Science Bulletin 63 (2018) 1200–1207

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Article

The TanSat mission: preliminary global observations

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ARTICLE INFO

Article history:
Received 28 April 2018
Received in revised form 9 August 2018
Accepted 10 August 2018
Available online 16 August 2018

Keywords:
TanSat
Carbon dioxide
Retrieval algorithm
Carbon flux inversion

ABSTRACT

The Chinese global carbon dioxide monitoring satellite (TanSat) was launched successfully in December 2016 and has completed its on-orbit tests and calibration. TanSat aims to measure the atmospheric column-averaged dry air mole fractions of carbon dioxide (XCO_2) with a precision of 4 ppm at the regional scale, and in addition, to derive global and regional CO_2 fluxes. Progress towards these objectives is reviewed and the first scientific results from TanSat measurements are presented. TanSat on-orbit tests indicate that the Atmospheric Carbon dioxide Grating Spectrometer is in normal working status and is beginning to produce L1B products. The preliminary TanSat XCO_2 products have been retrieved by an algorithm and compared to NASA Orbiting Carbon Observatory-2 (OCO-2) measurements during an overlapping observation period. Furthermore, the XCO_2 retrievals have been validated against eight ground-site measurement datasets from the Total Carbon Column Observing Network, for which the preliminary conclusion is that TanSat has met the precision design requirement, with an average bias of 2.11 ppm. The first scientific observations are presented, namely, the seasonal distributions of XCO_2 over land on a global scale.

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1. Introduction

Carbon dioxide (CO_2) can be released into the atmosphere by anthropogenic activities and biological respiration, while it is absorbed from the atmosphere via processes that occur at both land and ocean surfaces, such as photosynthesis by vegetation. Since the beginning of the industrial age, humans have disrupted the carbon balance by using fossil fuels and through deforestation. The increase in atmospheric CO_2 concentrations has resulted in global warming and subsequently, climate change.

Many ground-based stations make up networks that observe atmospheric CO_2 concentrations from the surface, offering accurate CO_2 measurements around the world. Compared to ground-based observations, monitoring atmospheric CO_2 from space, using near infrared (NIR) and shortwave infrared (SWIR) spectra, can provide the global distribution of CO_2 with high accuracy and precision, which helps to improve our understanding of CO_2 fluxes (i.e., sources and sinks). One of the main approaches for the inversion of surface carbon fluxes, namely, the top-down method, tries to assimilate column CO_2 concentration measurements to constrain surface CO_2 fluxes. The distribution of surface CO_2 fluxes improves understanding of the carbon cycle. The first satellite to measure atmospheric column-averaged dry air mole fractions of carbon dioxide (XCO_2) was the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) onboard ESA ENVISAT [1–3]. A new generation of instruments and satellites is required for future greenhouse gas (GHG) monitoring. In 2009, the Japanese Greenhouse Observing Satellite (GOSAT) was successfully launched and it has become the first GHG monitoring satellite with an on-orbit operation time of more than 9 years [4–6]. Following this, the NASA Orbiting Carbon Observatory 2 (OCO-2) was launched in July 2014 [7–9].

Studies of the assimilation of GOSAT data using different inverse models and different retrieval algorithms have demonstrated the impact of satellite measurements on the CO_2 surface flux estimation. GOSAT data have been confirmed to significantly improve our knowledge of the CO_2 surface fluxes over terrestrial vegetated areas [10,11]. The Observation System Simulation Experiment (OSSE) on OCO measurement also indicated consistent results [12]. However, in flux inversion, regional biases of only a few tenths of a part per million in XCO_2 can result in yearly

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https://doi.org/10.1016/j.scib.2018.08.004
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sub-continental fluxes biased (in the opposite direction) by a few tenths of a gigaton of carbon [13–15]. Simulations indicate that the measurements from space can significantly improve CO_2 flux estimates if they meet the required accuracy and precision [16]. Therefore, the accuracy and precision of CO_2 measurements from space is a critical constraint on satellite design and manufacture.

As the largest developing country, China faces serious problems from GHG emissions. To pursue sustainable development and reduce GHG emissions, quantification of the carbon budget at global and regional scales is critical and has become a significant challenge. The Chinese Global Carbon Dioxide Monitoring Scientific Experimental Satellite (TanSat) was established by the National High Technology Research and Development Program of China (863 Program). The main objective of TanSat is to monitor the XCO_2 distribution and CO_2 fluxes at regional and global scales [17,18]. In December 2016, TanSat was successfully launched and commenced on-orbit tests and calibration.

2. TanSat mission

2.1. Instruments and requirements

TanSat is an agile satellite platform deployed in a sun-synchronous orbit, which operates in three observation modes, namely, nadir, sun-glint, and target. The nadir mode is the most common one used over land surfaces, in which the instrument records data along the satellite ground track. The ocean surface has low surface reflectance and thus the nadir mode cannot yield high-precision measurements due to the low signal-to-noise ratio (SNR). To deal with this problem, the satellite tracks the sun glint spot, where sunlight is reflected specularly from the ocean, with the instrument boresight pointed within five degrees of the principal plane. TanSat also has a target mode that observes a stationary surface target as the satellite flies overhead. The main purpose of this mode is to validate measurements with ground-based observations, but it can also record multi-angle ($-60°$ to $60°$) observations over one surface target to investigate emissions from hot spots. These measurements can also be compared to ground-based observations to validate the quality of the satellite CO_2 measurements. There are two scientific instruments onboard TanSat, namely, a hyperspectral grating spectrometer (Atmospheric Carbon dioxide Grating Spectrometer, ACGS) and a moderate-resolution imaging polarization spectroradiometer (Cloud and Aerosol Polarization Imager, CAPI).

2.1.1. Atmospheric Carbon Dioxide Grating Spectrometer (ACGS)

ACGS is the primary instrument onboard TanSat and is designed to measure NIR/SWIR backscattered sunlight in the molecular oxygen (O_2) A-band (0.76 μm) and two CO_2 bands (1.61 and 2.06 μm). Total column CO_2 is mainly determined from measurements of its absorption lines in the weak band (1.61 μm). Sunlight is significantly scattered and absorbed by air molecules and suspended particles (e.g., clouds and aerosols), which results in serious errors in CO_2 retrievals. In the approach pioneered by the SCIAMACHY, GOSAT, and OCO-2 teams, determining CO_2 from the weak band measurement alone cannot avoid this interference. More information from cloud and aerosol measurements is required in the retrieval to correct the light path. Therefore, a light path correction factor is employed, which is represented by surface pressure as follows:

$$XCO_2 = \frac{\int_{p_0}^{0} \left[n_{\mathrm{CO_2}}(p)\right]_p \mathrm{d}p}{\int_{p_0}^{0} [n_{\mathrm{air}}(p)]_p \mathrm{d}p}, \tag{1}$$

where $n_{\mathrm{CO_2}}$ and n_{air} are the mole fractions of CO_2 and dry air, respectively, while the square brackets indicate the molecular fraction per unit variation in dry pressure. The integration actually represents the total column of CO_2 and dry air. The surface pressure p_0 impacts both the O_2–A and CO_2 bands at the same time, which means that the correction for cloud and aerosol interferences is the same in all bands. The O_2–A band contains some information about the altitude and total amount (optical depth) of aerosol and cloud due to almost constant and stable constant O_2 concentration [19]. In comparison, the interference from water vapor absorption is relatively weak. However, the CO_2 weak band is spectrally far away from the O_2–A band, and aerosol and cloud optical properties depend on wavelength. One of the purposes of the strong CO_2 band is to constrain this variation. The strong CO_2 band also provides information on water vapor and temperature, which reduces impacts from uncertainties in these parameters.

The design of the optical layout of ACGS and the specifications of instrument optical parameters can be found in a previous study [20]. The footprint is 2 km × 2 km in the nadir mode with nine footprints in each swath, while the total width of the field of view (FOV) is 18 km. Liu et al. [21] discussed the impact of spectral resolution and under-sampling effects on XCO_2 retrieval precision introduced by using a 500-pixel detector in both the weak and strong CO_2 bands. Finally, we decided to reduce the spectral resolution to satisfy the sampling rate, and hence the SNR is better than in the previous design [22].

Calibration accuracy affects XCO_2 retrieval precision. In this study, we used the Bayes-based Optimal Estimation Method (OEM) to evaluate the impact of calibration. Radiometric calibration is the most important factor affecting the quality of XCO_2 retrievals. Fig. 1 shows the relationship between the absolute and relative radiometric calibration accuracies with the XCO_2 retrieval precision at four solar zenith angles. Considering observations over the land, most measurements are completed in the nadir mode, so only the nadir geometry was simulated. The results indicate that the relative radiometric calibration requires more accuracy than the absolute values, as the relative calibration is more sensitive to relative changes in the ratio of absorption (i.e., online/offline) corresponding to the CO_2 concentration. The XCO_2 error pattern does not significantly change in going from 15° to 50° solar zenith angles (SZA), but as the SZA increases from 50° to 70°, the absolute radiometric calibration accuracy becomes more critical for XCO_2 errors. Unlike noise and relative radiometric calibrations, the absolute calibration introduces a linear bias as a systematic error in CO_2 retrievals in this simulation.

2.1.2. Cloud and Aerosol Polarization Imager (CAPI)

One of the most significant impacts on XCO_2 retrieval accuracy is the scattering of light from aerosols and cirrus clouds [23,24]. The information for aerosol and cloud scattering from the spectra themselves are limited and need to be improved for CO_2 retrievals, although the O_2–A and the strong CO_2 band are used to constrain the aerosol loading and wavelength dependence. NASA OCO-2 flies in the A-Train [7]. Therefore, other instruments also in the A-Train, such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua, and the Ozone Monitoring Instrument (OMI) onboard Aura, provide near-simultaneous measurements of clouds and aerosols for OCO-2. For GOSAT, an auxiliary sensor, namely, the Cloud and Aerosol Imager (CAI), is onboard and is used to screen out thick clouds and reduce scattering-induced errors from aerosols and cirrus clouds [25–27]. For TanSat, a similar concept synergistic observation of clouds and aerosols is required to improve the precision of CO_2 measurements. Therefore, the auxiliary instrument CAPI was designed and is located onboard TanSat. It observes the reflected sunlight in five bands from UV to NIR. To achieve more

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