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TanSat: a new star in global carbon monitoring from China

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Accurate monitoring of changes in atmospheric carbon dioxide (CO_2) concentration and carbon sinks/sources distribution are an important prerequisite for comprehensively understanding the global carbon cycle and correctly predicting future climate change. Satellite remote sensing is the only method to achieve this monitoring with high resolution. Although spaceborne hyperspectral remote sensing sensors have been successfully applied to monitor the concentration of CO_2 in the upper troposphere, they are not sensitive to changes in CO_2 concentrations near the Earth's surface. With the rapid development of sensor technology, quantitative remote sensing algorithms, satellites equipped with near-infrared and short-wave infrared hyperspectral sensors dedicated to CO_2 monitoring have been successively launched. In January 2009, the Japanese GOSAT (Greenhouse gases Observing SATellite) satellite was successfully launched as the world's first greenhouse gas observing satellite; in July 2014, the US OCO-2 (Orbiting Carbon Observatory) satellite was launched. Both satellites have the capability of high-precision detection for atmospheric CO_2, CH_4 and also solar-induced chlorophyll fluorescence (SIF) of terrestrial plants. The use of satellite-retrieved column-averaged dry-air mole fractions of atmospheric CO_2 (XCO_2) and SIF of plants in combination with atmospheric transport model and ground-based observation allows for the high-precision estimation of the surface carbon flux and vegetation primary productivity [1].

In recent years, China has made rapid progress in spaceborne hyperspectral sensors and models on monitoring atmospheric XCO_2 and terrestrial plant traits, which has been introduced to the international carbon monitoring community and received a high attention. The milestone is the successful launch of the first Chinese Carbon Dioxide Observation Satellite Mission (TanSat) on December 22, 2016. Independently-developed in China, TanSat is currently in orbit and has successfully collected observation data for nearly two years. TanSat also has made major achievements in various applications, such as the development of global ground-based XCO_2 products [2,3] and global SIF products [4].

TanSat is equipped with two core payloads, i.e., the "High-Spectrum Resolution Atmospheric Carbon-dioxide Grating Spectrometer (ACGS)" and "Cloud and Aerosol Polarimetry Imager (CAPI)". The ACGS contains an O_2-A absorption band at 0.76 μm, a CO_2 weak absorption band at 1.61 μm and a CO_2 strong absorption band at 2.06 μm, and the spectral ranges of these bands are 758–778, 1,594–1,624 and 2,042–2,082 nm, respectively. After instrument design optimization phase [5], the spectral resolutions are determined as 0.044, 0.12 and 0.16 nm, respectively, with a spatial resolution of 2 km. CAPI is mainly used to eliminate the scattering effects of clouds and aerosols by measurements in five broad bands at 0.38, 0.67, 0.87, 1.375 and 1.64 μm, respectively. Not only the intensity observation from ultraviolet (UV) to NIR, but polarized measurements at 0.67 and 1.64 μm are also feasible to get more aerosol information, especially fine particles and fine mode fraction [6]. TanSat supports three observation modes, i.e., nadir, sun-glint and target, and two calibration modes, i.e., sun and moon. Measurements staring at one target from multiple angles in target mode are useful for improving aerosol retrieval accuracy [7]. The performances of TanSat, such as spectral resolution, spatial resolution and signal-to-noise ratio (SNR), have reached the same level as OCO-2. After in-orbit testing and calibration, TanSat's hyperspectral data have been shared globally through the National Satellite Meteorological Center website (http://data.nsmc.org.cn).

Regarding the XCO_2 inversion technology, the Institute of Atmospheric Physics of the Chinese Academy of Sciences developed the China Carbon Satellite Inversion Algorithm (IAPCAS) [8,9]. In the framework of optimal estimation theory, the IAPCAS algorithm adjusts the observation spectrum to optimize the inversion results by iterative fitting between the observed spectrum and the simulated spectrum. The observations of thick clouds and heavy aerosol pollution were removed prior to the inversion, and the scattering effects of aerosol and cirrus clouds were simultaneously corrected during the inversion. Based on TanSat ACGS radiance spectrum (L1B v1.0) data, the global XCO_2 distribution products from February to July 2017 were obtained by the inversion algorithm. The XCO_2 product well reflects the distribution and seasonal variations of atmospheric CO_2, and the results are consistent with the data obtained by the OCO-2 product of the United States. Based on the TCCON (Total Carbon Column Observing Network) site observations, the global average accuracy is 2.11 ppm [2]. TanSat's XCO_2 inversion accuracy is comparable to that of the GOSAT and OCO-2 satellites and reaches international standards. With the progress of CAPI on-orbit calibration, the comprehensive application of CAPI

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in the future may more effectively eliminate the scattering effects of clouds and aerosol and further improve the accuracy of inversion.

Regarding the detection of vegetation primary productivity, SIF remote sensing provides a direct proxy for global vegetation photosynthesis and has become a new application direction for GOSAT and OCO-2 satellites. Because of the high spectral resolution and high signal-to-noise ratio in the O2-A (0.76 μm) band, the ACGS sensor of the TanSat satellite can capture the filling effect of the SIF of the vegetation on the Fraunhofer Lines, thereby enabling the application of TanSat in SIF detection. Recently, Du et al. [4] developed a singular value decomposition (SVD) data-driven algorithm to successfully retrieve the global SIF product at 758.8 nm based on an optimized training samples. Preliminary evaluations show that the accuracy is comparable to that of OCO-2 and likely superior to that of GOSAT [4,10]. TanSat SIF products well illustrate the spatial and temporal changes in the global vegetation primary productivity and carbon sink capacity, and are highly consistent with the OCO-2 satellite products, with a coefficient of determination of 0.86; thus, they expand and deepen the application of TanSat satellites to provide a new source of global vegetation SIF data.

In summary, with the success of sensor development and breakthroughs in core application technologies, the TanSat satellite truly achieves global carbon monitoring capabilities. The accuracy of the TanSat satellite XCO_2 products and chlorophyll fluorescent products is superior or equivalent to that of similar international satellite products, and its breakthrough quantitative application provides an example for the quantitative development of domestic satellites in the future. By combining atmospheric CO_2 concentration data and SIF data obtained by TanSat with statistical models [11] or integrating satellite carbon cycle data assimilation systems and simulation models [12], the precise estimation of global carbon flux can be achieved, which will greatly enhance our ability to monitor global carbon cycle. TanSat's success is China's major contributions to global climate change research. In the face of rapid climate change and increasing human interference, TanSat, together with other carbon monitoring satellites and the forthcoming FLEX (Fluorescence Explorer), will stimulate new insights into global carbon cycling from the satellite perspective, and improve our understanding of carbon cycle-climate interactions across a range of temporal and spatial scales.

Conflict of interest

The authors declare that they have no conflict of interest.

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