

» IWGGMS-21



Hyperspectral Remote Sensing of Greenhouse Gases Using Satellite-based Spatial Heterodyne Interferometry

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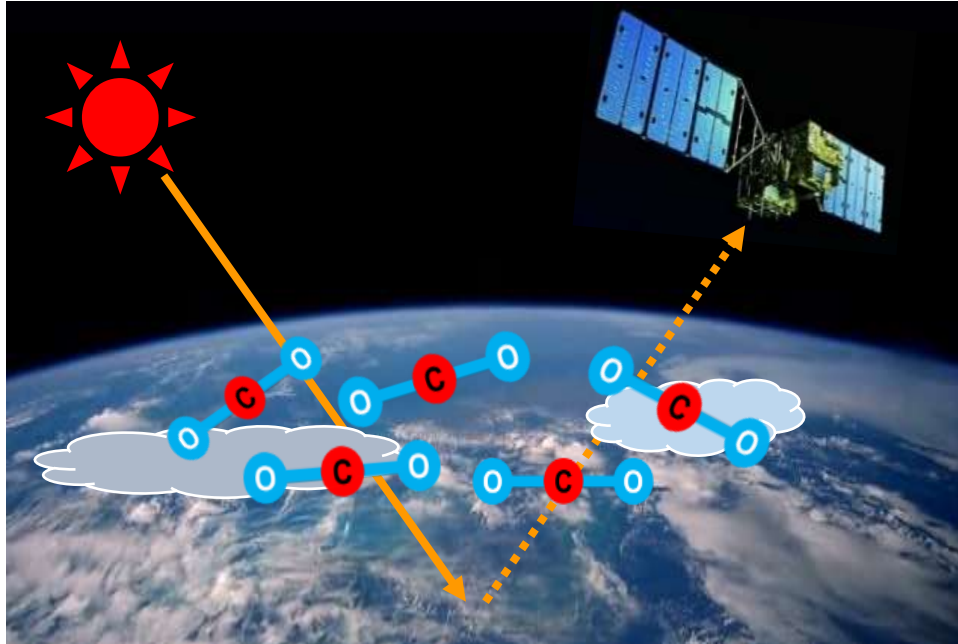
GMI Team
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2025.06 Takamatsu Japan

- 1. Super-Resolution Spatial Heterodyne Spectroscopy**
- 2. Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks**
- 3. Advances in Satellite Detection of Greenhouse Gas Point Sources**
- 4. Key Achievements and Future Prospects**

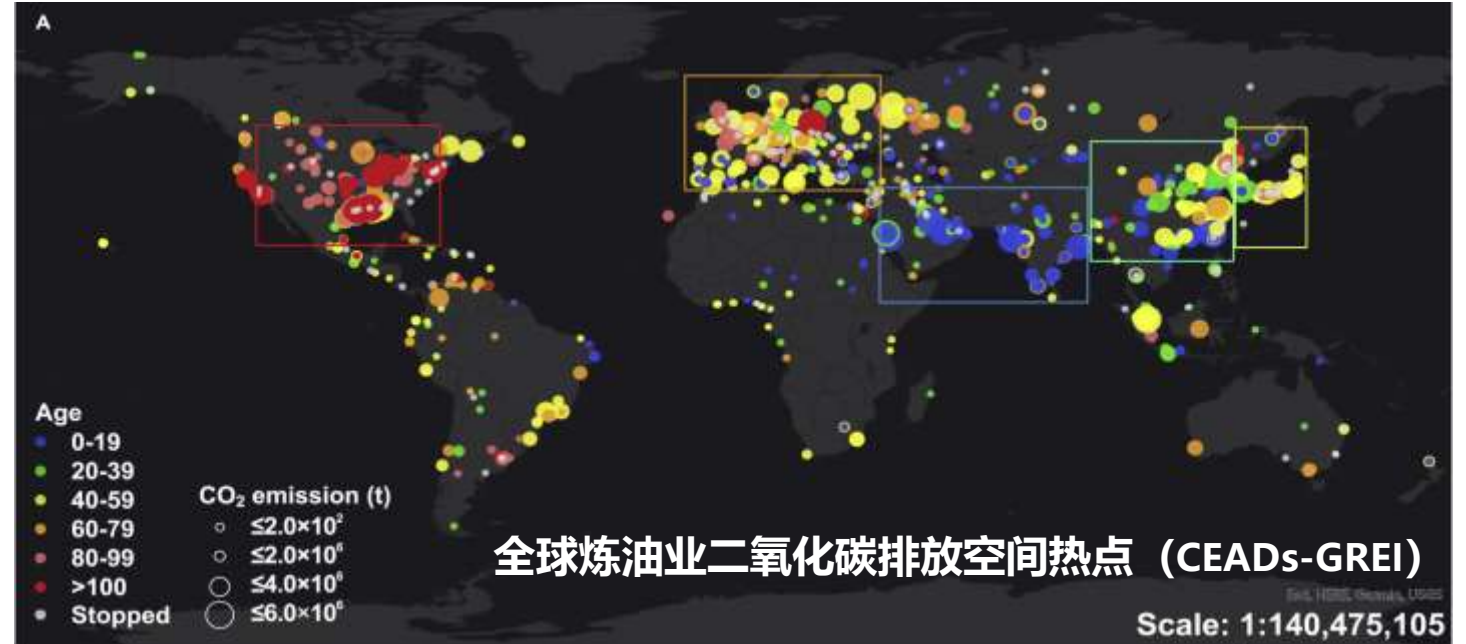
Critical needs

China's actions to jointly address global climate change - dual-carbon target.



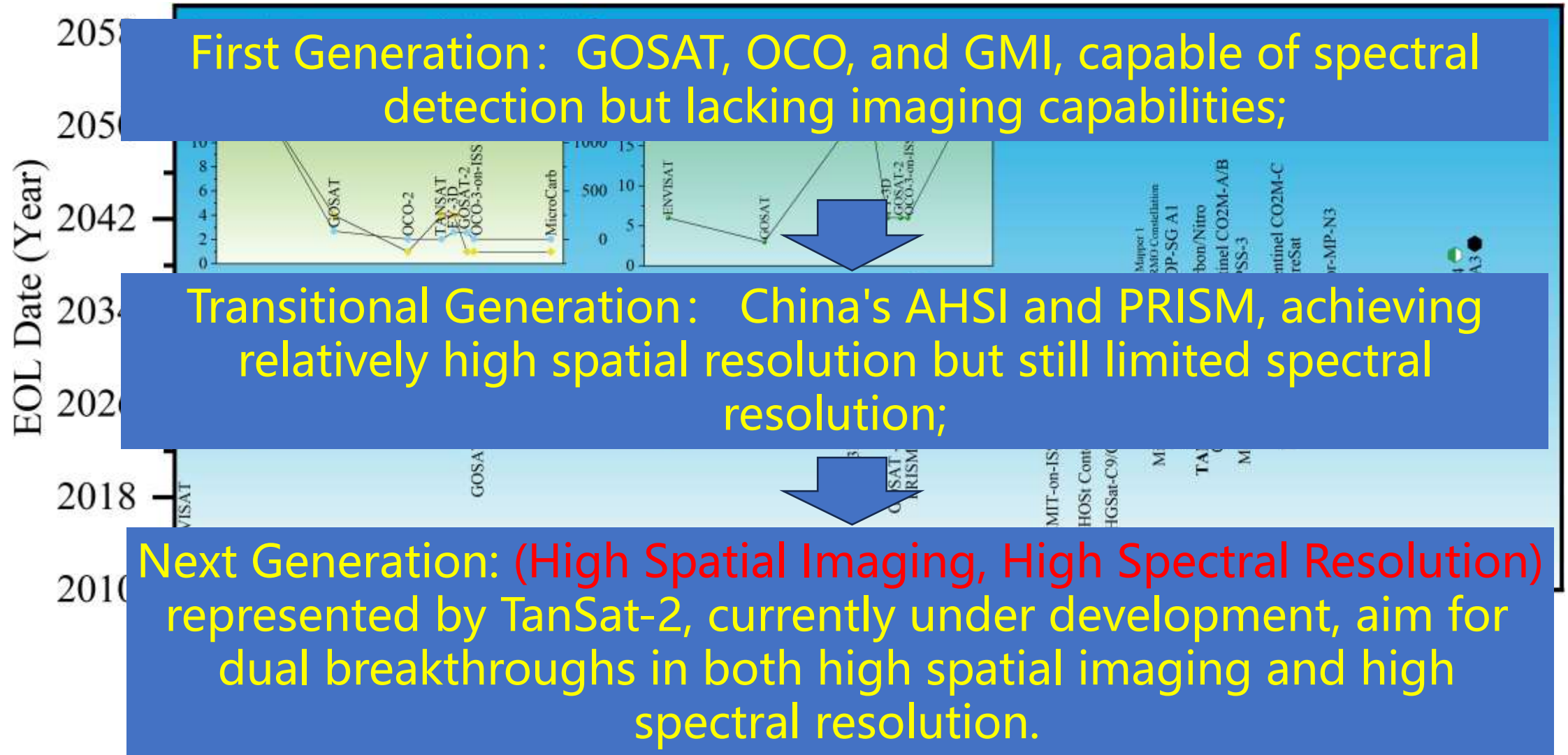
Critical pathways

Satellite remote sensing underpins global carbon source-sink dynamics and climate studies.

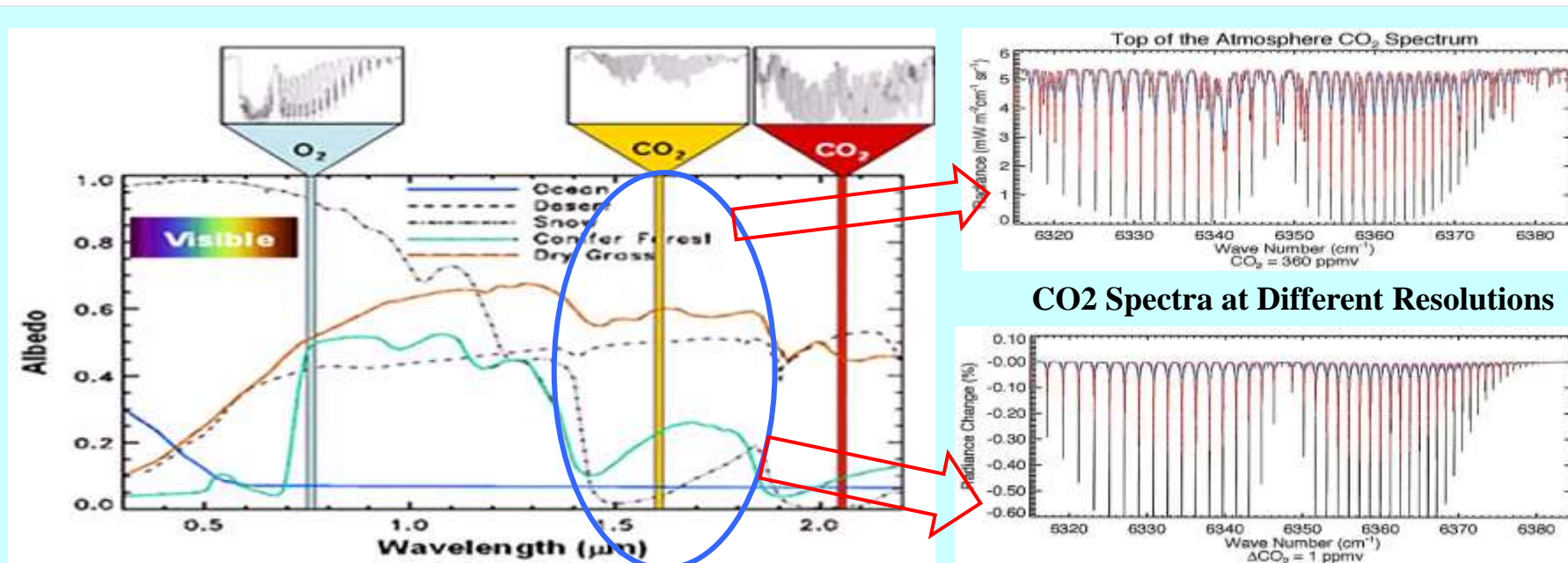


Tianyang Lei, et al., Nature, 2023

- **Regional Emissions:** Cities cover less than 3% of the Earth's land surface but emit roughly 44% of global CO₂ emissions, making their role crucial for estimating anthropogenic emissions.
- **Hotspot Emissions:** Power plants and refineries are major emitters and key to CO₂ reduction efforts.



Requirements for Satellite Remote Sensing of Greenhouse Gases



Satellite Remote Sensing Spectral Bands for Greenhouse Gases

Spectral changes corresponding to 1 ppm

- ◆ **Low Concentration:**
CO₂ ~430 ppm
- ◆ **Long Lifespan:**
Greenhouse gases are long-lived and **evenly distributed**.
- ◆ **Small Variation:**
Max concentration change ~20 ppm.

Hyperspectral

10 pm Spectral Resolution

High SNR

SNR > 300 under typical conditions ($\rho = 0.3$)

Multi-Element

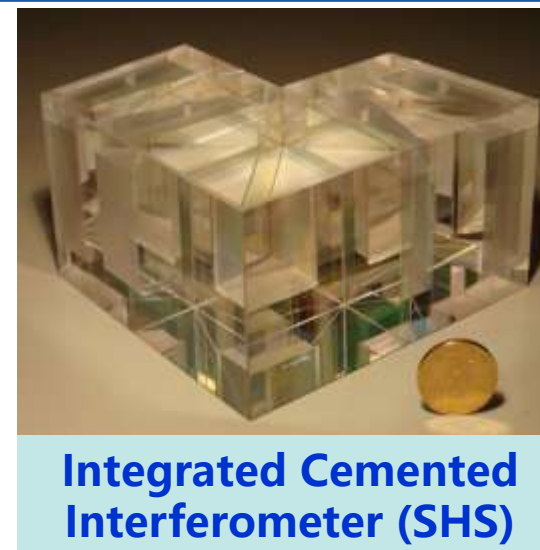
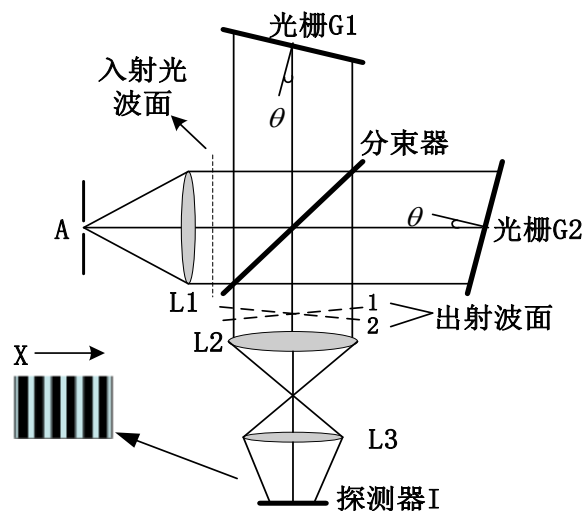
Monitoring capability for major greenhouse gases like CO₂, CH₄

High Stability

Long lifespan with precise radiometric calibration

Satellite remote sensing requires **high stability, high SNR, and hyperspectral** capabilities.

Super-Resolution Heterodyne Interferometric Spectroscopy



➤ SHS Advantages::

- High integration density, compact size
- Lightweight, low power consumption

➤ Requirements:

- Miniaturization
- Modularization
- Standardization

※Hyperspectral:

Grating diffraction combined with heterodyne interference enables hyperspectral resolution;

※High Sensitivity:

Expanded field of view with luminous flux 2 orders of magnitude higher than traditional grating solutions.

※Multi-Element Capability:

Supports multi-channel combinations for arbitrary, narrow wavelength ranges.

※Stability:

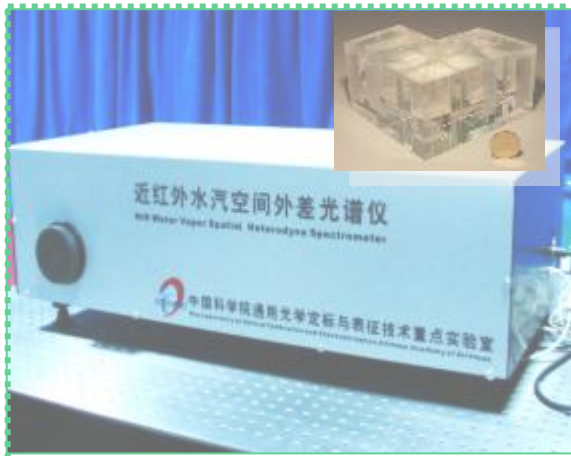
Monolithic cemented structure with no moving parts.

※Functionality:

Configurable as imaging/non-imaging systems.



2006



2009



CO

CH4



CO2 Airborne Platform

2010/Proof-of-Concept Prototype

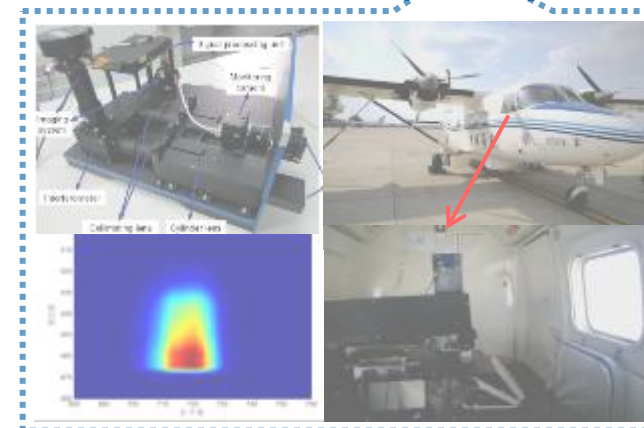
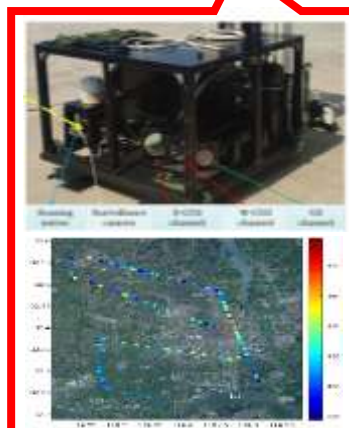
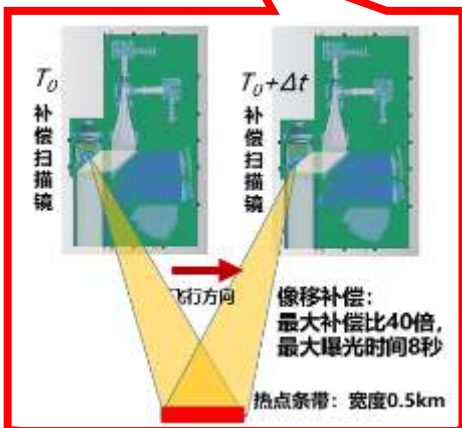
2026/0.5km

2024

2023/3km

2021~2018/10.3km

2015



Report Outline

- 1. Super-Resolution Spatial Heterodyne Spectroscopy**
- 2. Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks**
- 3. Advances in Satellite Detection of Greenhouse Gas Point Sources**
- 4. Key Achievements and Future Prospects**

Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

The major greenhouse gas monitoring instrument (GMI), a core payload for atmospheric CO₂ and CH₄ detection, is deployed on both the GF-5 (01) satellite (launched on 9 May 2018) and the GF-5B (02) satellite (launched on 7 September 2021).

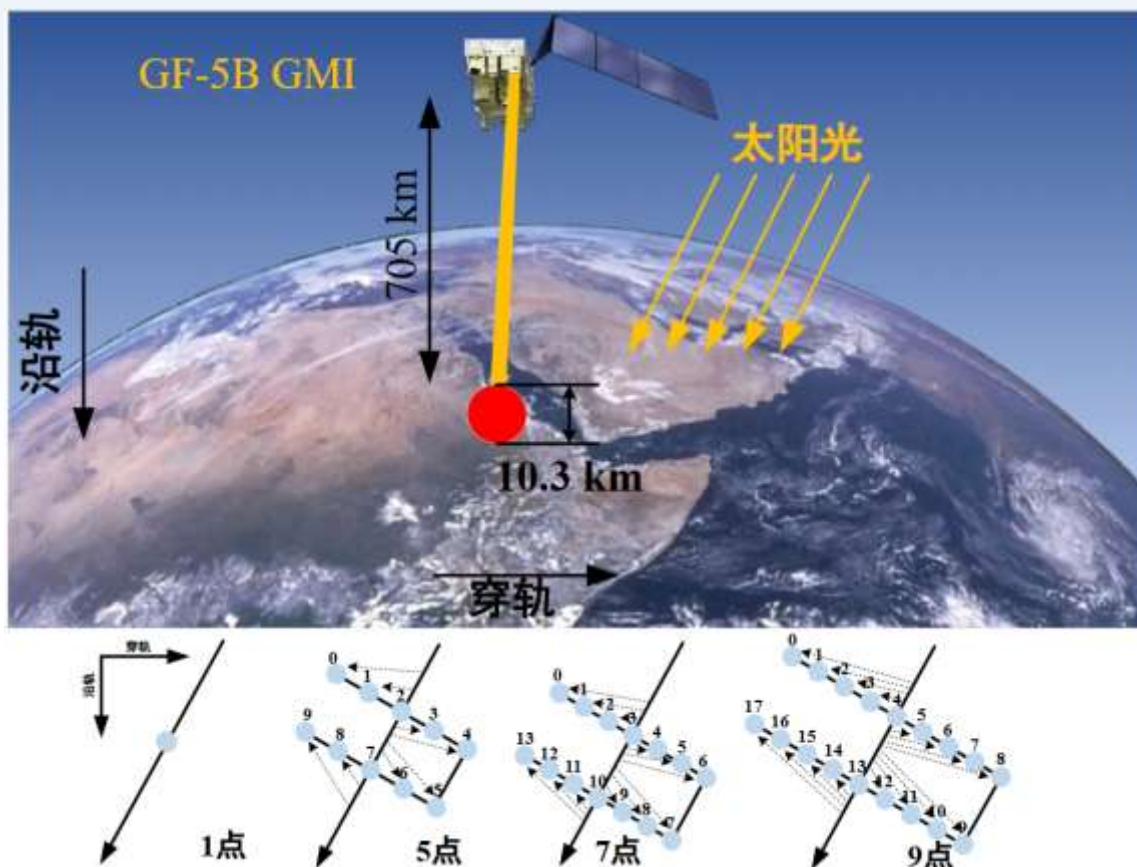


- Instrument Components:**
- Optical Head
 - Information Processing Unit
 - Drive Control Box
 - Temperature Control Box

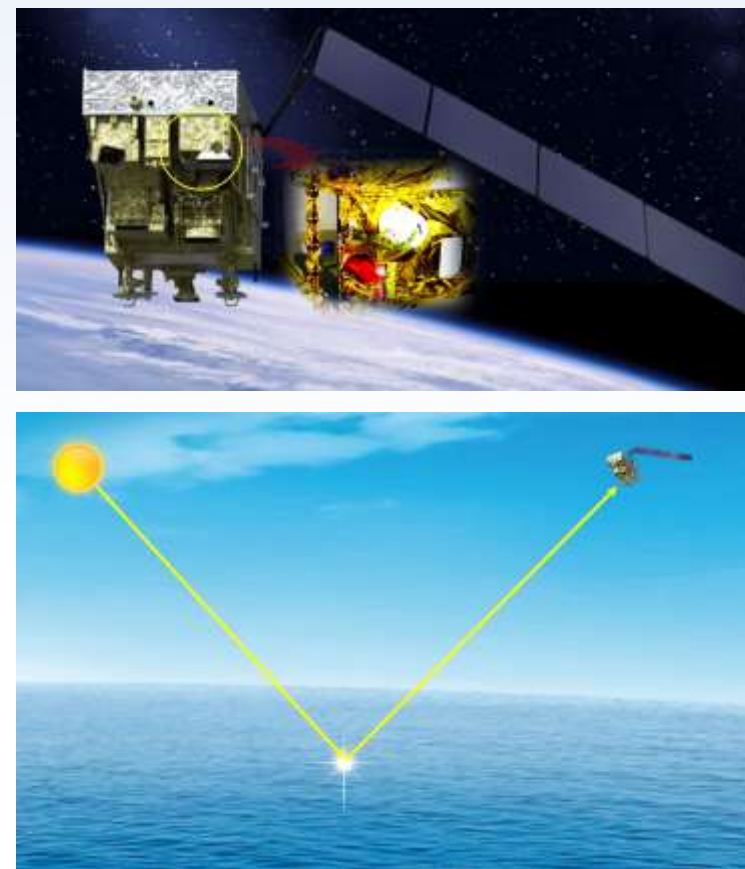


In practical operation, the onboard GMI instrument supports multiple observation modes:

Nadir Mode: Primarily for measuring absorption from Earth's surface-reflected radiation

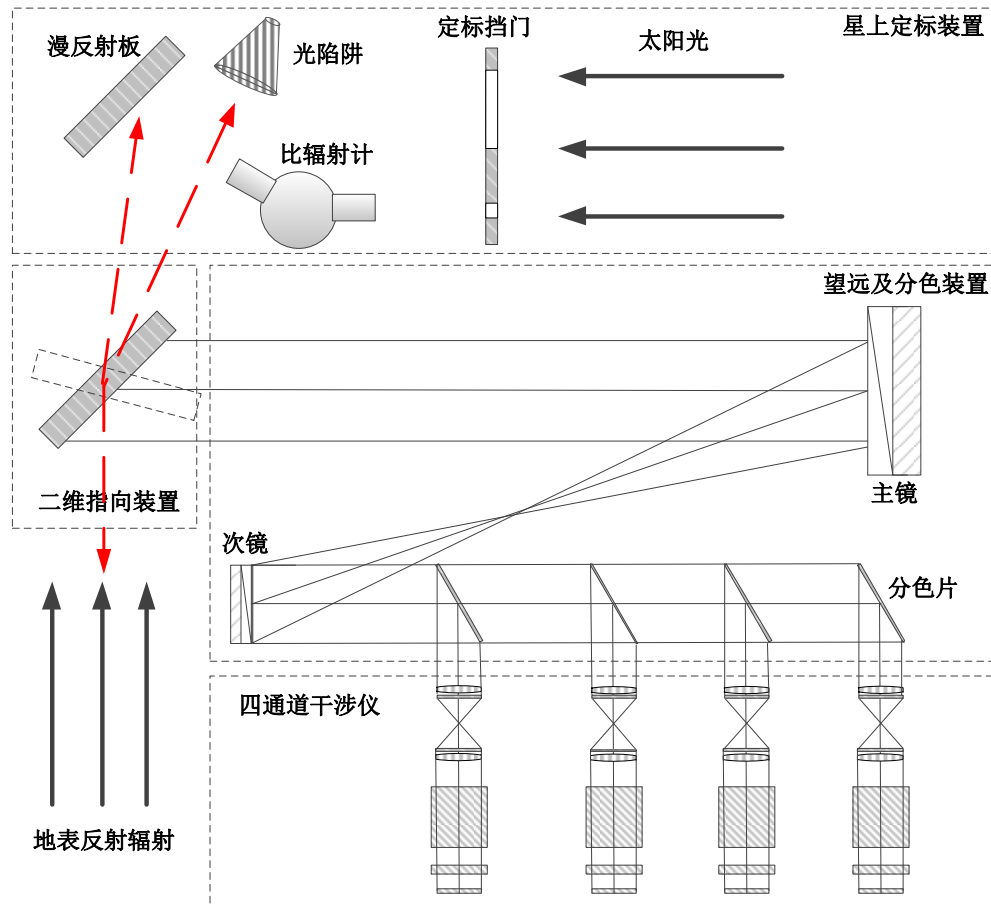


Glint mode: Uses direct sunlight reflection to enhance signal intensity.



Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

Optical Principle Schematic



H. Luo, et al., RS, 2023; H. Shi, AO, 2021

An onboard calibration device ensures long-term spectral and radiometric accuracy.

Technical Parameters

	O ₂	CO ₂	CH ₄	CO ₂
Spectral Range (μm)	0.759-0.769	1.568-1.583	1.642-1.658	2.043-2.058
Spectral Resolution	0.6cm ⁻¹	0.27cm ⁻¹	0.27cm ⁻¹	0.27cm ⁻¹
Spectral Calibration Accuracy	0.1cm ⁻¹	0.05cm ⁻¹	0.05cm ⁻¹	0.05cm ⁻¹
SNR)	300	300	250	250
Radiometric Calibration Accuracy	Absolute (incl. Dolp): 5% Relative: 2%			
FOV)	IFOV: 14.6mrad (10.3km@705km)			
Swath Width	860km (打点)			
Operating Modes	Nadir observation; Glint observation; Calibration; Standby.			
Quantization Level	14bits			

This positions GMI as one of China's most systematically operational instruments for greenhouse gas monitoring.

Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

Current Status: Conducted a detailed analysis of internationally prevalent inversion algorithms.

Limitations: Each algorithm excels differently in spectral line modeling and aerosol handling.

Measures: Based on specific features, designed a statistical-physical hybrid inversion method for GMI.

DE

DOAS Version : DOAS、WFM-DOAS、BESD-DOAS...

USA

FP Version : V3.7...V8.1 + Adjusted BESD-DOAS

Japan

PPDF Version : PPDF-D、PPDF-S + Adjusted FP



GMI

Combined Version: PCA + PPDF Series, PCA + Adjusted FP

- Statistical inversion and three-band spectral synergy for CO₂/CH₄, surface reflectance, and aerosol optical thickness, reducing scattering effects;
- Enhance regional statistical data for physical inversion;
- Path length correction;
- Aerosol inversion in high-value areas;
- Surface inversion in urban clusters.

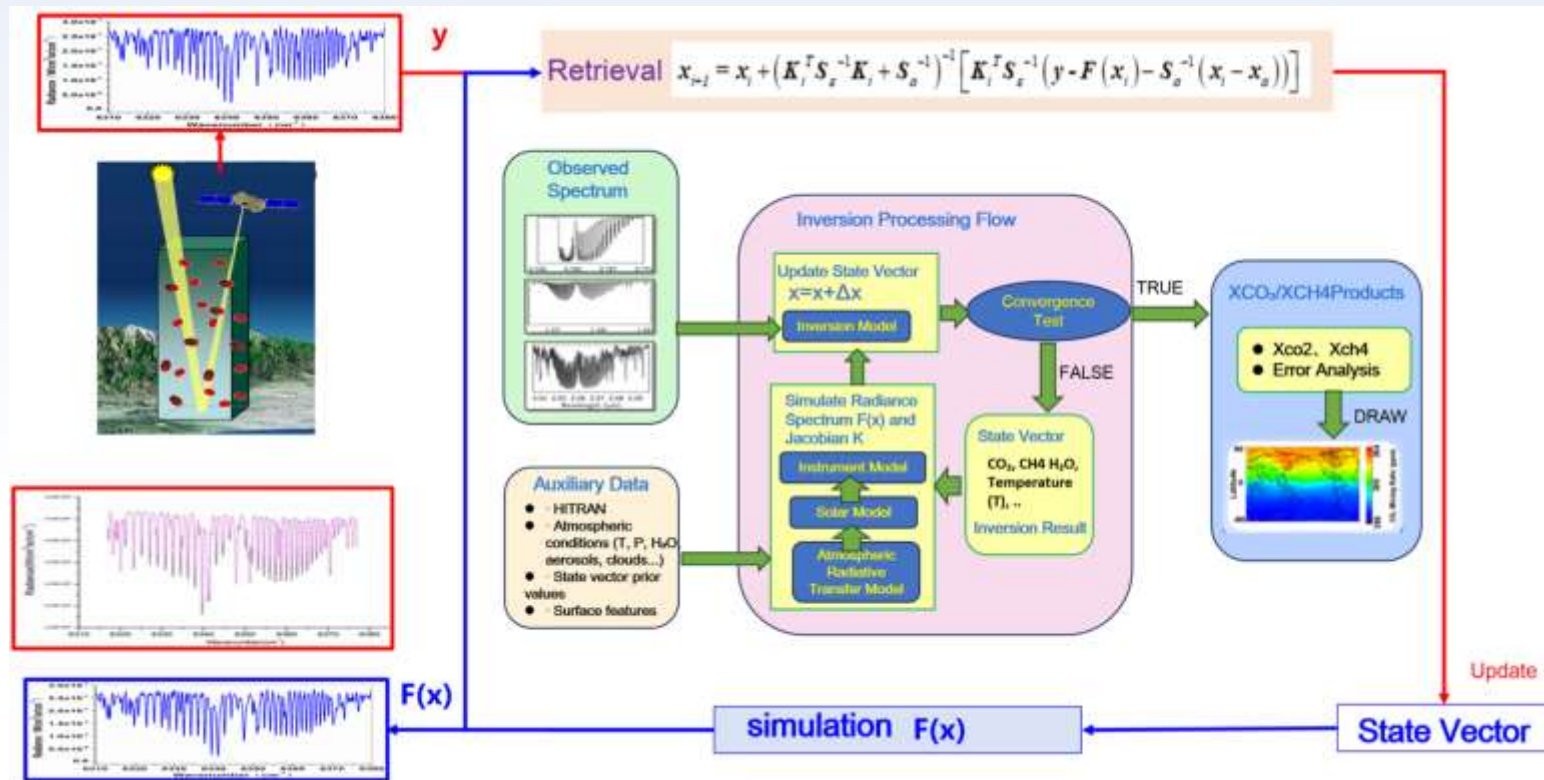
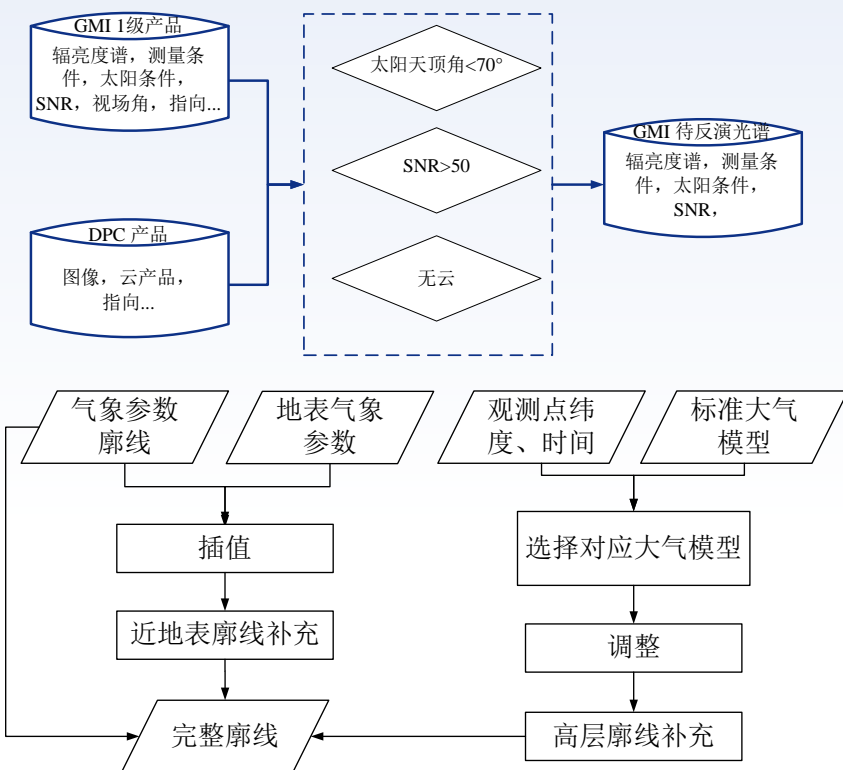
This significantly enhances retrieval accuracy within China.

Greenhouse Gas Concentration Data Product Production Process

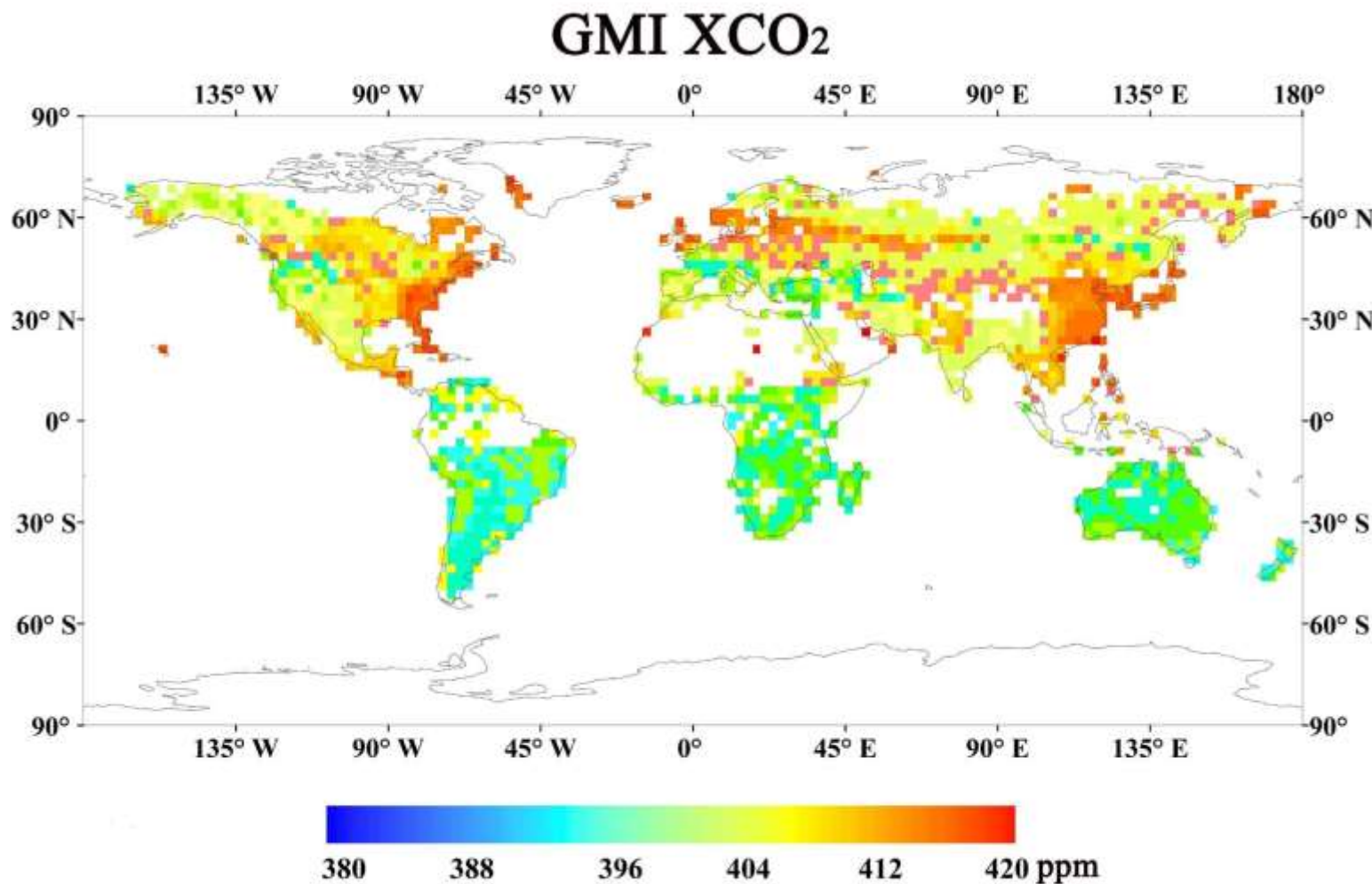
• Data Filtering

• Spectral Calibration

• Concentration retrieval

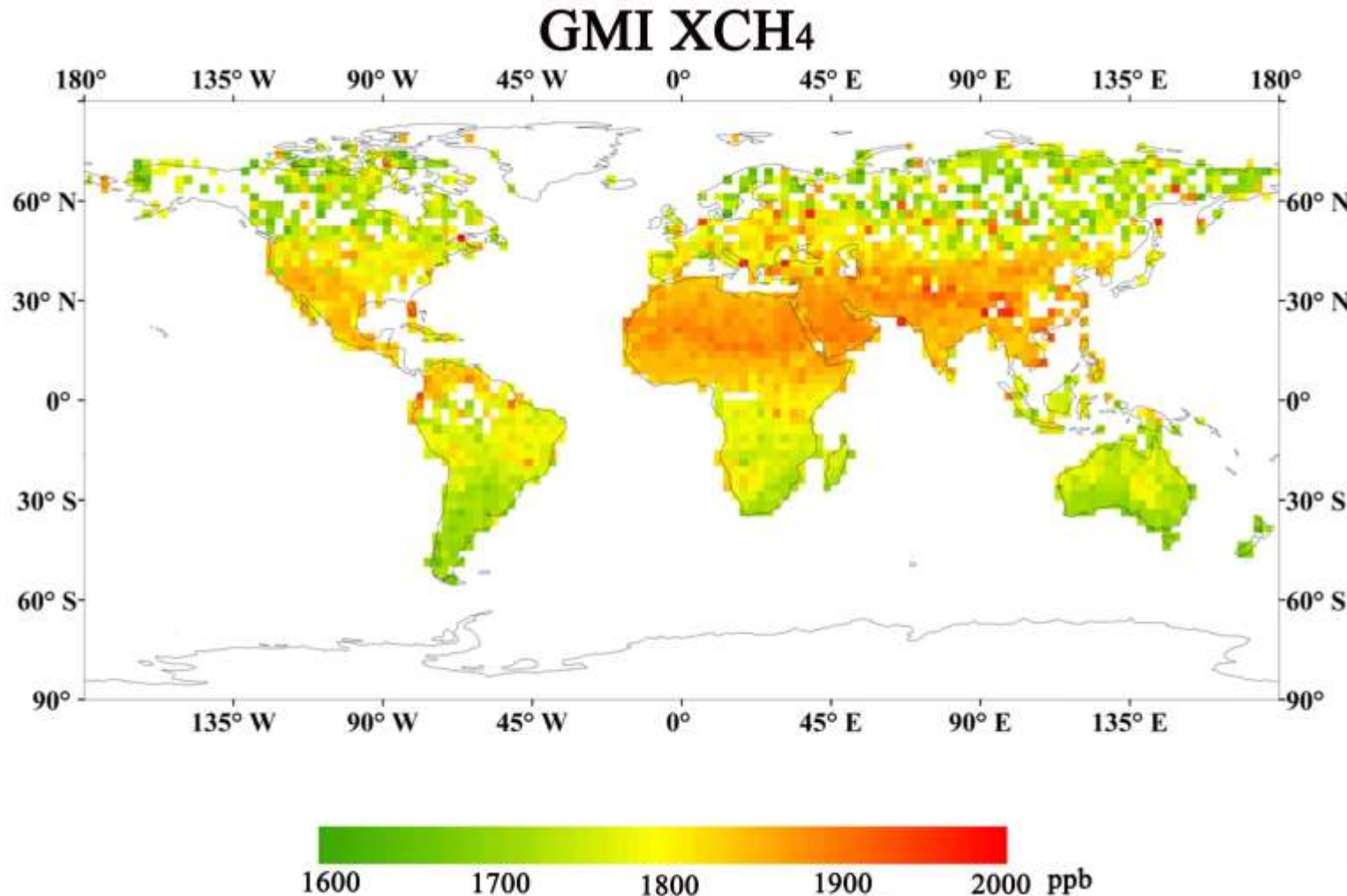


This integrated process yields standardized quantitative products for CO₂/CH₄ concentrations.



Hyperspectral Observation Satellite GMI Inversion Results

- Spring GMI CO₂ measurements cover land areas within 70° latitude, showing distinct CO₂ differences between hemispheres. Northern Hemisphere CO₂ is higher due to vegetation in summer.
- The overall CO₂ distribution trend from GMI is consistent with results from the GOSAT satellite.

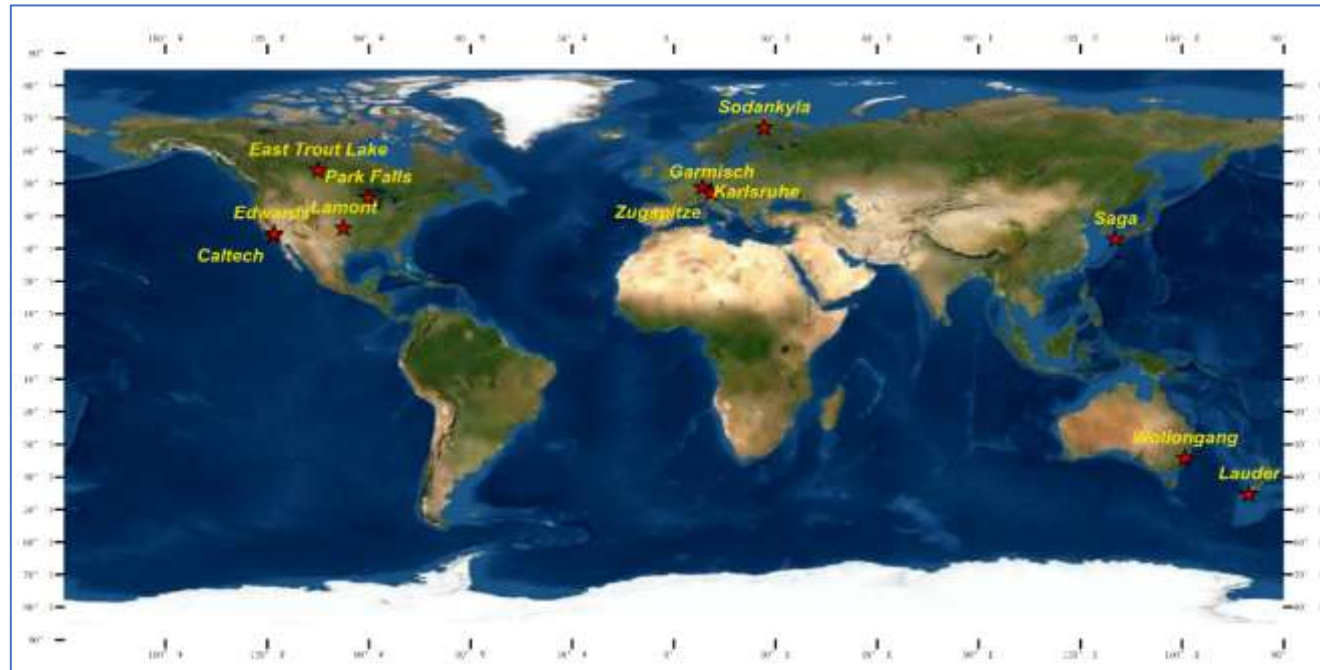


Hyperspectral Observation Satellite GMI Inversion Results

- In autumn, GMI global atmospheric CH₄ measurements show a clear latitude-dependent pattern, with higher CH₄ concentrations in low latitudes compared to high latitudes.
- The overall CH₄ distribution trend from GMI is consistent with GOSAT satellite results.

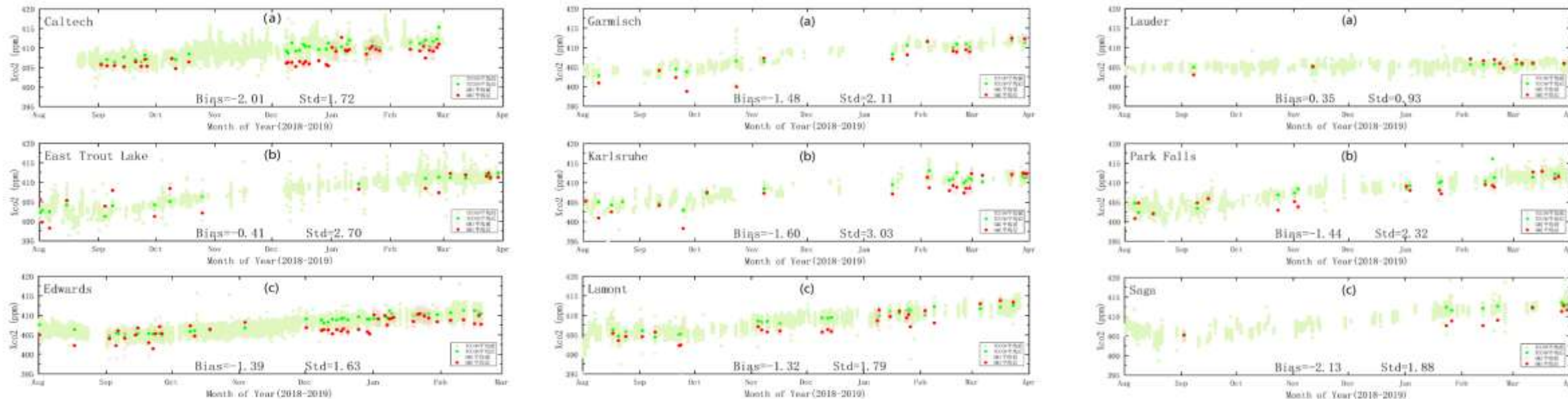


Lauder TCCON



- Accuracy Validation of GMI CO₂ with TCCON;
- Nine TCCON sites covering major global regions are used for comparison;
- Data is matched within $\pm 5^\circ$ latitude/longitude and a 1-hour time window for consistency.

站点名称	纬度/°	经度/°
Caltech	34.14	-118.13
East Trout Lake	54.35	-104.99
Edwards	34.96	-117.88
Garmisch	47.48	11.06
Karlsruhe	49.1	8.44
Lamont	36.6	-97.49
Lauder	-45.04	169.68
Park Falls	45.94	-90.27
Saga	33.24	130.29



Sites	Lat	(GMI SWIR XCO ₂)-(g-b FTS XCO ₂)			(GMI SWIR XCO ₂)-(g-b FTS XCO ₂)	
		Number of data	Average (ppm)	1 σ (ppm)	Average (%)	1 σ (%)
Saga	33.24	10	-1.93	1.96	-0.47	0.48
Caltech	34.14	136	-1.71	1.91	-0.42	0.47
Edwards	34.96	167	-1.21	1.94	-0.29	0.48
Lamont	36.6	102	-1.15	2.32	-0.28	0.57
Park Falls	45.94	33	-0.92	2.41	-0.23	0.59
Garmisch	47.48	39	-0.82	2.44	-0.20	0.60
Karlsruhe	49.1	56	-1.00	3.03	-0.24	0.74
East Trout Lake	54.35	25	-0.84	3.42	-0.21	0.84
Lauder	-45.04	15	0.26	0.90	0.06	0.22
Total		583	-1.21	2.26	-0.30	0.55

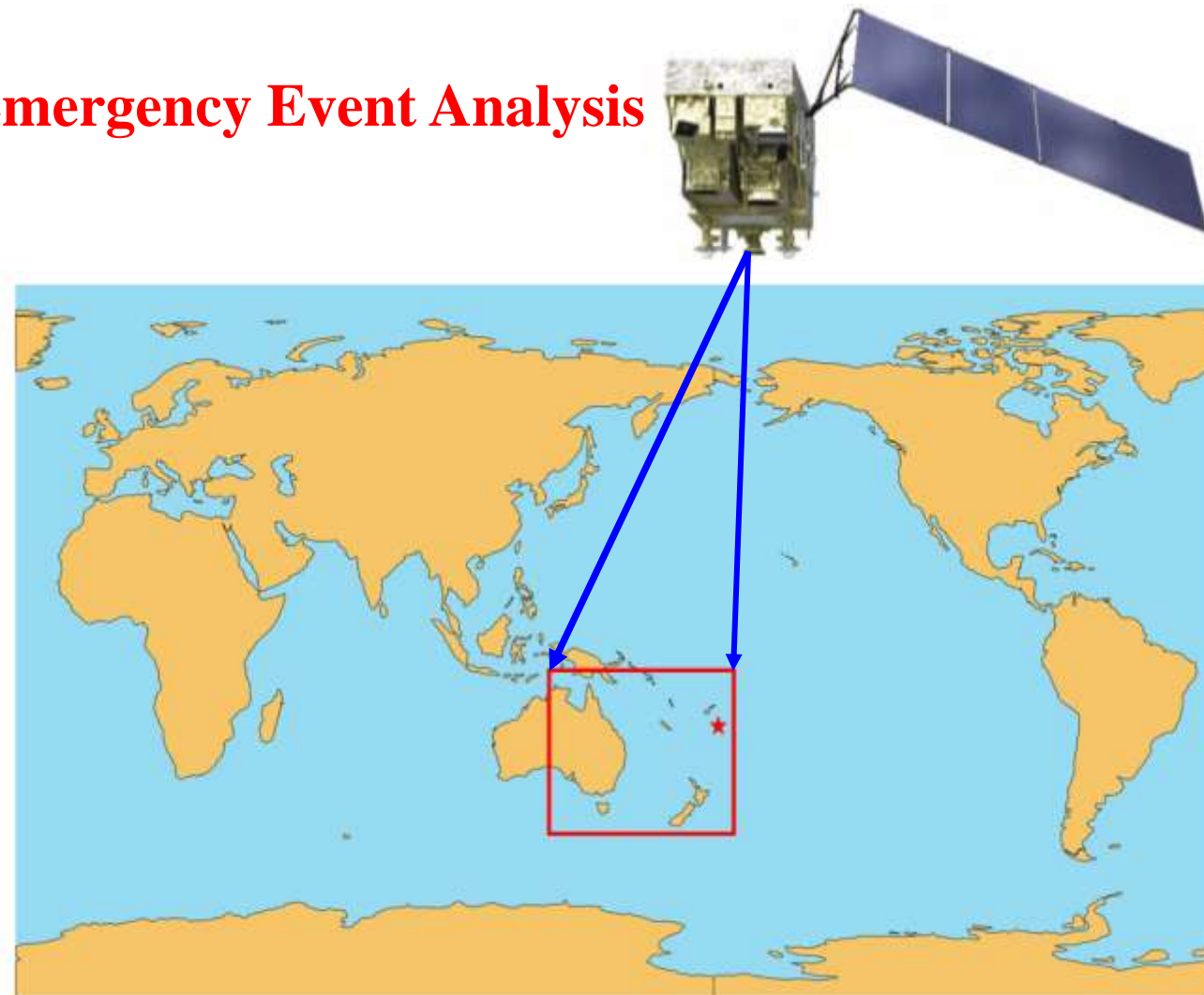
- GMI (red) and TCCON (green) results show a consistent increasing trend. High-latitude sites have errors up to ~3 ppm, while low-latitude sites are around 1 ppm. The combined validation of 9 sites gives an XCO₂ bias of **-1.21 ppm** and accuracy of **~2 ppm**.



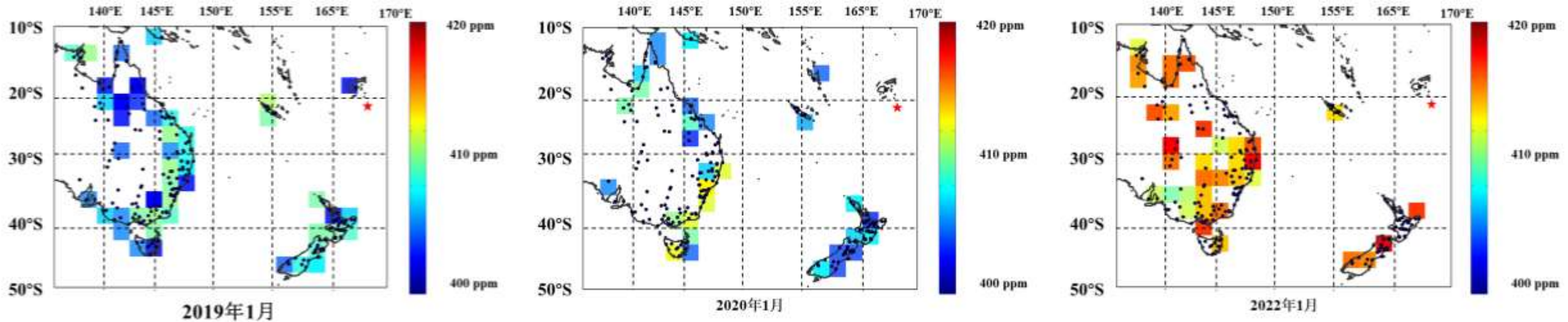
2022年1月15日
汤加海底火山喷发



Emergency Event Analysis



(submarine volcano in the Kingdom of Tonga)

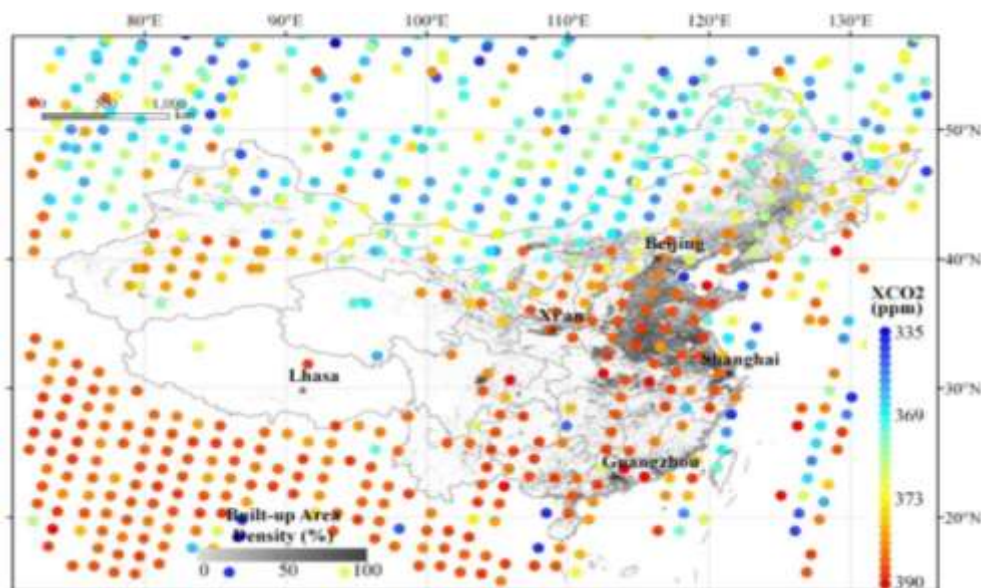


- In January 2019 and 2020, CO2 concentrations over the southern hemisphere's land were stable, with a 2 ppm fluctuation, consistent with ground-based observations.
- In January 2022, CO2 levels near Tonga increased by 3 ppm due to volcanic emissions.

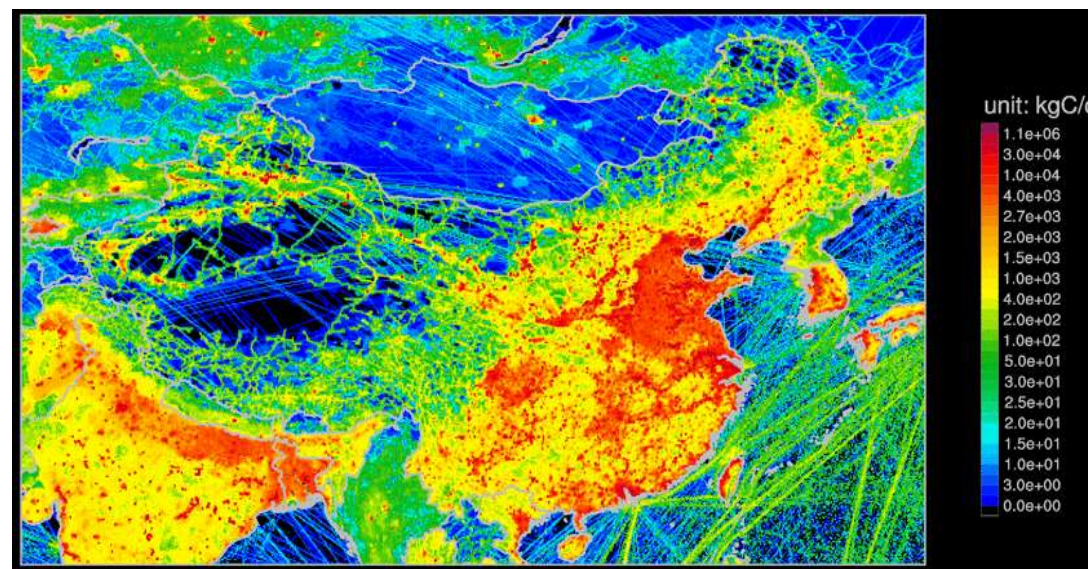
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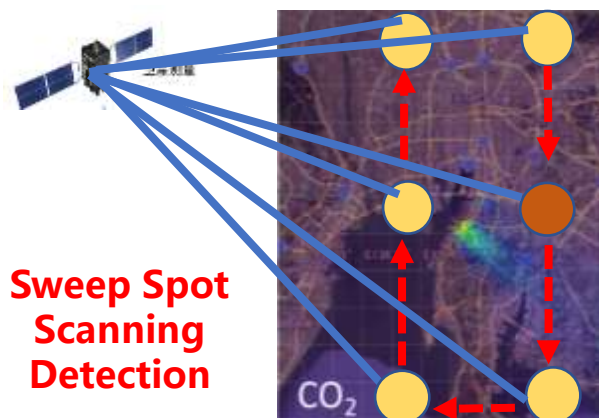
■ Non-Imaging Detection (Global Scale)



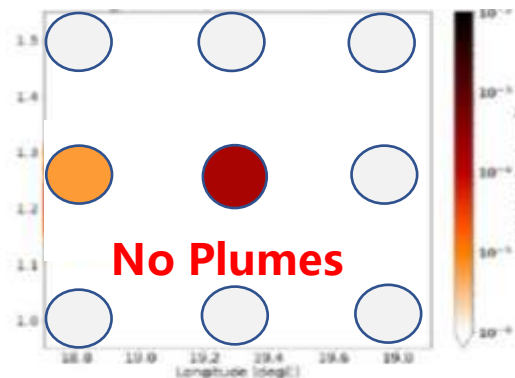
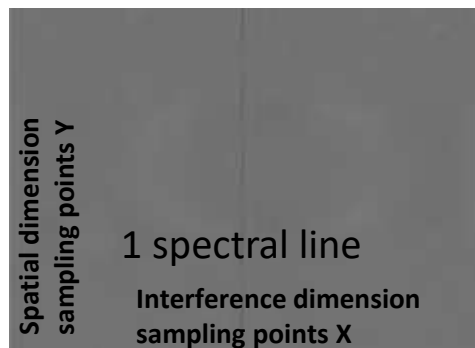
■ Imaging Detection (Urban/Point Sources)



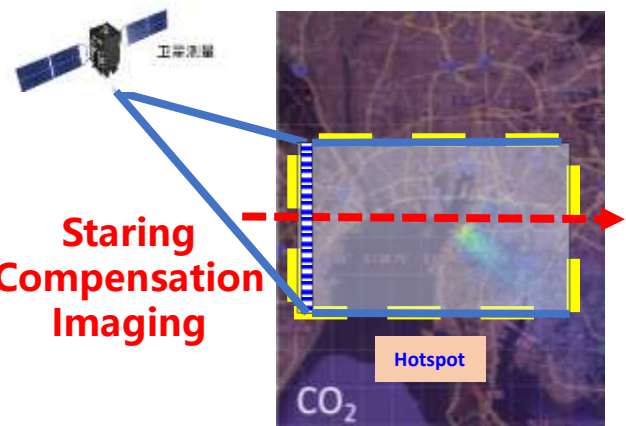
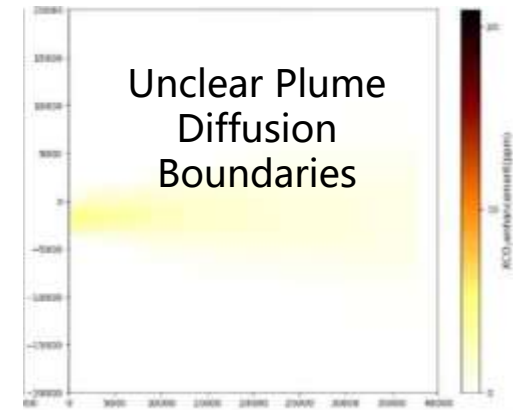
- Existing technologies focus on **non-imaging large-scale detection** (global greenhouse gas dynamics);
- Next-generation technologies prioritize **imaging regional-scale detection** (urban/point-source emissions);
- **Urgent need** : Development and data processing for **high-resolution imaging carbon satellites**.



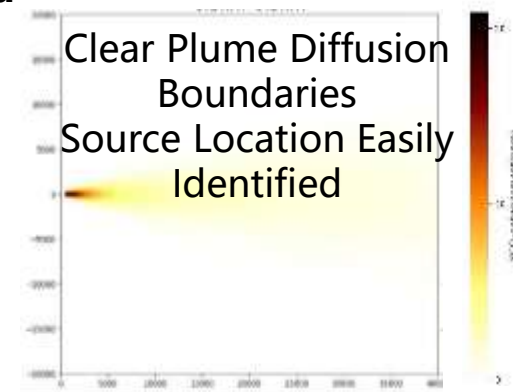
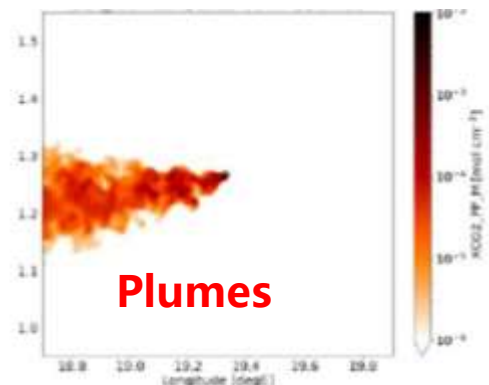
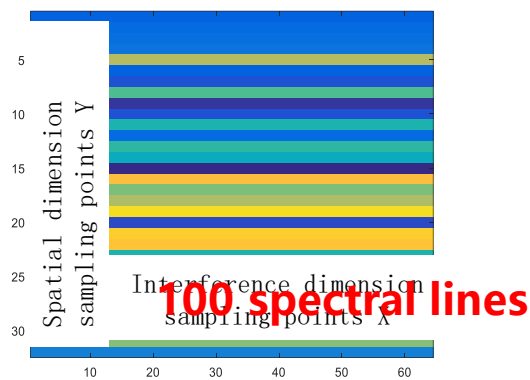
GF-5 Satellite : Greenhouse Gas Monitoring Payload



High-Resolution Support for Hotspot Carbon Emission Calculation

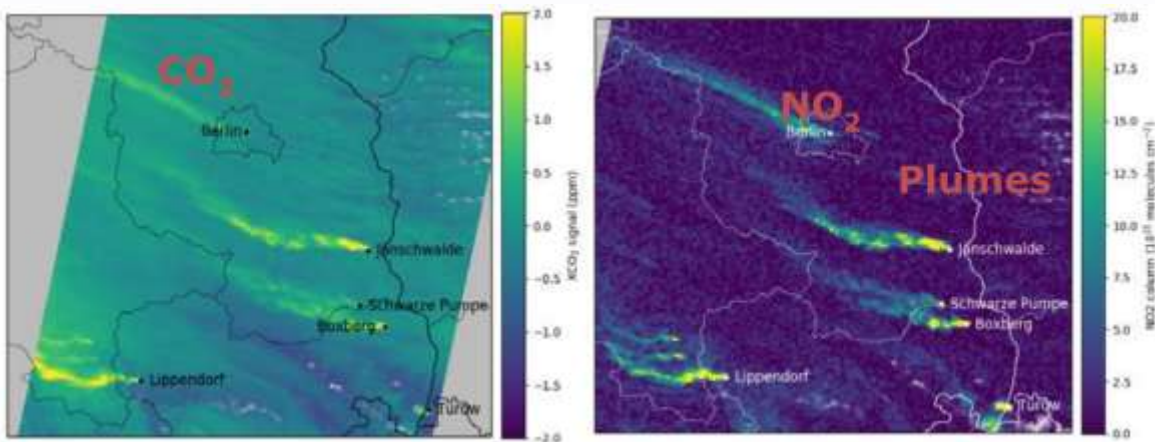


TanSat-2 Satellite : High-Resolution Hotspot Monitoring Payload



Achieve a spatial resolution of 0.5 km or higher, improving detection and increasing data volume by two orders of magnitude.

- ❑ Tansat-2 Application Efficacy:**
 - High-resolution monitoring of CO₂, CH₄ greenhouse gases and NO₂ pollutants in hotspot areas.**
 - Supports hotspot plume modeling for emission source identification and analysis.**

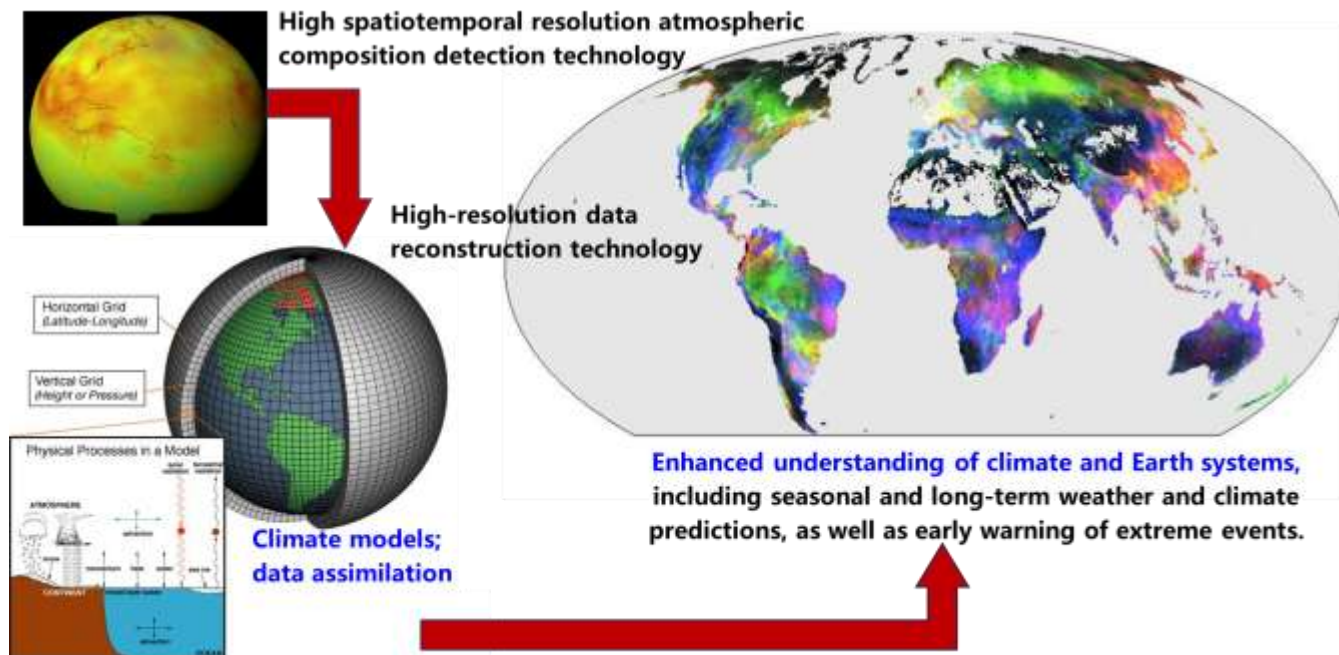


Parameter	Specification
Spectral Range	1565-1585 nm (CO ₂), 1635-1655 nm (CH ₄)
Spectral Resolution	0.15 nm (CO ₂), 0.15 nm (CH ₄)
SNR	CO ₂ :400 @ 7.85×10 ¹⁹ photons/sec/m ² /Sr/μm CH ₄ :250 @ 7.85×10 ¹⁹ photons/sec/m ² /Sr/μm
Spatial Coverage	50 km (at apogee)
Spatial Resolution	Regional: 1 km; Hotspots: 0.5 km
Spectral Calibration Accuracy	CO ₂ :0.06 cm ⁻¹ ; CH ₄ :0.06 cm ⁻¹
Radiometric Calibration Accuracy	Absolute: ≤4%; Relative: ≤2.5%
AD Quantization	14-bit
2D Pointing Mirror	Range: ±12° cross-track, ±4° along-track Accuracy: <2 arcsec

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Related Achievements and Future Prospects



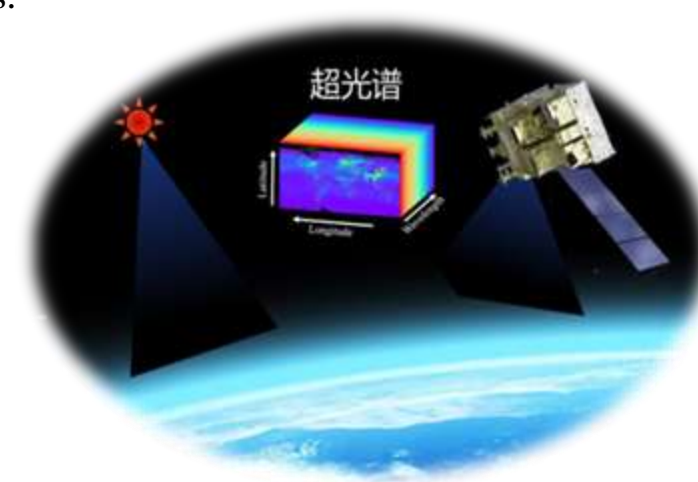
➤ Our research goes beyond payload-level innovations to encompass the full chain of carbon monitoring and climate system simulations:

- Enhanced characterization of atmospheric processes through high temporal and spatial resolution observations;
- Improved data product quality via high-precision calibration and data inversion technologies;
- Enhanced predictive capabilities for extreme events and long-term trends through the integration of climate models and data assimilation systems.

➤ This comprehensive approach aims to provide critical support for regional carbon budgeting, urban carbon verification, and international carbon certification. To summarize:

- We have constructed an internationally advanced SHS interferometric space remote sensing system;
- Realized global inversion and ground verification for CO₂ and CH₄;
- Promoted point-source-level imaging observation technologies toward satellite deployment;
- Established an initial "observation–inversion–verification–integration" technological chain.

➤ Looking forward, we will continue advancing high-resolution payload development and deepening synergistic research with climate modeling systems to serve China's "dual carbon" goals and global climate governance.



Thank you !!

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