ISSN 2959-6157

Progress and Case Study of Satellite Remote Rensing Technology for Carbon Dioxide

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Abstract:

As the primary cause of global warming, the increase in atmospheric carbon dioxide(CO_2) concentration has attracted more and more attention worldwide. With the slogan of “peaking carbon” and “carbon neutrality” in China, the need for quantitative, real-time, and large-scale monitoring of CO_2 concentration is becoming more urgent. As an all-weather, high-precision monitoring method for greenhouse gas emissions, satellite remote sensing has great potential in CO_2 monitoring. After studying the development and performance of remote sensing satellites for CO_2 monitoring, the conclusion drawn by this paper is that the monitoring accuracy of CO_2 monitoring sensors is gradually improved with increasing attention to CO_2 concentration detection in various countries and that because active remote sensing is not affected by aerosol and solar radiation, the current high-precision CO_2 concentration detection has gradually changed from passive remote sensing to a combination of active and passive remote sensing. By reviewing the development process of CO_2 monitoring remote sensing satellites and the research and application of CO_2 satellite data, this paper finds out the gaps in the current research of CO_2 remote sensing satellites. It inspires future scholars who want to carry out research in this field.

Keywords: Greenhouse gases, Carbon dioxide, Active and passive remote sensing

1. Introduction

Since humans stepped into the industrial age, human activities have intensified, and the consumption of fossil fuels has increased substantially, resulting in the concentration of greenhouse gases in the atmosphere rising yearly. The global warming caused by this situation has become a threat to the sustainable development of human society. According to the World Meteorological Organization (WMO) 2022 Greenhouse Gas Bulletin, the global average atmospheric concentration of the major greenhouse gases reached a new high in 2021, and CO_2 increased by nearly 50% compared to pre-industrial (pre-1750) levels [1]. As the main man-made greenhouse gas in the atmosphere, various countries have given CO_2 great importance. Many countries have introduced relevant policies and measures to control the emission of CO_2 gas generated by human activities. In the UN General Debate 2020, China proposed a „dual carbon“ goal: to achieve a carbon peak before 2030 and carbon neutrality before 2060. China has set up a nationwide carbon emission trading market to reach this goal in 2021. The European Union has also set up the Anthropogenic CO_2 Emissions Monitoring (CO2M) mission, which aims to accurately quantify anthropogenic CO_2 emissions [2]. The achievement and implementation of these initiatives cannot be achieved without accurate assessment and accurate detection of CO_2 gases on a global scale. Remote sensing satellites, operating for a long time and providing continuous global monitoring, have more advantages in long-term climate change assessment and large-scale greenhouse gas monitoring than traditional ground-based greenhouse gas observation facilities. Therefore, it is considered an effective means to obtain high-precision and high-resolution greenhouse gas concentration information from various countries. Since the 21st century, countries have launched many CO_2 monitoring satellites, and China‘s Gaofen-5 satellite (GF-5) and Atmospheric Environment monitoring satellite (DQ-1) have been launched in recent years to fill the current shortage of greenhouse gas monitoring; some of their parameters have reached the world‘s advanced level. There are also studies based on the detection data of these two satellites. DQ-1 is the first satellite in the world that can carry out active remote sensing monitoring. At present, in the field of CO_2 remote sensing satellite monitoring, the research direction has gradually shifted from passive remote sensing to the combination of active and passive remote sensing. This paper introduces the current development status and future application of remote sensing satellite detection of CO_2 by combining the launch history, relevant parameters of CO_2 satellites, and the relevant research results based on these satellite data.

2. A review and analysis of the current systematic research in the field of carbon dioxide remote-sensing satellites

Up to now, some scholars have carried out a summary study in the field of CO_2 satellite remote sensing. Bu et al. [3] studied the satellite detection of CO_2. They introduced the parameters of some CO_2 monitoring satellites, the performance of the sensors related to CO_2 detection, and their main products from the perspectives of passive remote sensing satellites and active remote sensing satellites. Flight tests of active remote sensing satellites carried out by some countries around the world have also been introduced. It is suggested that the number of active remote sensing satellites should be increased, and the airborne test should be accelerated. Li et al. [4] conducted a comprehensive study on the research status of atmospheric environment satellite monitoring of greenhouse gases and aerosols. In this study, they first introduced the inversion algorithms of greenhouse gases and aerosols used on some satellites. Then, they introduced the satellites and sensors launched by China, Japan, the United States, and Europe after entering the 21st century, as well as related satellite platforms and verification networks, from the two aspects of greenhouse gas monitoring satellites and integrated detection satellites of greenhouse gases and aerosols. Finally, the development of greenhouse gas and aerosol cooperative observation satellites is advocated.

By reviewing the relevant research on CO_2 remote sensing satellite monitoring, this paper finds that the introduction of CO_2 remote sensing monitoring satellites in the current research is not perfect. Most of the current research introduces the CO_2 remote sensing satellites launched in the last ten years, and there are few introductions for the earlier satellites. Besides, there is less research on the use of CO_2 remote sensing satellite monitoring data. The purpose of this paper is to fill the gap in this area and carry on the role of subsequent research in this area.

3. Relevant parameters of carbon dioxide remote sensing satellite and related research results

Table 1. Part of the relevant data of the spaceborne CO2 sensor

Satellite	Sensor	Country / Year	Spectral range/ um	Spectral resolution	Product accuracy/ppm	References
ENVISAT	SCIAMACHY	ESA /2002	0.60-0.81, 0.97-1.77	$0.24nm^{-1}$-$1.48nm^{-1}$	--	[3] [5]
EOS/Aqua	AIRS	America /2002	0.4-1.1, 3.7-15.4	$0.25um^{-1}$-$1.0um^{-1}$	1.5-2	[6]
METOP-A	IASI	ESA /2006	3.62-15.4	$0.25cm^{-1}$	2	[7]
GOSAT	TANSO-FTS	Japan /2009	1.56-1.72, 1.92-2.08, 5.56-14.3	$0.2cm^{-1}$	1.0-4	[8]
OCO-2	Three-channel Imaging Grating Spectrometer	America /2014	1.59-1.62 2.04-2.08	$0.076nm^{-1}$ $0.097nm^{-1}$	1.0-2	[9] [10]
Note:-- indicates missing data						

With the development and improvement of satellite measurement, which can cover the whole world, the United States, Japan, and many European countries have launched satellites that can observe CO_2, as shown in Table 1.

3.1 Carbon dioxide passive detection remote sensing satellite

Existing (including discontinued) spaceborne sensors with CO_2 detection capabilities include SCIAMACHY, TES, AIRS, IASI, GOSAT, OCO-2, TANSAT, Fengyun-3D meteorological satellite (FY-3D), Gaofen-5 (GF-5) series satellites and Atmospheric Environment monitoring satellite (DQ-1) [11]. Only GOSAT, OCO-2, TANSAT, Gaofen-5 series satellites, and Atmospheric Environmental Monitoring satellites are dedicated greenhouse gas detection satellites/sensors.

(1) GOSAT

GOSAT is an Earth observation satellite dedicated to measuring greenhouse gases, mainly CO_2 and CH4, launched into a Sun-synchronous quasi-regressive orbit on January 23, 2009, by an H-2A launch vehicle. It is 2.0 meters long, 1.8 meters wide, and 3.7 meters high and can weigh up to 1.75 tons. It has an orbital altitude of 567 km, an orbital apogee of 683 km, an orbital inclination of 98°, an orbit period of about 98 minutes, and a satellite life of 5 years. Its near-infrared carbon sensor is equipped with two optical remote sensing units, wherein the Fourier transform spectrometer is used to observe the data fluctuations caused by the absorption of infrared rays by greenhouse gases such as CO_2 and then calculates the CO_2 concentration and the cloud and aerosol imager is used to observe clouds and aerosols that can cause errors to improve the accuracy of greenhouse gas observations. Its main products are XCO_2 and XCH_4.

(2) OCO-2

OCO-2, the first satellite launched by NASA specifically for CO_2 monitoring, was launched into a very high solar synchronous orbit on July 2, 2014, by a Delta-II 7320 launch vehicle. Its orbit is an A-Train orbit with an altitude of 705 km, an inclination of about 98.2°, and an orbital period of 98.8 minutes. It is equipped with three high-resolution grating spectrometers, which can conduct nadir, flare, and target observation. Its main product is XCO_2.

(3) TanSat

TanSat, a satellite developed by China to conduct CO_2 observation experiments, was launched into a sun-synchronous orbit on November 21, 2016, with an ascending junction time of 13:30. It has a weight of 620 kg, an orbital altitude of 712 km, an orbital inclination of about 98.16°, and a designed service life of three years. It is equipped with the Atmospheric Carbon dioxide Grating Spectrometer(ACGS) and the Cloud and Aerosol Polarimetry Imager (CAPI). ACGS is Tan Sat's primary CO_2 monitoring instrument for CO_2 measurements in the 1594-1624nm and 2041-2081nm bands with spectral resolutions of 0.12 nm^{-1} and 0.16 nm^{-1}, respectively. Its launch mainly aims to detect the distribution of atmospheric CO_2 concentrations at the continental scale and obtain first-hand global and regional atmospheric CO_2 concentration data. Its main product is XCO_2.

(4) FY-3D

FY-3D was launched into a near-polar sun-synchronous orbit by the Long March 4C carrier rocket on November 15, 2017. It has an orbital altitude of 836 km, an inclination of 98.75°, an orbital period of 101.5 minutes, a weight of about 2.3 tons, and a designed service life of 5 years. It is equipped with a near-infrared hyperspectral Greenhouse Absorption Spectrometer (GAS), which is used to measure the CO_2 band of 1560~1720nm and 1920~2080nm band, and the spectral resolution can reach $0.02nm^{-1}$. It uses Fourier interference detection technology to obtain high-precision atmospheric temperature and humidity profiles, thereby improving the ability to detect greenhouse gases.

(5) GF-5

The GF-5 was successfully launched into a sun-synchronous return orbit on May 9, 2018. It has an orbital altitude of 705 km, an inclination of 98.203°, an orbital period of about 98.723 minutes, and a return period of about 51 days. It is equipped with the Greenhouse gas Monitoring Instrument (GMI), and the loads associated with CO_2 detection on the GMI (Table 2) use methods that differ from traditional hyperspectral spectroscopy techniques. Spatial Heterodyne Spectroscopy (SHS) was used to obtain remote sensing data in the near-infrared to short-wave infrared (759nm-2058nm) spectral range. It is the world's first full-spectrum hyperspectral satellite to achieve comprehensive observation of the atmosphere and land. Also, it fills the gap in China's regional air pollution monitoring, meeting the demand for comprehensive environmental detection.

Table 2. Basic parameters of GMI sensors

Parameter	Technical index	
	Carbon dioxide	Carbon dioxide
Central wavelength/nm	1575	2050
Spectral range/nm	1568-1583	2043-2058
Signal-to-noise ratio	300@ERLIN	250@ERLIN
Radiometric calibration	absolute accuracy:5%	relative accuracy:2%
Field of view	14.6mrad(10.3 km@705km)	
Weight/kg	109	
Power/W	120	
Observation method	Nadir observation	Flare observation

The band 1568nm-1583nm is a weakly absorbing band of CO_2 with a spectral resolution of $0.6cm^{-1}$, while 2043nm-2058nm is a strongly absorbing band of CO_2 with a spectral resolution of $0.27cm^{-1}$.

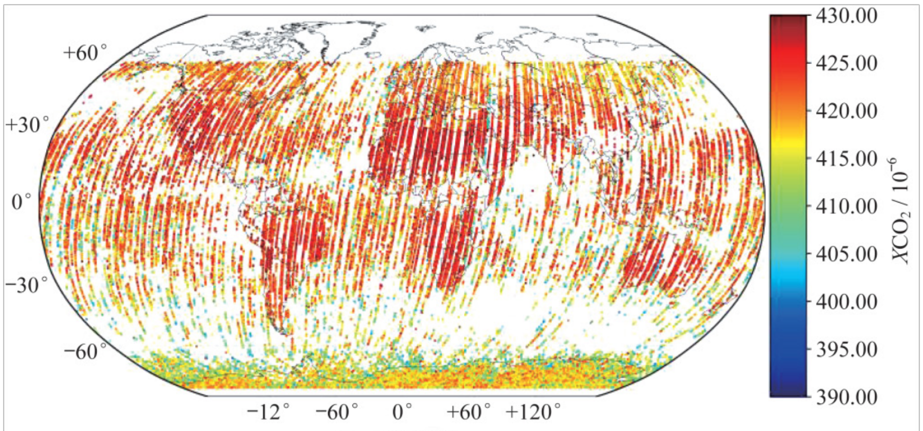
3.2 Carbon dioxide active detection remote sensing satellite

The satellite-borne passive remote sensing system has many advantages, such as a simple structure, mature technology, and lightweight. However, for the high latitude region, the passive remote sensing system lacks sensitivity due to insufficient light caused by the large solar altitude angle. Besides, because passive remote sensing relies on the solar background radiation, it cannot be observed at night, which poses a challenge for continuous and real-time monitoring of regional CO_2 concentrations. At the same time, the results of passive remote sensing are greatly affected by clouds and aerosols, which affects the accuracy of data [11]. These factors impede the improvement of passive remote sensing image data quality, and active remote sensing technology can solve these problems. In addition, more CO_2 concentration information can be obtained than passive remote sensing. Many countries have carried out research in the field of active remote sensing, but because of the high difficulty in research and development, the launched loads are less.

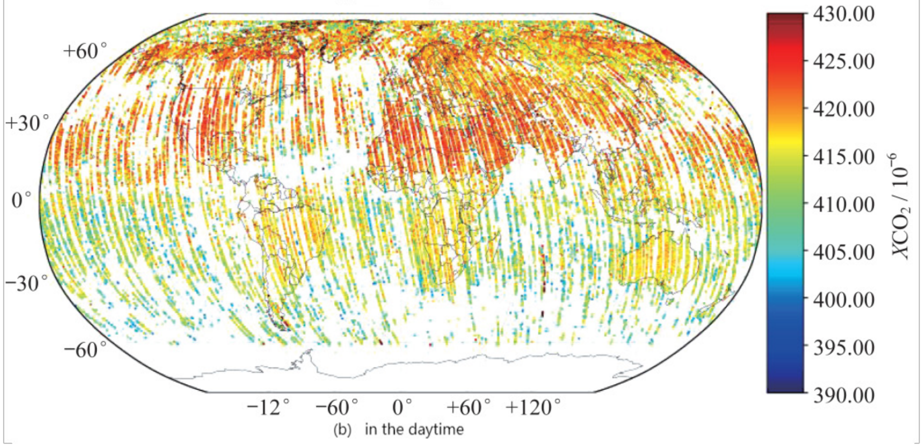
(1) DQ-1

DQ-1 was launched into Sun-synchronous orbit on April 16, 2022, by a Long March 4C carrier rocket. It has an orbital altitude of 705 km, an inclination of about 98.1°, a revisit period of 51 days, a weight of 2,600 kg, and an expected service life of eight years. It carries the world's first spaceborne path-differential absorption Lidar instrument, the Aerosol and Carbon Detection Lidar (ACDL), which can measure CO_2 and aerosols in the atmosphere.

As the only active remote sensing satellite for CO_2 in the world, the influence of water vapor can be ignored through the active emission of laser. In contrast, the influence of aerosol and other factors is canceled out and will not be influenced by solar radiation conditions. This improves the accuracy of CO_2 monitoring in real time.



(a) in the night



(b) in the daytime

Fig.1 Daytime and nighttime XCO_2 retrieved from the ACDL in June 2022[12]

According to the information in Fig.1 (a) and (b), the concentration and distribution of XCO_2 on a global scale during the day and the night can be seen. Fig.1(a) is the global distribution of CO_2 at night detected by LiDAR for the first time, which indirectly reflects the advantage of active remote sensing in that it is not affected by time and the position of the sun.

3.3 Related research results based on carbon dioxide satellite data

Many pieces of research have been based on carbon dioxide remote sensing satellite data. The research based on CO_2 detection data of TANSAT and GF-5, serving as representative examples, is selected in this paper.

YANG et al. [13] analyzed the global carbon sink by using TANSAT satellite data. By comparing TANSAT data with OCO-2 and GOSAT data, they found a strong correlation between measurements of terrestrial carbon sinks over North Asia, much of Europe, and the Americas, as well as over central Africa and India. However, at the global annual carbon sink, the net carbon flux of OCO-2 is 23.5% lower than the TANSAT result. At the same time, TANSAT data are still not enough to meet the standards of the Paris Agreement in terms of pixel size, coverage times, and accuracy, and it is proposed to deploy several more satellites in low orbit around the world to improve accuracy. Bi et al. [14] calculated the in-orbit spectral calibration accuracy of the TANSAT satellite by using the method of independent solar Fraunhofer absorption line to study the annual change rate of the central wavelength of the three spectral channels of ACGS. They concluded that the wavelength offset was less than 10% of the spectral resolution. It has helped to improve the quality of TANSAT satellite products.

Ye et al. [15] calculated the accuracy of monthly average CO_2 concentration obtained by satellite detection by inverting GMI observation data of GF-5 from 2018 to 2019. Through the inversion algorithm of spatial extrinsic interference spectrum designed by ourselves, the global CO_2 concentration data of GMI was compared with that of each ground measurement station. The average relative error obtained was 0.67%, which reached the application requirement of 1% and contributed to the promotion of product accuracy.

Through the introduction of the application of GF-5 and TANSAT satellite data, it can be seen that the current utilization of CO_2 remote sensing data is mainly in the aspect of improving the accuracy of remote sensing products, and there are few studies on global carbon emissions, which is a place for future research to explore.

4. Conclusion

As more and more countries pay attention to carbon emissions and China has made the goal of “carbon peak” and “carbon neutrality”, the use of remote sensing satellites for high-precision monitoring of CO_2 has a good development prospect. This paper introduces and reviews some CO_2 remote sensing monitoring satellites launched by China, Europe, Japan, and the United States in this century, from two aspects of passive and active remote sensing satellites. The conclusions of this paper are as follows: The world’s investment in CO_2 monitoring satellites is gradually increasing. CO_2 monitoring sensors have become the focus of research from the original attention, and the current high-precision CO_2 concentration detection has changed from passive remote sensing to a combination of active and passive remote sensing.

However, due to the difficulty of relevant technology development, only a few countries have launched active remote sensing monitoring satellites for CO_2 for the time being, so there is little research in the field of active remote sensing monitoring for CO_2. Therefore, it is necessary to speed up the testing and launch of active remote sensing satellites to provide data for research in related fields. Besides, through the analysis of the utilization of CO_2 satellite data in the field of remote sensing research, this paper finds that the current utilization of CO_2 remote sensing satellite data mainly focuses on the inspection and improvement of product accuracy. At the same time, there is relatively little research on the analysis of data products in the global carbon cycle, which is a place to explore in future research. Of course, this study still has some shortcomings. Here, the following prospects are proposed.

On the one hand, the introduction of CO_2 sensing satellites only involves relevant parameters and relevant indicators of the CO_2 detector on board, and the sorting of algorithms involved in subsequent data processing is not adequate because the optimization of algorithms is also one of the ways to enhance CO_2 remote sensing monitoring means. The research on the optimization of algorithms can be further discussed.

On the other hand, the discussion of the combination of active and passive remote sensing in this study only stays at the theoretical level, lacking the assistance of relevant experimental data. In the future, when more active CO_2 remote sensing satellites are launched, further research will be carried out in this area.

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