Figure A.2-5 Overview of the optical system

(4) Band-to-band/sensor-to-sensor registration

Band-to-band/sensor-to-sensor registrations are determined as follows:

(1) Band-to-band registration within FTS: 0.05 pixels or less

(2) Registration between TANSO-FTS and TANSO-CAI: 0.5 pixels of TANSO-CAI or less

(3) A monitoring camera (for checking the FOV of FTS) is attached at the light entrance section of FTS for the sake of determining registration with TANSO-CAI.

A.2.3 Observation mechanism of TANSO-FTS

(1) Principles of TANSO-FTS observation

The sun can be regarded as a blackbody light source which has an absolute temperature of slightly less than 6,000 K. It emits light mainly in the range covering from ultraviolet to visible and short wavelength infrared bands. Most of visible and short wavelength infrared light emitted by the sun reaches the earth's surface while some is absorbed and scattered by clouds and aerosols on the way. An earth-observing satellite detects light reflected by the ground and returned to the satellite through the atmosphere. The measured light provides information on the concentrations of CO_2, CH_4, and water vapor (H_2O), whose absorption bands are in the visible and short wavelength infrared range.

The ground surface and clouds radiate thermal infrared waves with intensities commensurate with their temperatures and their own wavelength characteristics. There are numerous absorption bands of major and minor atmospheric constituents in these bands. Each atmospheric constituent has its own absorption bands within the visible and short wavelength infrared bands or thermal-infrared band. Though the strength of absorption varies with spectra of each constituent, the use of databases established in laboratories will help identify the relationship among the wave number within the absorption bands, absorption strength, and constituent concentration. The basic principle of molecular spectroscopy goes as follows: spectroscopic observation is performed by detecting the absorption spectra of the atmospheric molecules of interest, the detected light is converted into electric signals (photoelectric transfer), radiance per spectrum is calculated, and the amount of atmospheric molecules is derived from the radiance level.

A space-borne observing sensor points its scanning mirror at the target to be observed, introduces the observed light into the system, converts it into electric signals at the detector assigned to each bandwidth through the diffraction grating, interferometer or another types of spectrometer, and transmits electric signals onto the ground. The data received on the ground will be analyzed to extract necessary information, which will then be transformed into spectral data, based on which the volume of each atmospheric constituent is calculated.

(2) Principles of the Fourier interferometer

The Fourier interferometer first splits the light with its beam splitter (BS) into two with different optical path lengths, which interfere with each other. It acquires the spectra of the light source by inverse-Fourier-transforming the interferograms obtained while changing continuously the path length difference.

This method is characterized by the following two factors:

(1) High gain of the light

(2) Acquisition of spectra over a wide wavelength range at a high spectral resolution

The Fourier interferometer has come into practical use owing to the development of advanced computers, which has made inverse Fourier transform faster, and higher-accuracy mechanical scanning by means of laser range finders. Figure A.2-6 shows a diagram describing the principles of the Michelson interferometer. Typically, M1 and M2 are a fixed mirror and a moving mirror, respectively. In case of TANSO-FTS, however, M1 and M2 are installed on a single swinging arm so that the two mirrors move by the same distance with opposite phases. As a result, the path difference is doubled, making it possible to scan faster. Thus, the interferometer can achieve both a high spectral resolution and a high spatial resolution without sacrificing one or the other.

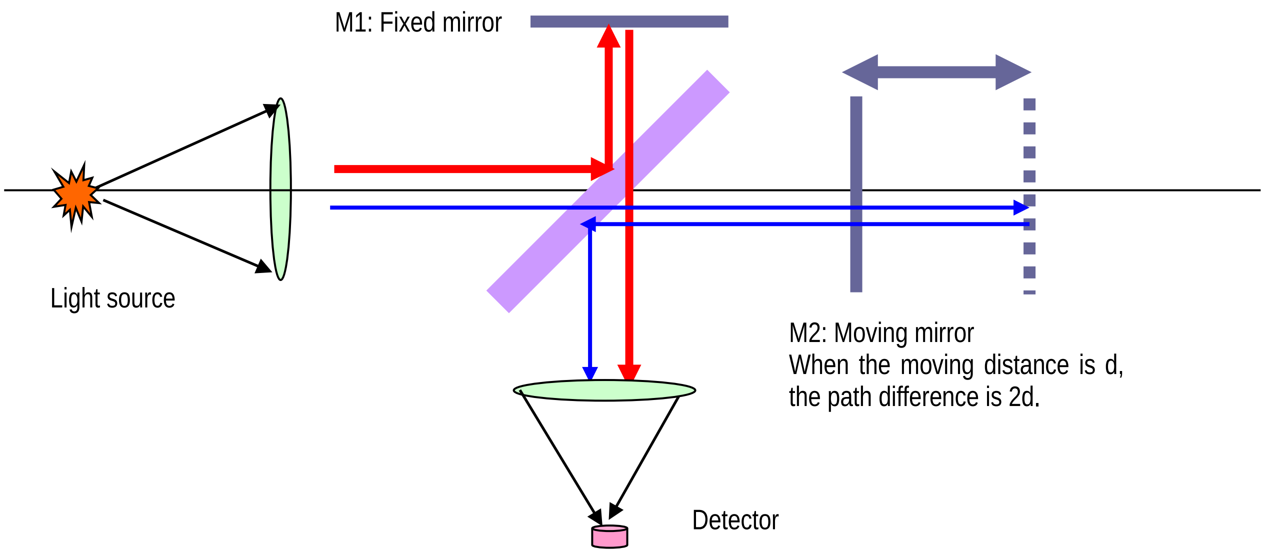

Figure A.2-6 Principles of Michelson Interferometer

Further, space-borne interferometers are designed with attention paid to the vibration environment while being launched on rockets and the thermal environment in outer space.

The Fourier interferometer acquires signals called interferogram as shown in Figure A.2-7 below.

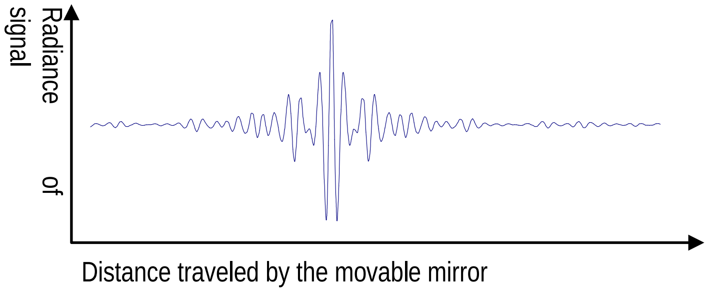

Figure A.2-7 Interferogram data

When this interferogram is inverse-Fourier-transformed, the spectra absorbed in the air are obtained, as shown in Figure A.2-8. The spectra depicted here are those of the sunlight absorbed by H_2O, CO_2, and CH_4 in the atmosphere as observed by the GOSAT ground test model in November 2005.

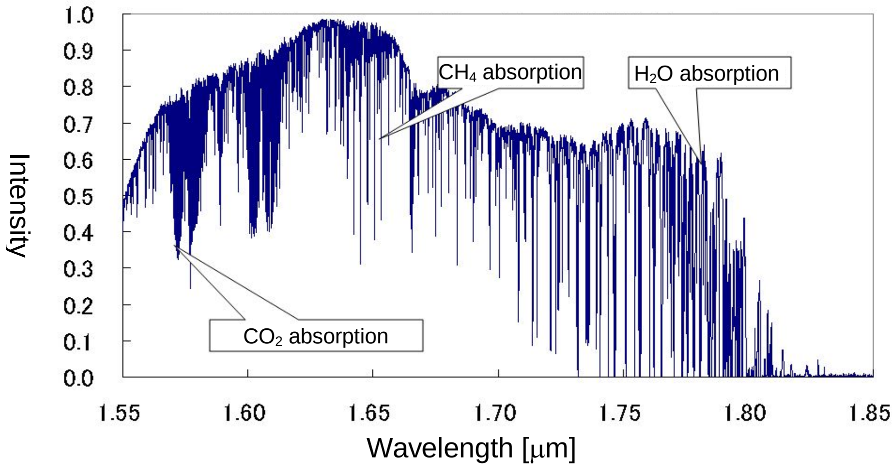

Figure A.2-8 Atmospheric scattering spectra observed by the GOSAT ground test model at the top of Mt. Tsukuba in November 2005

Since the satellite can acquire observation data fairly frequently, the amounts of atmospheric constituents can be derived from the above spectral data and plotted into a global distribution diagram, as shown in Figure A.2-9. There has been no such example of global distribution data provided by satellites.

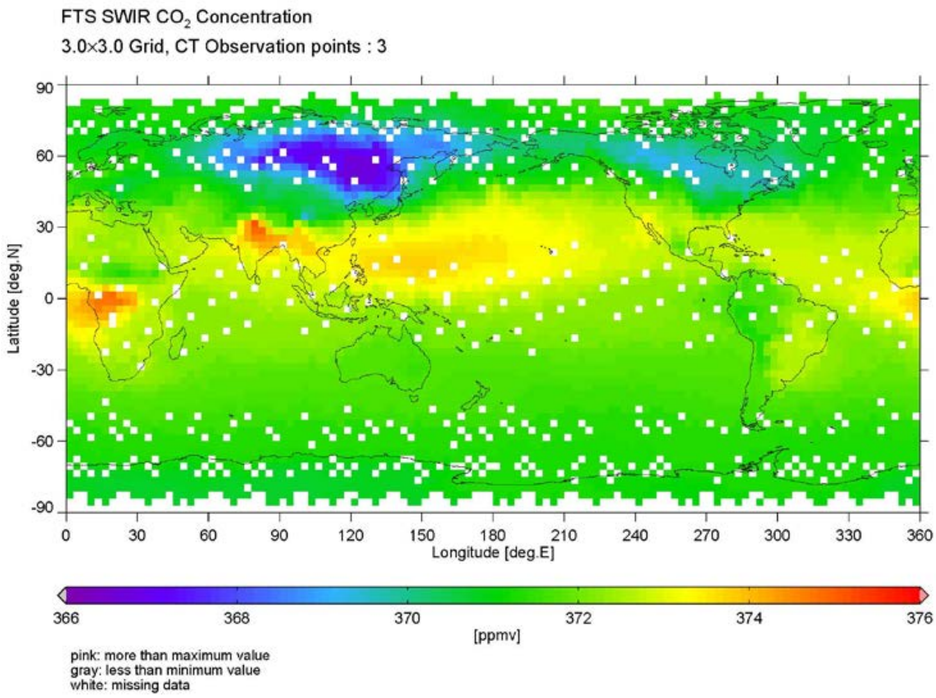

Figure A.2-9 Global distribution of carbon dioxide (CO_2)

The global distribution of net CO_2 flux, as shown in Figure A.2-10, can also be derived from the satellite data referred to above, and by using atmospheric inverse transport models.

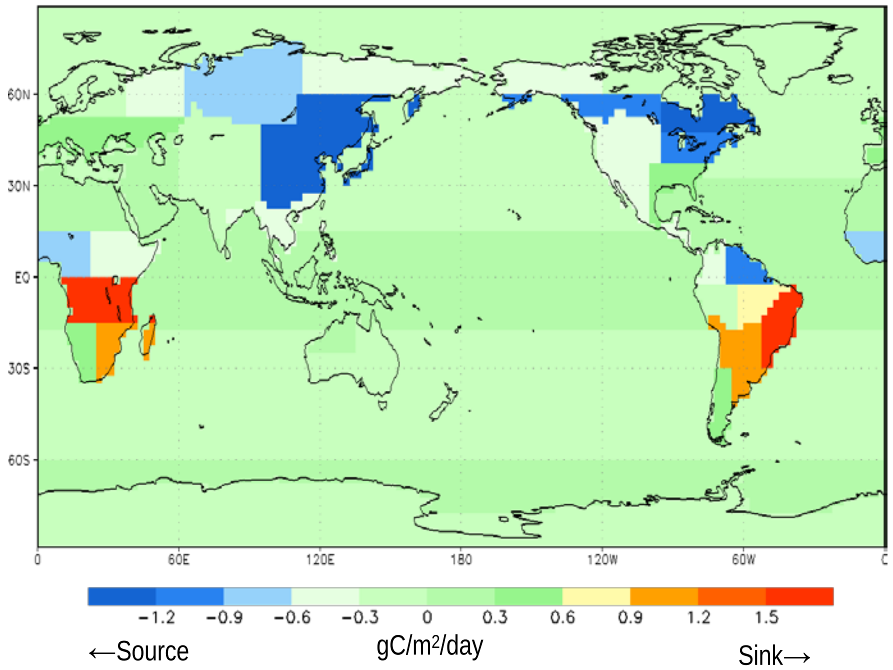

Figure A.2-10 Global distribution of net CO_2 flux

Furthermore, a global distribution of CO_2 can also be obtained, as shown in Figure A.2-11 in three-dimensional (3D) image, using the above net CO_2 flux distribution and atmospheric transport models.

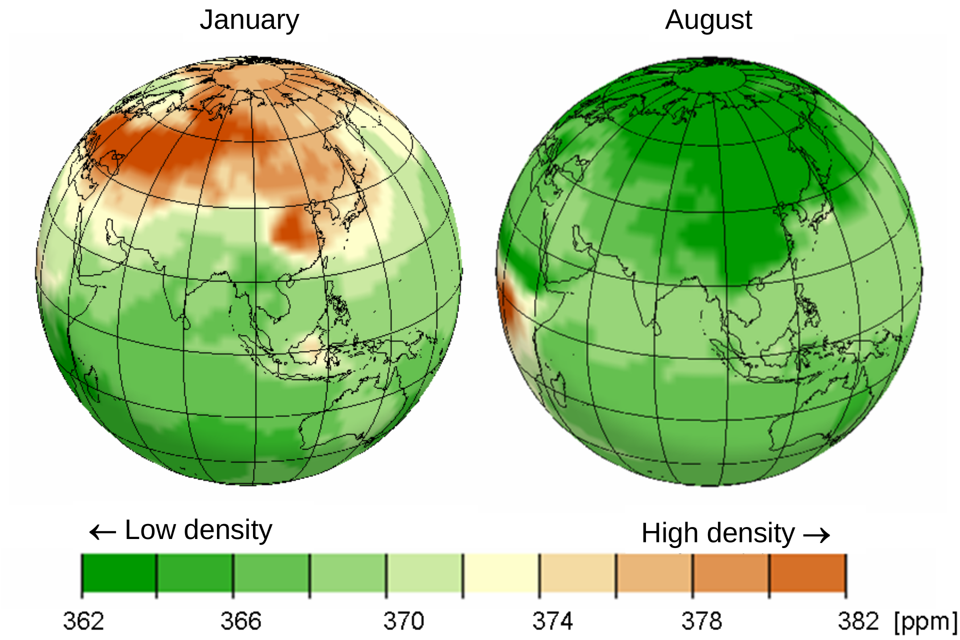

Figure A.2-11 3D global distribution of CO_2 obtained based on the net CO_2 flux distribution using atmospheric transport models

(3) Observation by GOSAT

In case of GOSAT, Figure A.2-12, GOSAT observes visible and SWIR radiation of the sun reflected by the earth's atmosphere and by the earth surface and thermal radiation in TIR band from the earth surface and the atmosphere.

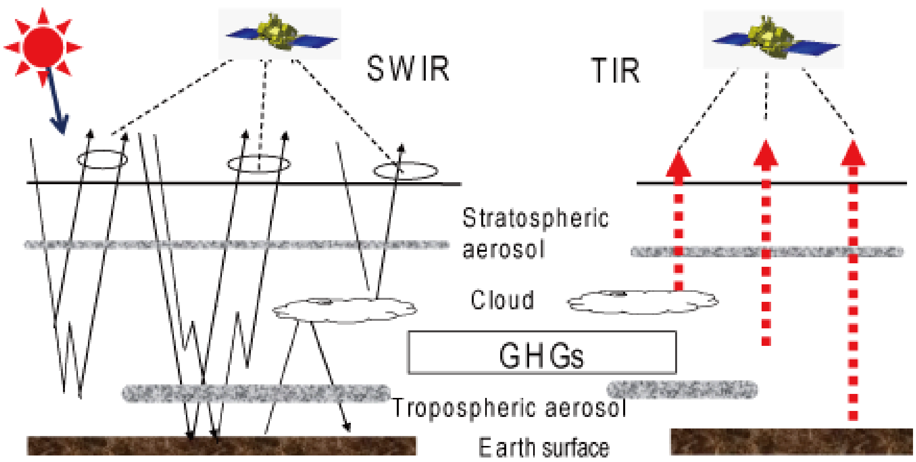

Figure A.2-12 Observation by GOSAT

TANSO-FTS observes the light reflected by the earth in the range covering from visible 0.76 μm to thermal infrared 4.3 μm. (See Figure A.2-13.) The vertical distribution of air temperature is measured in TIR bands, whereas the air pressure can be obtained from the absorption by oxygen molecules (O_2) and the air column abundance is derived by referring to the absorption by O_2, which has much higher concentration remaining constant than CO_2.

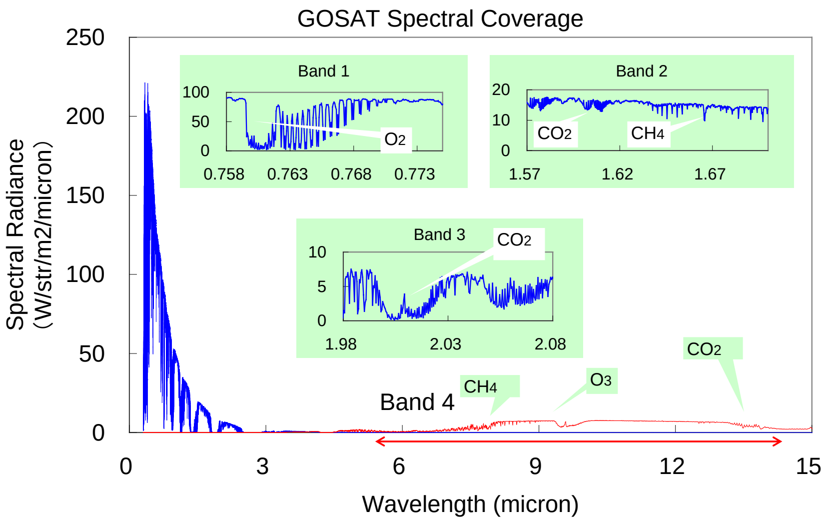

Figure A.2-13 Observation band of TANSO-FTS and air absorption bands

A.3 Overview of GOSAT/TANSO-CAI

A.3.1 Overview of TANSO-CAI

Table A.3-1 below explains the purposes of the TANSO-CAI sensor.

Table A.3-1 Purposes of TANSO-CAI

Purpose 1	Assessment of the effectiveness of FTS footprint area	Determines whether data should be discarded or not in case there is a thick cloud. It is desirable that the cloud thickness can be assessed in addition to the cloud coverage.
Purpose 2	Detection of clouds and aerosols in FTS footprint area and correction of resulting errors	Provides information necessary for correcting the errors caused by clouds and aerosols in FTS footprint area. Evaluates the characteristics of cloud and aerosol (e.g. optical thickness, type). Thus, it is desirable that the spectral characteristics of aerosol can be derived.

TANSO-CAI is expected to derive the types and optical thickness of aerosol of each type. To this end, the bands selected for CAI observation must be those where there is no absorption by atmospheric dominant constituents, and, consequently where the best signal-to-noise ratio (SNR) is attained, and where the spectral characteristics of the optical thickness of aerosols can be observed. In addition, scattering by aerosols is significantly polarized, in general; thus polarimetric observation is preferred. However, as TANSO-CAI observes at a fixed angle very close to the nadir, the degree of polarization is quite low, which makes it difficult to estimate the aerosol amount. Therefore, more stress is put on securing enough number of bands than polarimetric observation in choosing the bands. Given these considerations, the four bands shown in Table A.3-2 were selected for TANSO-CAI.

Table A.3-2 Observation bandwidth of TANSO-CAI and selection criteria

	Criteria
Band 1 (0.380 μm)	No O_3 absorption in the ultraviolet range where reflectance is low on the ground
Band 2 (0.674 μm)	No interference between the rise of reflectance on the vegetation and absorption by O_2 *B* and H_2O bands.
Band 3 (0.870 μm)	No interference with absorption by H_2O
Band 4 (1.60 μm)	The maximum wavelength width is achieved while avoiding the absorption by H_2O, provided that the absorption by CO_2 and CH_4 can be corrected. At the same time, the band should be free of any impact of possible effect on the detector cut-off due to temperature fluctuation.

TANSO-CAI is composed of the following two units.

(1) TANSO-CAI Optical Unit

(2) TANSO-CAI Electrical Circuit Unit

Figure A.3-1 is a block diagram of TANSO-CAI.

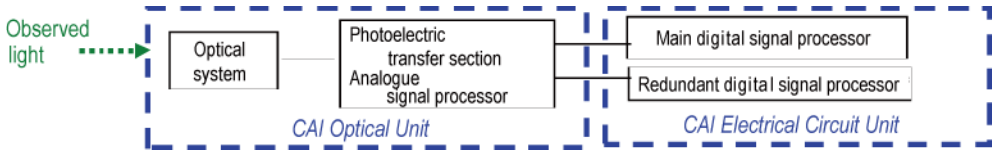

Figure A.3-1 Block diagram of TANSO-CAI

An overview of TANSO-CAI is given in Figure A.3-2 below.

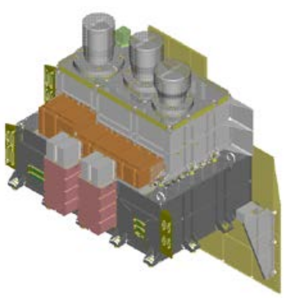

Figure A.3-2 Overview of TANSO-CAI

A.3.2 Specifications of TANSO-CAI

(1) Bandwidth and performance

Table A.3-3 below summarizes the specifications of TANSO-CAI.

Table A.3-3 Specifications of TANSO-CAI

	Band 1	Band 2	Band 3	Band 4
Center wavelength (μm) (Note 1)	0.380 ± 0.005	0.674 ± 0.005	0.870 ± 0.005	1.60 ± 0.01
Wavelength width (μm) (Note 1)	<0.02	<0.02	<0.02	<0.10
Out-of-band characteristics (i) (μm)(Note 2)	1% or lower in the ranges of <0.36 and >0.4	1% or lower in the ranges of <0.658 and >0.692	N.A.	1% or lower in the ranges of <1.0 and >1.69
Out-of-band characteristics (ii) (μm)(Note 2)	N/A	1% or lower in the range of >0.696	1% or lower in the ranges of <0.840 and >0.890	N/A
Out-of-band characteristics (iii) (μm)(Note 3)	0.15% or lower in the range of >0.45	N/A	N/A	N/A
Out-of-band characteristics (iv) (μm)(Note 3)	0.03% or lower in the range of >0.7	N/A	N/A	N/A
Polarization	None			

Note 1: The center wavelength and wavelength width are specified based on the first and second moments, taking into consideration the spectral characteristics of the optical system, filters and detectors for an overall efficiency.

Note 2: The sensitivities in the range specified in 'out-of band (i)' should be lower than 1% of that at the central wave length, and the sensitivity in the range specified in 'out-of-band (ii)' should be lower than 0.1% of that at the central wave length in order to avoid the H_2O absorption band in the above described bands.

Note 3: The sensitivity in the range specified in 'out-of-band (iii)' must be 0.15% or lower and in the range specified in 'out-of-band (iv)' 0.03% or lower, of that at the corresponding center wavelength.

(2) Instantaneous FOV and the look angle in the cross-track direction

The instantaneous FOV is set at 500 m (in Bands 1, 2, 3) and 1.5 km (in Band 4) at the nadir point. The look angle in the cross-track direction is set at ±35 degrees, with which the sensor can observe the entire globe during daylight hours in three days except band 4. Figure A.3-3 below illustrates the geometries of the instantaneous FOV and the normal FOV.

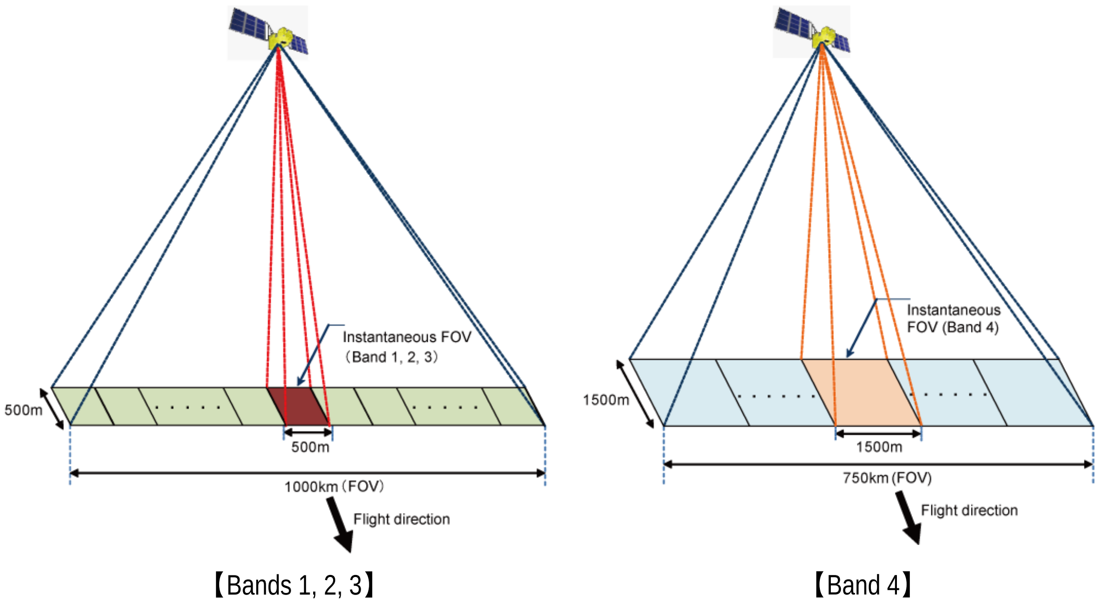

Figure A.3-3 Instantaneous and normal FOV of TANSO-CAI

A.3.3 Observation mechanism of TANSO-CAI

The column abundances of CO_2 and CH_4 are derived from the amount absorbed in the optical path between the sun, the ground surface and the satellite. The path length is obtained through the amount of absorption for the 0.76 μm band by O_2 whose density is known, with TANSO-FTS. As cloud or aerosol on the path affect the effective path length, correction is needed if there is any. In order to improve the accuracy of correcting errors caused by clouds and aerosols, electronic scanning imagers with multiple bands covering ultraviolet, visible and short wavelength infrared bands are installed, which also make it possible to observe cloud coverage and aerosols over the land and ocean areas. The FOV in the cross-track direction is used for ascertaining the spatial distribution of aerosols over a wide range (1,000 km).

Registration between TANSO-FTS and TANSO-CAI data should be performed after the launch using the FOV check camera installed in the TANSO-FTS sensor. Figure A.3-4 shows a sample of CAI observation data.

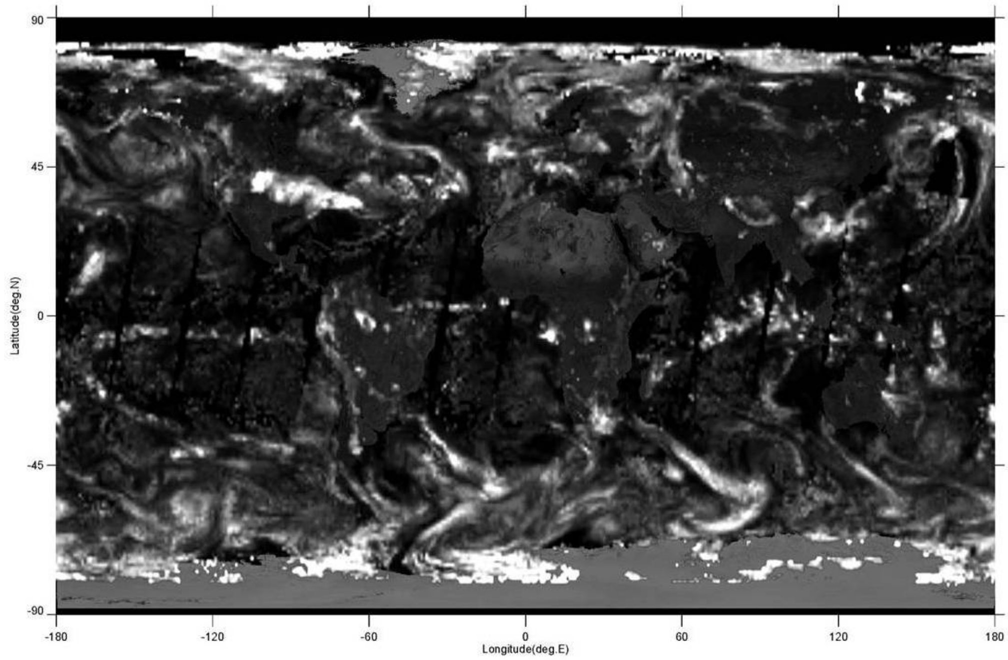

Figure A.3-4 A CAI observation image (equivalent to Band 2)
generated based on MODIS data