International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

Fourier transform spectrometer on GOSAT and GOSAT-2

M. Nakajima

Hiroshi Suto

K. Yotsumoto

K. Shiomi

et al.

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105634O · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304062

FOURIER TRANSFORM SPECTROMETER ON GOSAT AND GOSAT-2

M. Nakajima[1], H. Suto[1], K. Yotsumoto[1], K. Shiomi[1], T. Hirabayashi[1]
[1]*Japan Aerospace Exploration Agency,Japan*
[1]*2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505 Japan*
nakajima.masakatsu@jaxa.jp

I. INTRODUCTION

In January of 2009, GOSAT which is the first satellite dedicated to observing greenhouse gases, that is Carbon Dioxide and Methane was launched. GOSAT stands for Greenhouse Gases Observing Satellite.

GOSAT is loaded with two mission instruments which are called TANSO which stands for Thermal and Near Infrared Sensor for Carbon Observation altogether, and one of TANSO is Fourier Transform Spectrometer (FTS) which is the main instrument to observe the carobon dioxide and methane and another one is Cloud and Aerosol Imager (CAI) whose data are used to compensate the FTS data..

GOSAT has been operated on orbit over five and half years and has accomplished the accuracy targets. Therefore it has provided a lot of useful scientific data sets to users and interesting articles for carbon source and sink evaluation have been produced and published.

The data acquired globally are believed to be useful for the research about the global phenomena, and these results have been supporting to well understanding of carbon cycle. Currently, the importance of space-based carbon observation has been approved and desired the continuous observation in toward

On the other hand, we learned through the GOSAT operation that the data accuracy is not enough for the political use such as the global warming countermeasures and what we should improve in the following mission to meet political requirements regarding the measurement instruments, processing algorithm and so on.

Our experiences regarding observation performances as well as hardware design were reflected on the mission requirements on GOSAT-2.

The requirements on GOSAT-2 observation are improvements of the observation performance of the FTS such as signal to noise ratio, increase of the number of the useful data and addition of the carbon monoxide observation band for a good understanding of CO2 and CH4 sources and sinks to elucidate the carbon cycle more precisely. The cloud and aerosol imager, CAI, data on GOSAT have been used to compensate the FTS data for the aerosol and to detect clouds. And the CAI-2 for GOSAT-2 will have the additional observation channels to reinforce the aerosol observation abilities and observes the air pollution.

Based on the feasibility studies, the hardware system requirements were defined and the design was started.

Table 1 shows the principal specification of GOSAT and GOSAT-2. GOSAT-2 is now under development and the specifications are tentative right now.

II. THE FOURIER TRANSFORM SPECTROMETER(FTS) ON GOSAT:

A. Outline of the FTS on GOSAT

The FTS on GOSAT has three spectral bands in the SWIR, ShortWave InfraRed, region and one spectral band in the TIR, Thermal InfraRed, region, and measure the SWIR radiance reflected from the earth's surface with two linear polarized light and TIR radiated by the ground and the atmosphere. The wavelength range of the three bands in SWIR, band 1,2 and 3, are 0.758 to 0.775μm, 1.56 to 1.72 μm and 1.92 to 2.08μm, respectively, and the one of the TIR, band 4, is 5.56 to 14.3 μm.

Table 1. Specifications of GOSAT and GOSAT-2

Size (H*W*D)		3.7m x 1.8m x 2.0m (Wing Span 13.7m)	5.3m x 2.0m x 2.1m (Wing Span 13.7m)
Mass		1,750 kg	1700 kg
Power		3.8 kW	5.0 kW
Life Spac		5 years	5 years
Orbit		sun synchronous orbit	sun synchronous orbit
	Local time	13:00+/-0:15	13:00+/-0:15
	Altitude	666km	613 km
	Inclination	98deg	98deg
	Recurrent Period	3 days	6 days
	revolution	44 (14 2/3 a day)	89 (14 5/6 a day)

The sampling interval of the interferogram is 0,2cm-1, and the spectral resolution, defined as the full width of half maximum (FWHM) of the instrument line shape(ILS), is lower than 0.6cm-1 for band 1 and lower than 0.27cm-1 for band two to four. The concentrations of CO_2 and CH_4, that is XCO_2 and XCH_4 are mainly retrieved from 1.6μm and 2.0μm band coupled with O_2A band (0.76μm).

Table 2 shows the major specifications of the TANSO-FTS.

The measurement targets of the GOSAT is to observe CO_2 and CH_4 column density with relative accuracy of 1 % for CO_2 and 2 % for CH_4 at 1,000 km square spatial scale and in 3 months average.

B. Details of the FTS on GOSAT

TANSO-FTS on GOSAT consists of three units, Optical Unit, Control Unit and Electrical Circuit Uni. Fig.1. shows a block diagram of TANSO-FTS. The optical Unit consists of a pointing mechanizm, a monitor camera, relay optics, a FTS mechanism, detectors and analog signal processors. The optical configuration including the band separation anad detector optics is illustrated in Fig. 2.

Two-axes pointing mechanism rotating in the cross track and along track direction is used to point the line of sight to the target points, solar diffuser, black body and deep space as well as compensating the image motion due to the satellite orbiting.

Two pointing mechanisms are installed and one of them is redundant one.

Driving the pointing mechanism is performed according to the on-board table uploaded to the satellite.

A small two-dimensional CMOS camera whose spacial resolution is 50m and FOV is 30km by 30 km which is about three times of the FOV of the FTS is installed in the FTS coaxially adjusted to the optical axis of the FTS to monitor the field of view of the FTS. The monitor camera images are acquired coincident with the FTS data acquisition.

Table 2. the major specifications of TANSO-FTS

Items		Band 1	Band 2	Band 3	Band 4
Ground Pointing Mechanism and Fore Optics	configuration	2-axes pointing mirror (fully redundant) for ground pointing, calibration and IMC(Image Motion Compensation)			
	pointing (line of sight)	Cross Track:±35 deg, Along Track: ±20 deg,			
	Field of Voew	IFOV : 10.5kmϕ			
	distance between observation points	160km (in 5 points observation mode)			
Fourier Transform Spectrometer	Scan Speed	4, 2, 1.1 seconds/interferogram			
	observation bands	0.75-0.78μm	1.56-1.72μm	1.92-2.08μm	5.5-14.3μm
	sampling resolutioon	0.2 cm-1			
	Detector	Si	InGaAs	InGaAs	PC-MCT
	Calibration	Solar Irradiance, Deep Space, Moon, Diode Laser(ILS,1.55μm)			Black Body Deep Space

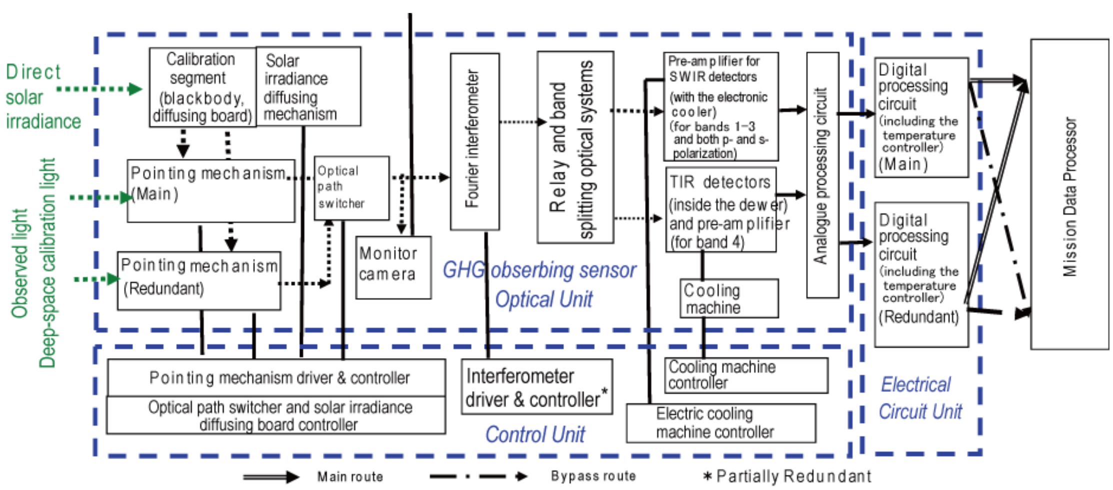

Fig. 1. Block Diagram of TANSO-FTS on GOSAT

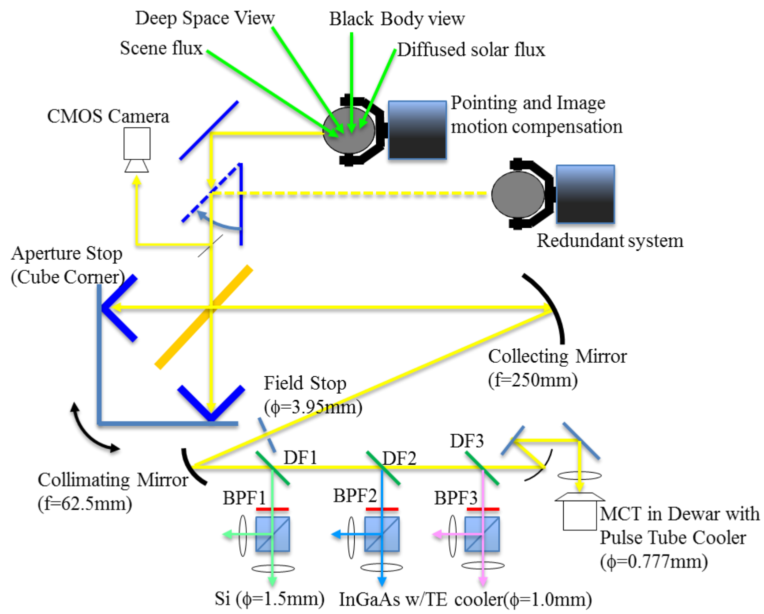

Fig. 2. Optical Configuration of the optical Unit

FTS mechanism is a double pendulum type interferometer with two cube-corner reflectors made from three gold-plated Zerodur plates on an invar structure, which creates a ±2.5cm optical path difference (OPD). The two cube-corner reflectors are mounted at the edges of a V-shape arms as indicated by the Fig. 3. These cube-corner reflectors are carefully aligned with each other to permanently maximize modulation efficiency with the minimum optical shear. The surfaces of the cube-corner reflectors are better than λ = 20 (RMS) at 633 nm. A maximum beam divergence smaller than 1 arc sec shows excellent orthogonality. The backsides of the cube-corner reflectors are gold coated to minimize thermal radiation coupling with the environment. The thickness of the beam splitter is selected to be larger than the maximum OPD to avoid channeling, and its surface has high quality (better than λ = 20 at 633 nm) and no AR coating to maintain high optical efficiency over a wide spectral range. Bare Zn–Se material has a spectrally flat index of refraction and transmittance higher than 65% over the wide spectral region from 0.76 to 15 µm. Modulation efficiency is a key parameter to characterize the FTS performance, especially at SWIR. In general, modulation at shorter wavelengths is lower and FTS application becomes more difficult. With careful manufacturing and screening of the optical components, the modulation efficiencies are 70±3% at 13,200 cm^{-1}, 91±3% at 6200 cm^{-1}, and 95±3% at 5000 cm^{-1} PFM).

The swing arm is mounted on the beam splitter holder with a flexible blade.

A fully redundant metrology sampling system using 1.31µm distributed-feedback (DFB) lasers and two InGaAs detectors is used to sample the signal. The temperature of these diode lasers are controlled up to 0.001°C above or below 25.000°C using thermoelectric controller because the diode laser wavelength depend on the temperature strongly. The actual wavelength stability ($\Delta\lambda/\lambda$) is better than 10^{-7}.

All optical components making up the optical unit are mounted on the optical bench whose temperature is maintained within the range from 20˚C to 26 ˚C. This optical bench is mounted on the satellite structure with three kinematic mounts to isolate the thermal distortion.

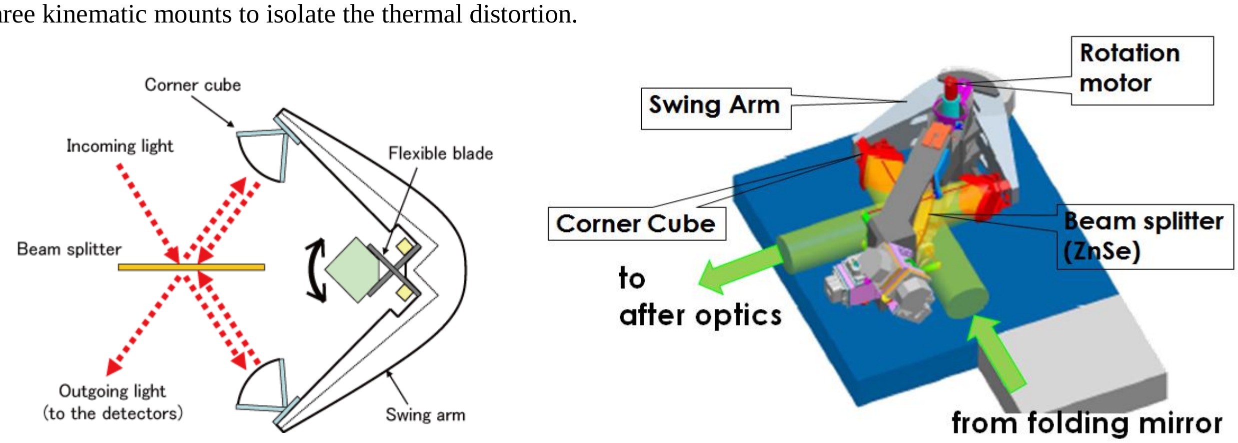

Fig. 3. FTS mechanism of TANSO-FTS and Swing arm and cube-corner reflector

The scene flux passed the FTS mechanism is steered into the after optics(shown in Fig. 4), and is drawn in order of increasing wavelength. The each drawn scene flux is divided into two polarizations except Band 4.

Layout of the components in the Optical Unit of the TANSO-FTS is shown in the Fig. 5.

The after optics and detector unit including the pre-amp are mounted on the separate small bench from large one that other optics are mounted, and this small bench is mounted on the large one.

The black body and the window to see the deep space for calibration are mounted on the side wall and the pointing mechanism is rotated about 90 degrees to see them.

The solar diffuser are mounted on the top cover and the solar ray scattered on the diffuser is observed for solar irradiance calibration.

C. THE ANOMALIES OF TANSO-FTS ON GOSAT ON ORBIT

After the launch, TANSO-FTS on GOSAT has encountered several anomalies. And we have investigated the root cause of these anomalies to reflect on the design of GOSAT-2.

(1) Unstable behavior and offset of pointing mirror

TANSO-FTS steer the line of sight using pointing mirror with two axes which works as the IMC, too, to sees the identical point continuously during data acquisition. And two anomalies had happened to this mechanism.

One is the pointing offset which is the phenomenon that FTS sees the slightly shifted place from the planned targtet. We are considering that this had been caused by three root causes listed in the table 3.

Another one is the pointing mirror wobble. This phenomenon has happened at the specific AT angle and it's assumed that this wobble is caused by the dead band of the control system.

The unstable motion of the pointing mirror affect the motion of the scan arm of the FTS and the ZPD position.

The data acquired when the pointing mirror wobble happened are excluded from the processing.

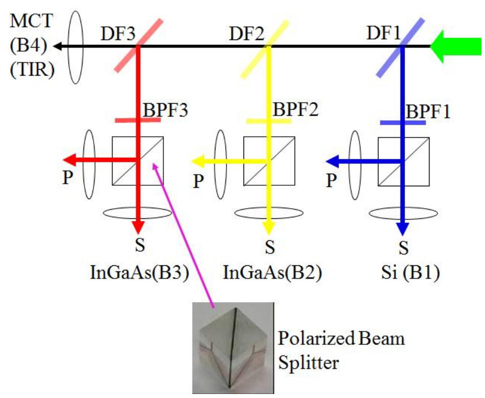

Fig. 4. The after optics of TANSO-FTS

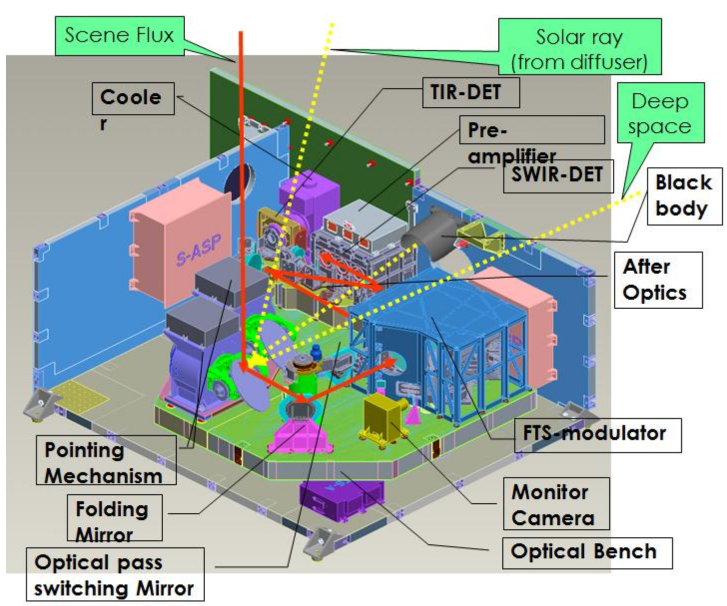

Fig. 5. Layout of the Components in the Optical Unit of the TANSO-FTS on GOSAT

(2) Sampling laser signal level decrease and ZPD shift

The output of sampling laser is travelling to the detector through the FTS and the scene signal is sampled at the zero cross points of the interference wave of the sampling laser. And this becomes the trigger of the turn around of FTS by counting the zero cross point. It is recognized that the output signal of this laser has declined. It's assumed that this has been caused by the alignment shift of the pick up mirror glued to the pedestal in the optical path of the sampling laser due to the moisture desorption from the adhesive. This laser signal level decrease has caused the ZPD position shift combined with the pointing mirror wobble. The extension of the ZPD shift brings the degradation of the spectral resolution, so it has been corrected the ZPD position when the shift exceed the 40 counts.

(3) unequally-spaced sampling

The unequally-spaced sampling has happened due to the misalignment of the swing arm in the FTS mechanism. This anomaly causes the degradation of the spectral resolution.

(4) anomalies in the analog signal processor

A few anomalies were found in the analog signal processor. One is the non linearity of low pass filter caused by the capacitors and unoptimized circuit design. This non linearity was evaluated and reflected on the level one algorithm. Another one is the missing bit and non linearity of the ADC. But this anomalies have not affected the products derived from the data obtained in the gain H. But the one obtained in gain M may be affected, so we will investigate in detail.

Table 3 shows the summary ot the anomalies happened on the GOSAT.

III. THE FOURIER TRANSFORM SPECTROMETER(FTS) ON GOSAT-2:

A. Requirements for GOSAT-2 mission

GOSAT has accomplished the accuracy targets, but on the other hand, we learned a lot of things on the instruments, processing algorithm and so on through the GOSAT operation, and we understood what we should improve in the following mission, and our experiences regarding observation performances as well as hardware design were reflected on the mission requirements on GOSAT-2. The principal requirement is to estimate the Carbon Dioxide flux with the accuracy of ±100% which means that it's possible to distinguish between source and sink accurately. In addition to this requirement, it was required to evaluate the method to determine the anthropogenic emission. So the measurement accuracy required to meet these mission were studied and the target of the GOSAT-2 observation were defined as below.

Table 3. Anomalies happened on the GOSAT

components	issue	root cause	reflection on GOSAT-2
Ground Pointing Mechanism	pointing offset	anomaly of the bearing behavior	use other mechanism which is space proven without dead band
		anomaly of the resolver	
		shift of the rotate axis	
	unstable pointing mirror behavior at a specific angle	dead band of the control system	
Fourier Transform Spectrometer	decrease of the intensity of the sampling laser	shift of the tilt of pick up mirror	adoption of the monolithic pick up mirror
	unequally-spaced sampling	misalignment of the swing arm(flexible pivot)	change the requirement for the component
	the shift of ZPD position	decrease of the intensity of the sampling laser	countermeasures to the decrease of the intensity of the sampling laser
	backup method of sampling	(as the back up of the sampling laser problem)	adopt angular sensor to detect the arm position as the sampling backup
	influence of the micro vibration	the consistence of the natural frequency of the FTS scan arm with the vibration frequency of the satellite	-design change to shift the natural frequency of the scan arm -optimization of the delay time
signal processor	non linearity of low pass filter	analog circuit characteristic bad capacitor	change of the design and capacitor
	missing bit of ADC / non linearity of ADC	the characteristic of ADC	use other type of ADC

(1)Improvement of the concentration precision
GOSAT-2 aims at 0.5 ppm for CO2 and 5 ppb for CH4 in 1 month at 500km mesh over the land and 2000km mesh over the ocean. This is the accuracy which is required to meet the requirement for the estimation accuracy of Carbon Dioxide flux.
(2)Improvement of the estimation accuracy of Flux
The requirement for GOSAT was to reduce the estimation error to half. But even if the estimation error becomes half, the discrimination between source and sink is contrary to the actual one in some area. So it was required to distinguish source and sink correctly. "+/-100%" means that it's possible to distinguish source from sink. This is applicable to the area where the source and sink is over +/-0.2GtC/year/area.
(3)Estimation of the anthropogenic emission
It's expected that the measurement of the correlated matter is useful to distinguish the anthropogenic emission from the natural emission. So we will examine the feasibility of the anthropogenic emission estimation with the observation of CO.
(4)Monitoring of the aerosols
GOSAT-2 will aim to calcurate the optical thickness of the aerosols at 550nm and 1.6 micrometer with 0.1 accuracy. And the Ångström exponent will be calculated with the accuracy of 0.3 to estimate the Particle Matters with the accuracy of $20 mg/m^3$ and black carbon with the accuracy of 10%.
Table 4 shows the observation targets of GOSAT-2 compared with GOSAT.

B. Measurement Requirement for TANSO-FTS-2 on GOSAT-2

It's necessary to improve the observation performances of the FTS such as signal to noise ratio, the number of the useful data and addition of the carbon monoxide observation band to meet the targets of the GOSAT-2 mission. Not only the performance of the FTS but also the one of the cloud and aerosol imager, CAI, data should be improved because the CAI data are used to compensate the FTS data for the aerosol and to detect clouds. And the CAI-2 for GOSAT-2 will observe the additional observation channels to reinforce the aerosol observation abilities and observes the air pollution. In this paper, CAI-2 is not mentioned.
Based on the feasibility studies, the hardware system requirements were defined and the design was started.
Table 5 shows the principal specifications of TANS-FTS-2 on GOSAT-2 compared with FTS on GOSAT.

C. Approaches to Achieving the targets

To achieve the mission targets, it's necessary to improve the concentration measurement precision of the CO2 and CH4. And the targets of the measurement precision is defined by the average in the area. So it's effective to increase the number of the useful data and the signal to noise ratio of each data.
(1)Increase of the number of the useful data
Even if the cloud in the FOV is small, those data have been eliminated from the processing, and large part of the GOSAT data haven't been processed. So the number of the useful data of GOSAT have been reduced. Therefore GOSAT-2 will equipe the function to detect the cloud in the FOV and steer the line of sight to the cloud free area.
(2)Increase of the SNR of each data
To incease the signal level, we will expand the effective aperture size to 73mm from 64mm of GOSAT. The wavelength of the band 1 is around 760nm, and the sampling laser wavelength is 1.31μm, that is, the scan signal is sampled every 0.655μm. So the aliasing has affected the SNR. Therefore the over sampling will be adopted for the band 1 to avoid the aliasing. The spectral region of band 1 and 2 will be changed based on the results of GOSAT observation, and the spectral region of band 3 was expanded to include the absoption lines of CO. TIR region was devided into two bands to increase the SNR of the shorter wavelength region. The spectral range of TIR bands may be changed to increase the SNR of band 5.
The SNR of band 1 is required to exceed 400 to improve the O2A and chlorophyll fluorescence information.
The Scan duration of 2 and 1.1 seconds have not been used in GOSAT operation. So to simplify the design of the electronics of TANSO-FTS-2, only 4 second scan time will be adopted. In addition to the increase of the performance and function regarding the observation, the results of the investigation of the anomalies happened to TANSO-FTS on GOSAT will be reflected on the design of GOSAT-2. These are summarized in the table 3.

D. TANSO-FTS-2 Design Features

(1)TANSO-FTS-2 Intelligent pointing
Monitor camera whose optical axis is coaxially adjusted to the line of sight of the FTS has 50km by 30 km FOV and GSD is 500m. And the clouds in the FOV will be detected and the cloud free area which is larger than the circle with a diameter of 9.7km is selected. And the line of sight of FTS will be steered to the cloud free

area by the scan mirror. It's possible to rewrite the cloud detection software on orbit, so we are considering to improve the cloud detection algorithm through the GOSAT-2 on-orbit operation. Fig. 6 shows the conept of the intelligent pointing.

(2)The base of the TANSO-FTS-2 design

The TANSO-FTS-2 uses the heritage of CrIS which is the thermal infrared interferometer launced about three years ago. So A lot of components are same as CrIS and will be changed from the first TANSO-FTS. But the FTS mecjanism is different from CrIS. CrIS adopted the flat mirror interferometer, on the other hand, TANSO-FTS-2 will adopt the cube-corner type interferometer which is almost same design as the one of TANSO-FTS on GOSAT except the cube-corner size and relevant parts. Whereas the flat mirror type has the advantage that it's easy to expand the aperture and increase the signal, corner-cube type has the advantage having strong resistance to the alignment shift.

Table 4. Observation targets of GOSAT-2

issue	GOSAT-2	GOSAT
improvement of concentration measurement precision	0.5 ppm (CO2) 5 ppb (CH4) - 1 month - 500 km mesh (land) - 2,000 km mesh (ocean)	4 ppm (CO2) 34 ppb (CH4) - 3 months - 1,000 km mesh (land)
improvement of the estimation accuracy of flux	estimate the monthly net fluxes with the accuracy of ±100% - 1,000 km mesh (land) - 4,000 km mesh (ocean)	reduce the annual estimation error to half compared with the existing estimation error -sub-continental scale
estimation of the anthropogenic emission	examine the feasibility of the estimation of the anthropogenic emission with the observation of CO which is the correlated matter	----------
monitoring of the aerosols in the atmosphere	calculate the optical thickness of the aerosols at 550nm and 1.6mm with 0.1 accuracy	----------

Table 5. Principal specifications of TANSO-FTS-2 on GOSAT-2 compared with FTS on GOSAT

Items	GOSAT-2	GOSAT
Measurement Gases	CO2, CH4, O3, H2O, CO	CO2, CH4, O3, H2O
FOV/number	9.7 kmϕ	10.5 kmϕ
Spectral Ranges (μm)(cm-1)	band 1 : 0.75- 0.77 (12,950-13,250) band 2: 1.56- 1.69 (5,900-6,400) band 3: 1.92- 2.33 (4,200-5,200) band 4: 5.5- 8.4 (1,188-1,800) band 5: 8.4- 14.3 (700-1,188)	band 1: 0.75-0.77 (12,900-13,200) band 2: 1.56-1.72 (5,800-6,400) band 3: 1.92-2.08 (4,800-5,200) band 4: 5.5-14.3 (700-1,800)
SNR	band 1: 528 (P@13,050cm^{-1}) (>400) band 2: 617 (P@6,200cm^{-1}) (>300) band 3: 454 (P@5,000cm^{-1}) (>300) 489 (P+S@4,250cm^{-1}) (>300) band 4: 1519 (@1,300cm^{-1}) (>300) band 5: 306 (@700cm^{-1}) (>300)	band 1: 345 (>300) band 2: 322 (>300) band 3: 412 (>300) band 4: 304 (>300)
Observation Mesh	160km (5 points in the CT direction)	160km (5 points in the CT direction)
Scan duration	4 seconds / interferogram	4, 2, 1.1 seconds / interferogram
Sampling resolution	0.2cm^{-1}	0.2cm^{-1}
Effective Aperture size	Φ73mm	Φ64mm
Gain steps	16	2
Quantization	14 bits (16 bits equivalent by over sampling)	16 bits
Avoidance of the cloud	Intelligent pointing	-------

The largest different point from TANSO-FTS is cooler. TANSO-FTS has adopted pulse tube type mechanical cooler, but TANSO-FTS-2 will adopt the passive cooler. This will be contribute to the reduction of the micro vibration which will affect the motion of the FTS.

Fig. 7 shows the TANSO-FTS-2 image and Fig. 8 shows the base components of the TANSO-FTS-2.

IV. CONCLISION:

Fourier Transform Spectrometer on GOSAT is the first FTS which observe the SWIR region from space, and all of the observation targets had been satisfied. On the other hand, a lot of issues have been made clear such as the hard wear behavior as well as the data accuracy which is necessary for the political use.

So new requirements for the greenhouse gases observation from space had been presented.

And GOSAT-2 mission was started.

GOSAT-2 adopts the same measurement method as GOSAT, that is Fourier Transform Spectrometer with cube-corner reflector.

To improve the measurement accuracy, the signal to noise ratio will be improved and the number of the useful data will be incresed.

To satisfy these improvements, the size of the cube-corner reflector, that is the effective aperture size will be expanded, and the intelligent pointing which is the function to avoid the clouds.

We intend to launch GOSAT-2 in 2017 Japanes Fiscal Year.

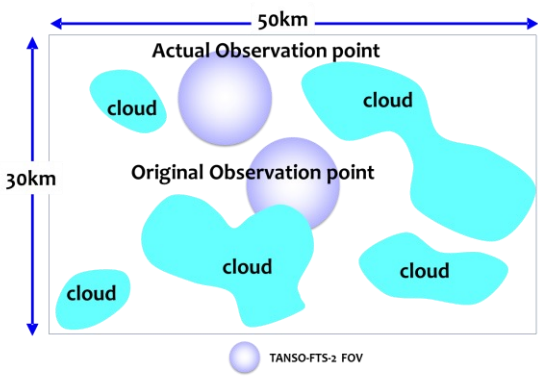

Fig. 6 concept of the intelligent pointing

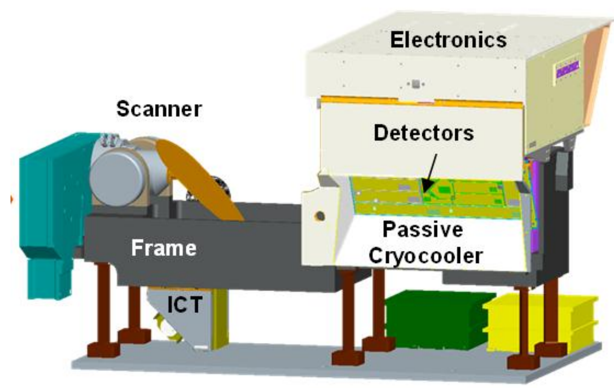

Fig. 7. Image of TANSO-FTS-2

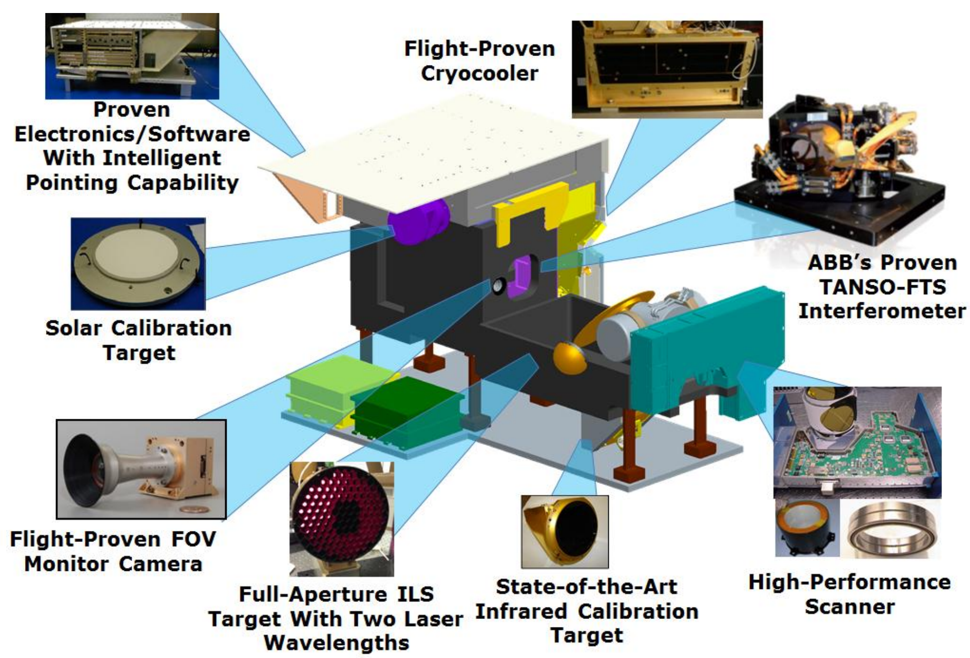

Fig. 8 Base components of TANSO-FTS-2 design