IWGGMS-21

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

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2025.06 Takamatsu Japan

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

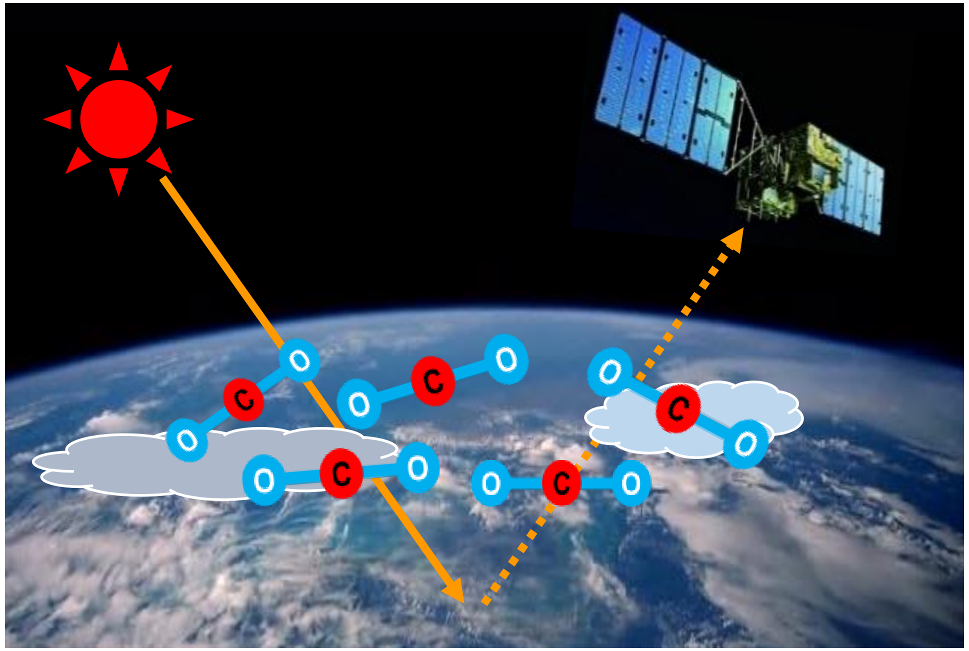
Requirements for Satellite Remote Sensing of Greenhouse Gases

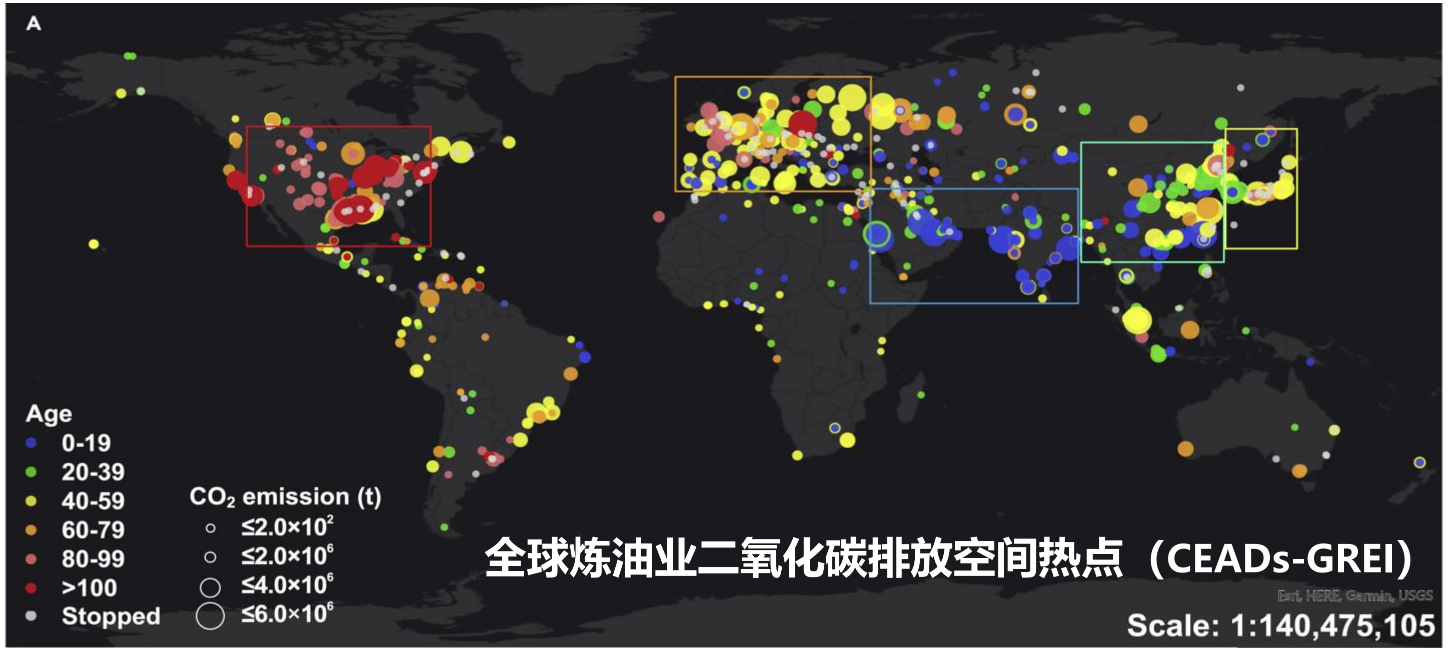
Critical needs

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.

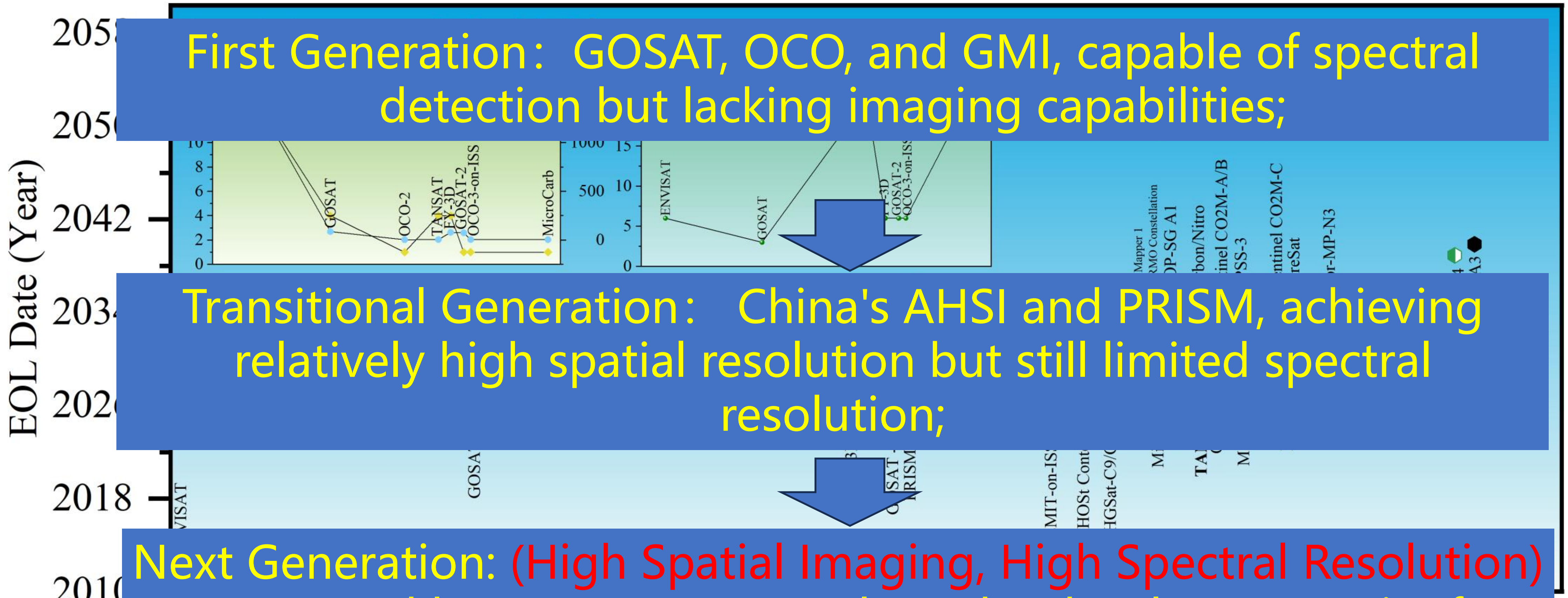




Tianyang Lei, et al., Nature,2023

- 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

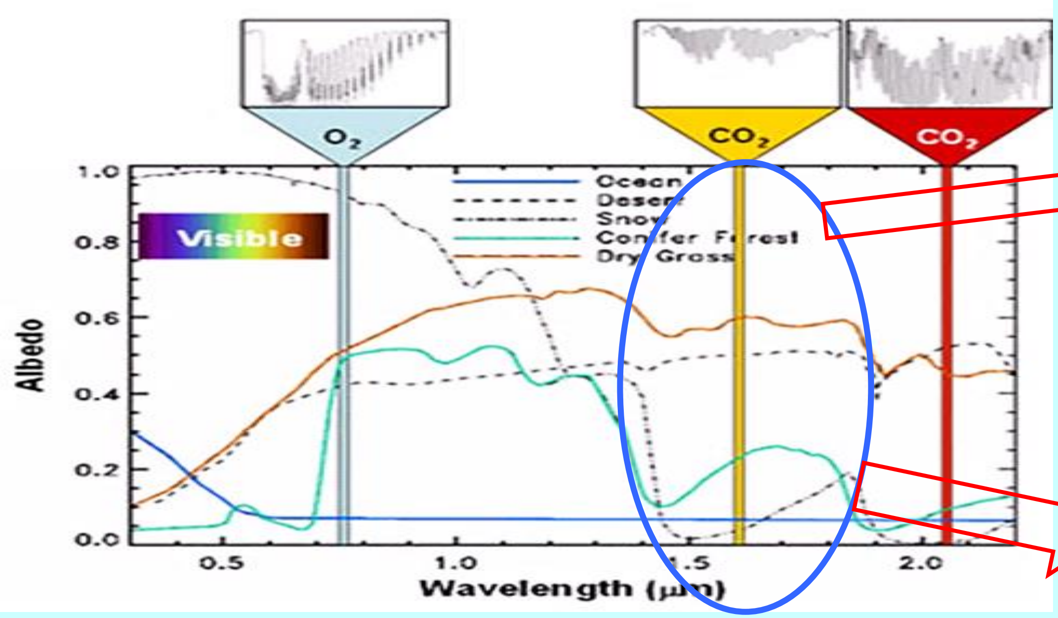


First Generation: GOSAT, OCO, and GMI, capable of spectral detection but lacking imaging capabilities;

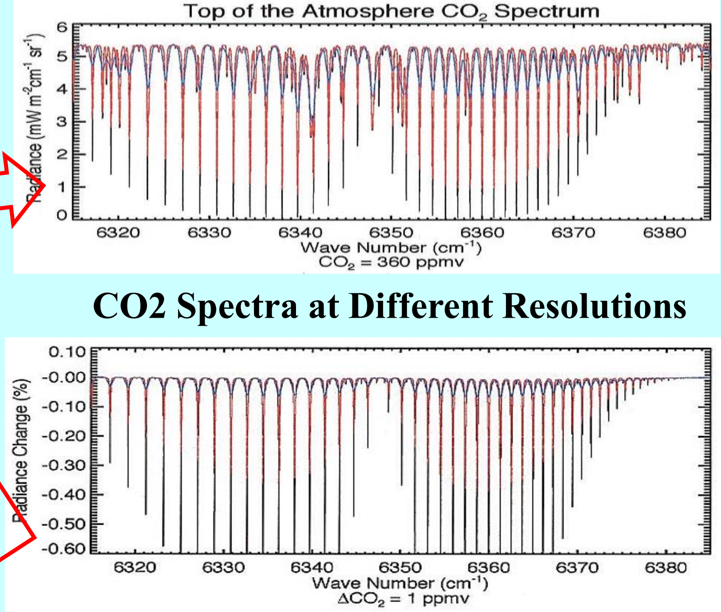
Transitional Generation: China's AHSI and PRISM, achieving relatively high spatial resolution but still limited spectral resolution;

Next Generation: (High Spatial Imaging, High Spectral Resolution) represented by TanSat-2, currently under development, aim for dual breakthroughs in both high spatial imaging and high spectral resolution.

Requirements for Satellite Remote Sensing of Greenhouse Gases



Satellite Remote Sensing Spectral Bands for Greenhouse Gases



CO2 Spectra at Different Resolutions

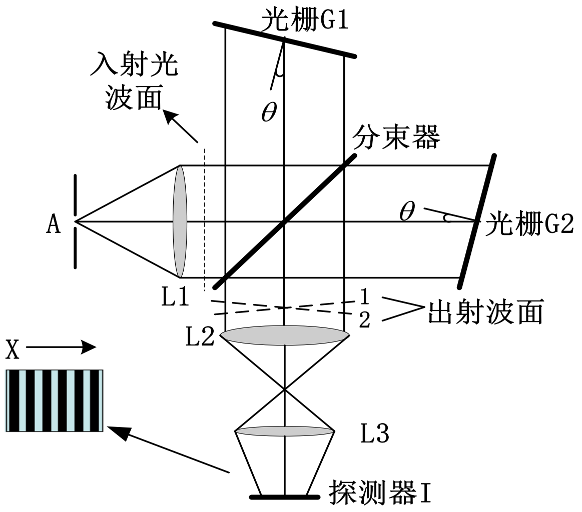
Spectral changes corresponding to 1 ppm

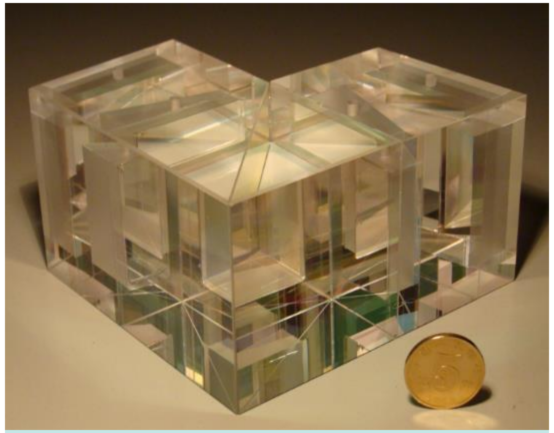
- **Low Concentration:** CO2 ~430 ppm
- **Long Lifespan:** Greenhouse gases are long-lived and evenly distributed.
- **Small Variation:** Max concentration change ~20 ppm.

Hyperspectral	High SNR	Multi-Element	High Stability
10 pm Spectral Resolution	SNR > 300 under typical conditions (ρ = 0.3)	Monitoring capability for major greenhouse gases like CO2, CH4	Long lifespan with precise radiometric calibration

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

Super-Resolution Heterodyne Interferometric Spectroscopy





Integrated Cemented Interferometer (SHS)

➢ 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.

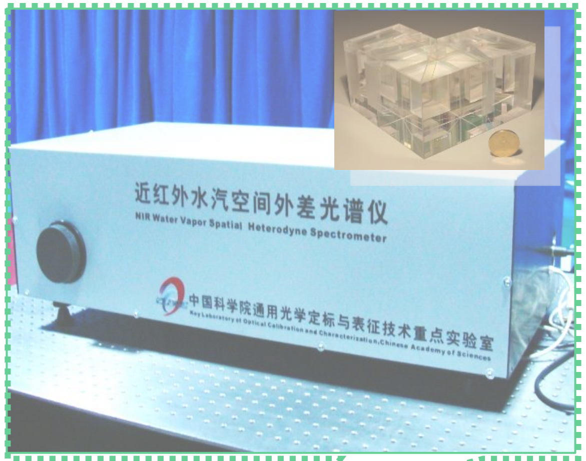
※Multi-Element Capability:
Supports multi-channel combinations for arbitrary, narrow wavelength ranges.

※Stability:
Monolithic cemented structure with no moving parts.

※Functionality:
Configurable as imaging/non-imaging systems.

Q. Wang, et al., Measurement, 2024

Super-Resolution Heterodyne Interferometric Spectroscopy



2006

2009

2010/Proof-of-Concept Prototype

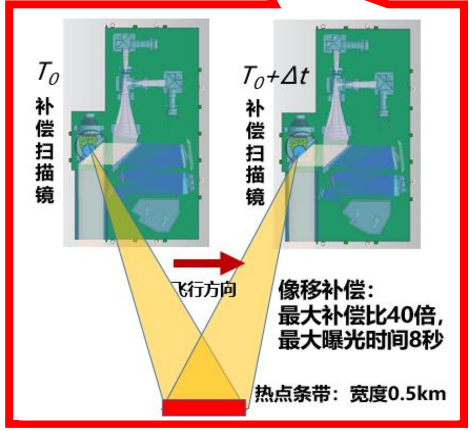
2026/0.5km

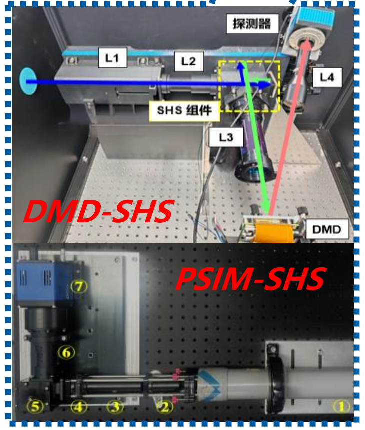
2024

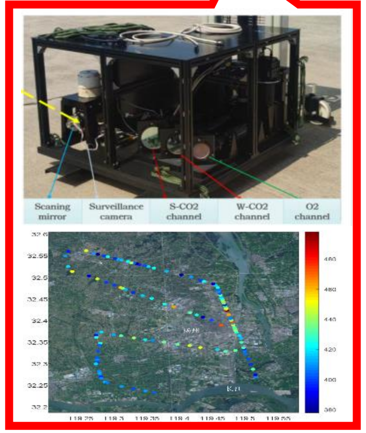
2023/3km

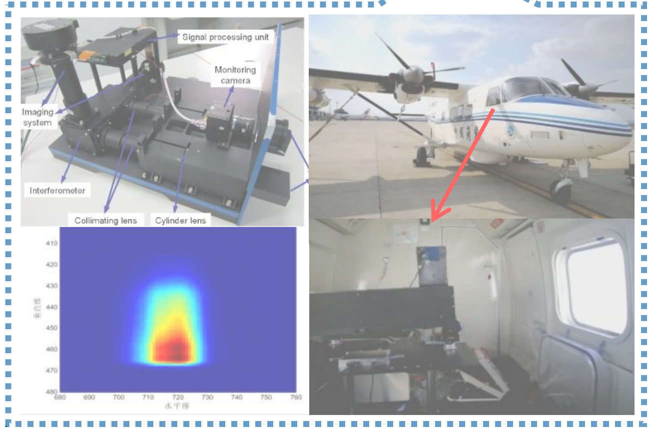
2021~2018/10.3km

2015









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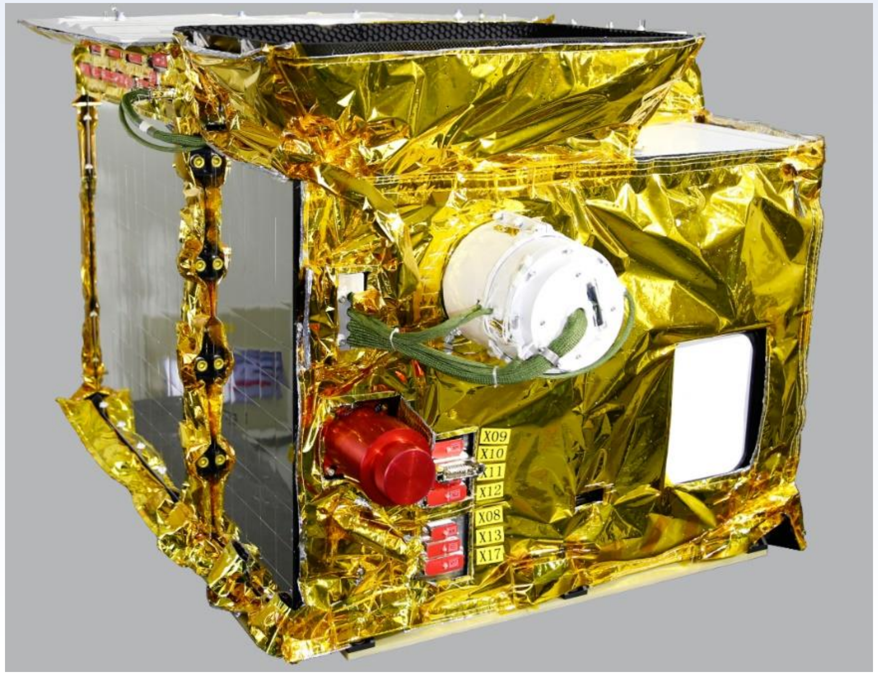
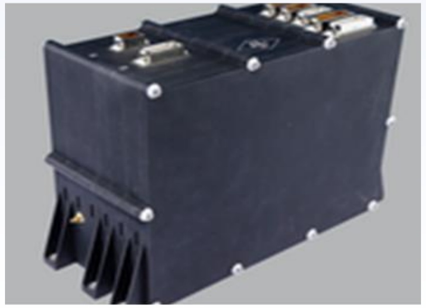
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

The major greenhouse gas monitoring instrument (GMI) , a core payload for atmospheric CO_2 and CH_4 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).





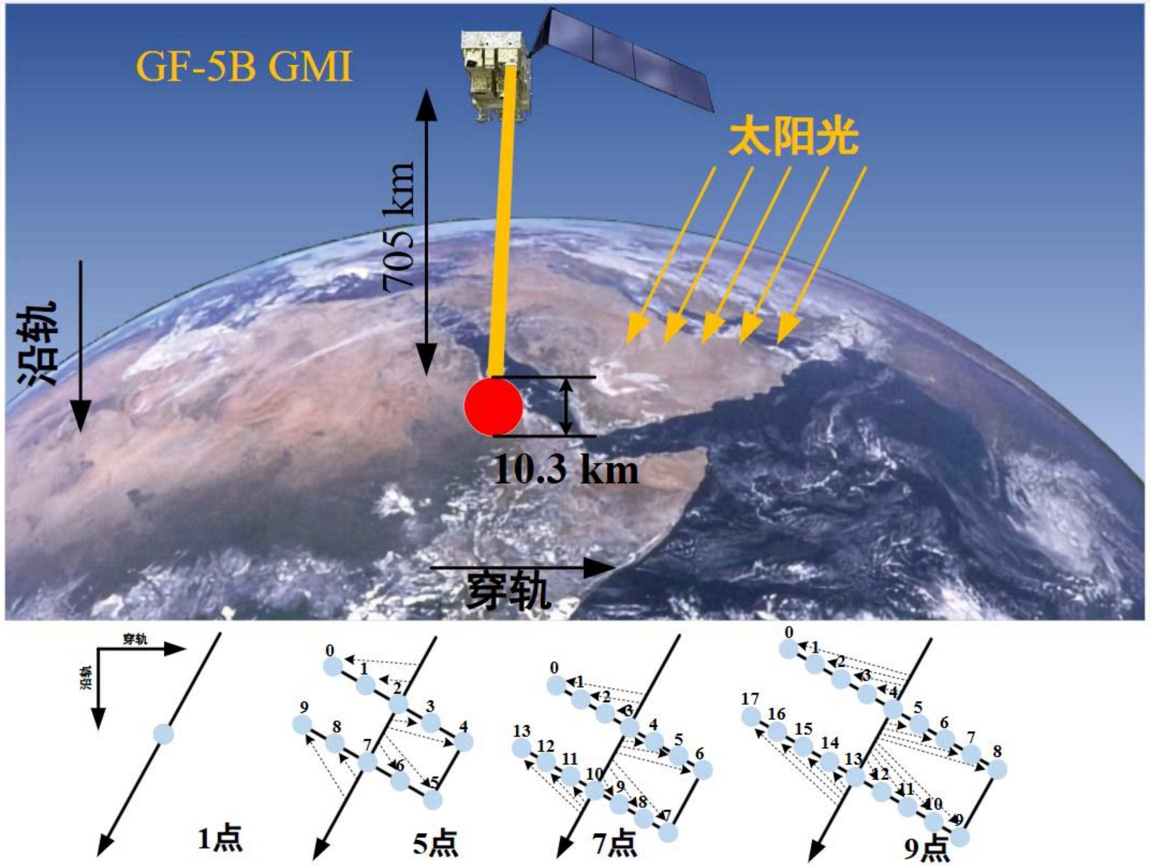
Instrument Components:

- Optical Head
- Information Processing Unit
- Drive Control Box
- Temperature Control Box

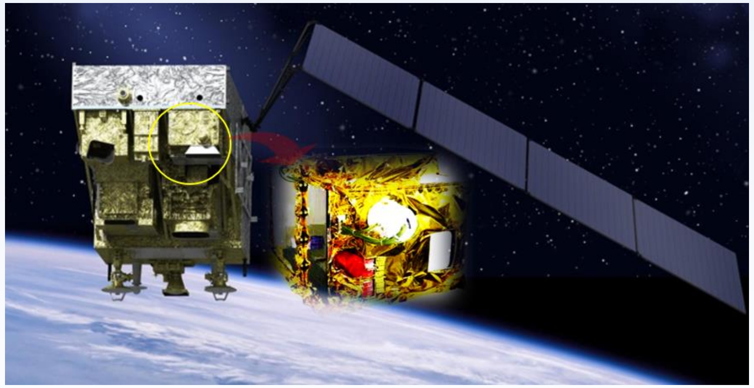
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

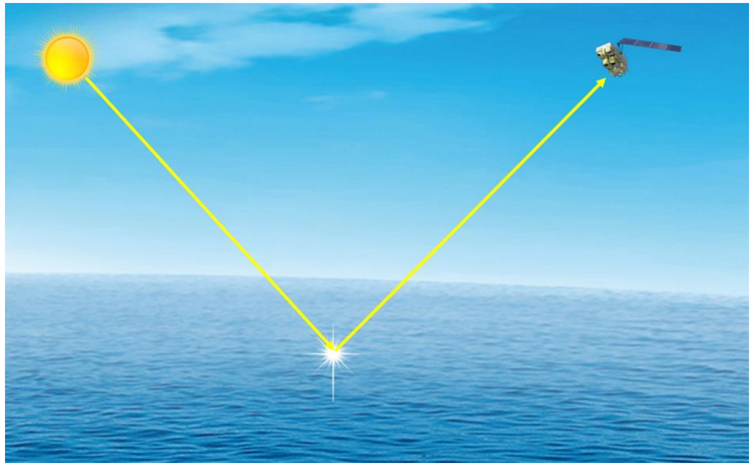
In practical operation, the onboard GMI instrument supports multiple observation modes:

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



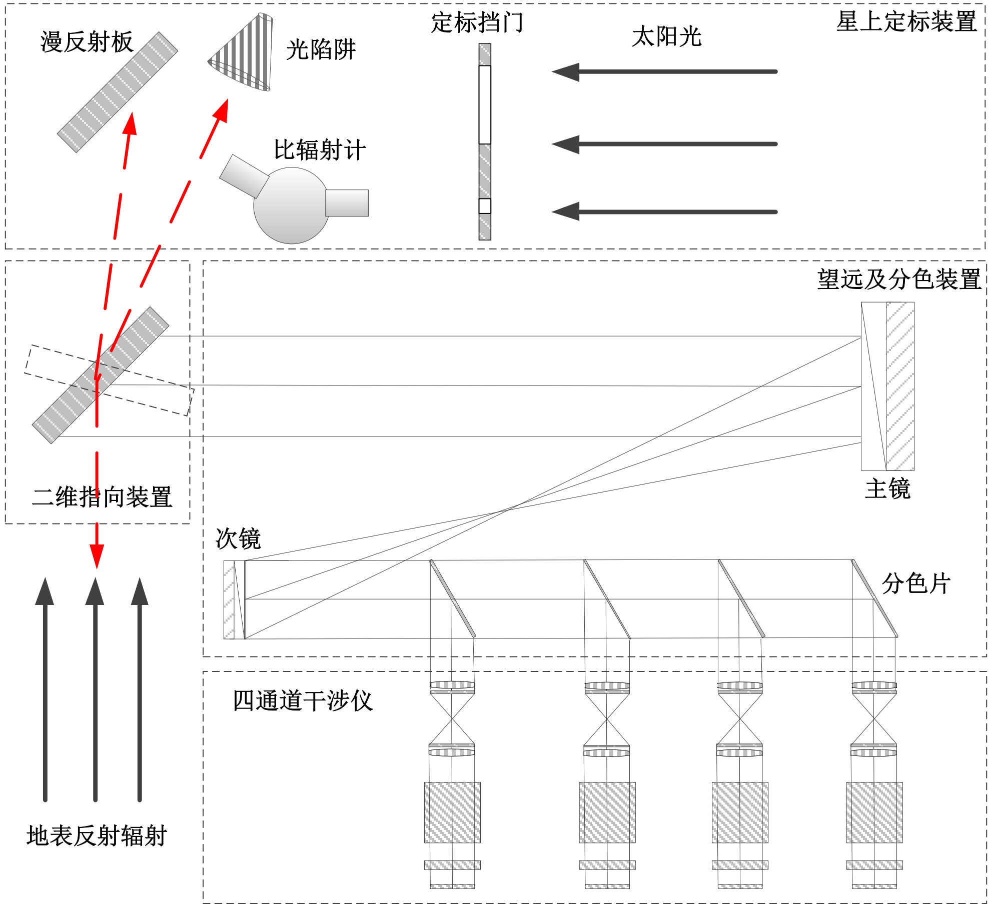
Glint mode: Uses direct sunlight reflection to enhance signal intensity.





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

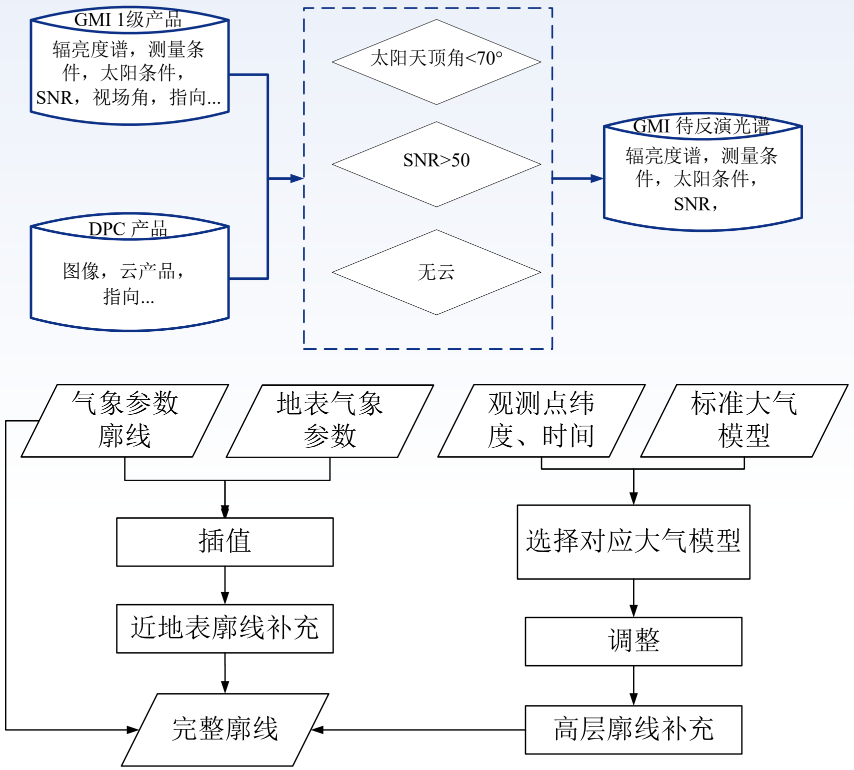
- **Statistical inversion and three-band spectral synergy for CO2/CH4, surface reflectance, and aerosol optical thickness, reducing scattering effects;**
- **Enhance regional statistical data for physical inversion;**
- **Path length correction;**
- **Aerosol inversion in high-value areas;**
- **Surface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

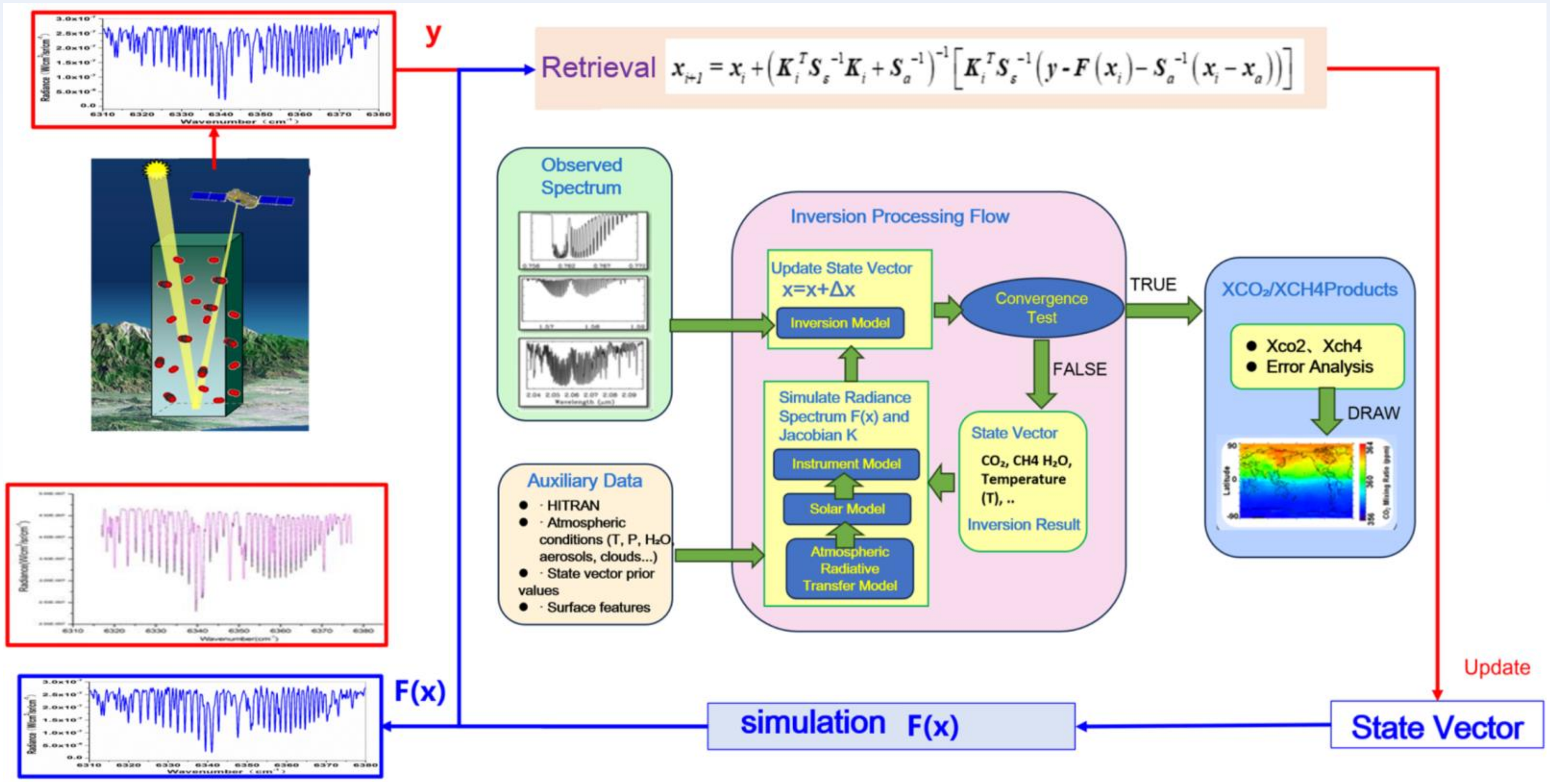
This significantly enhances retrieval accuracy within China.

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

□ Greenhouse Gas Concentration Data Product Production Process

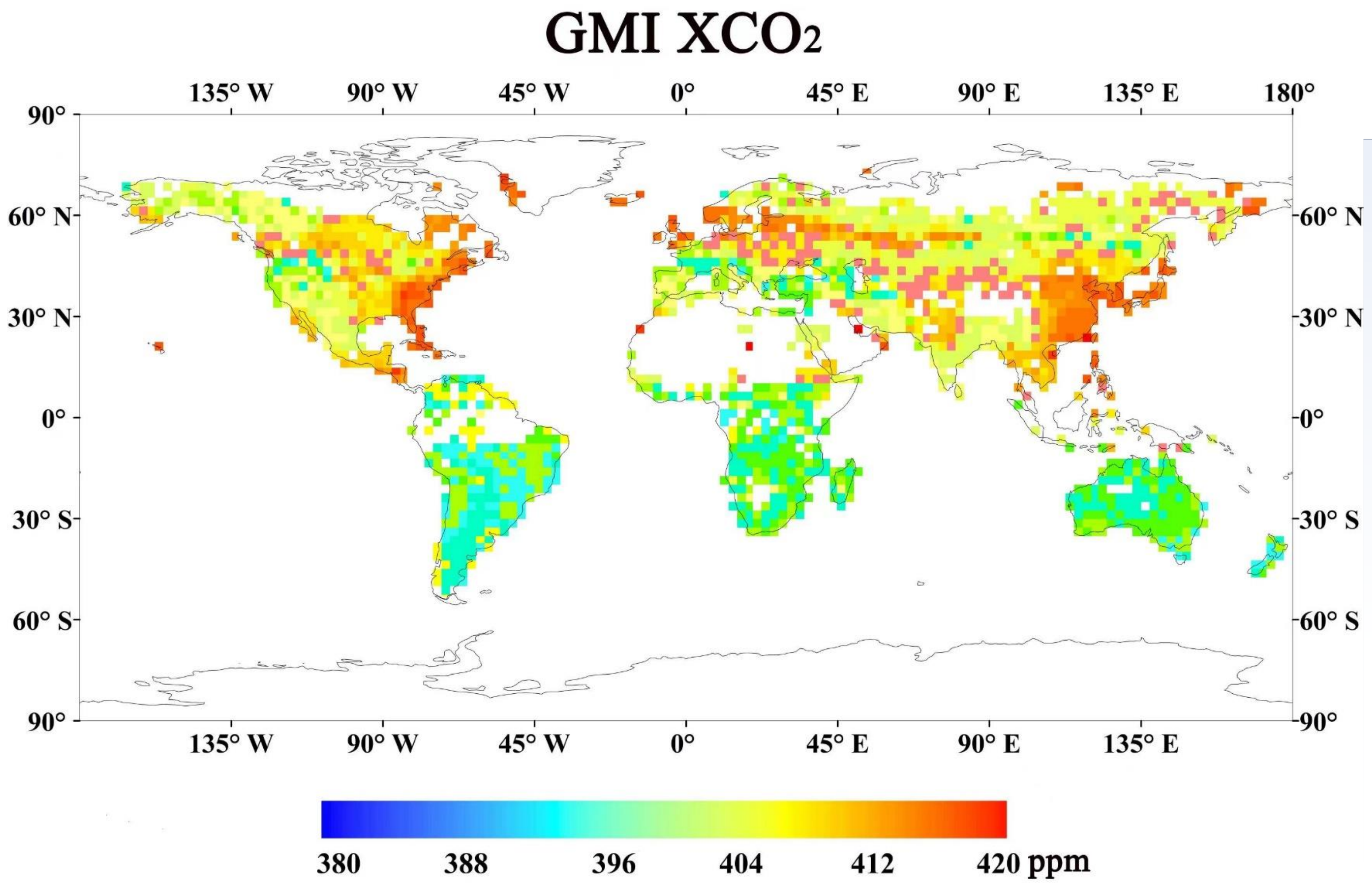
- Data Filtering
- Spectral Calibration
- Concentration retrieval





This integrated process yields standardized quantitative products for CO_2/CH_4 concentrations.

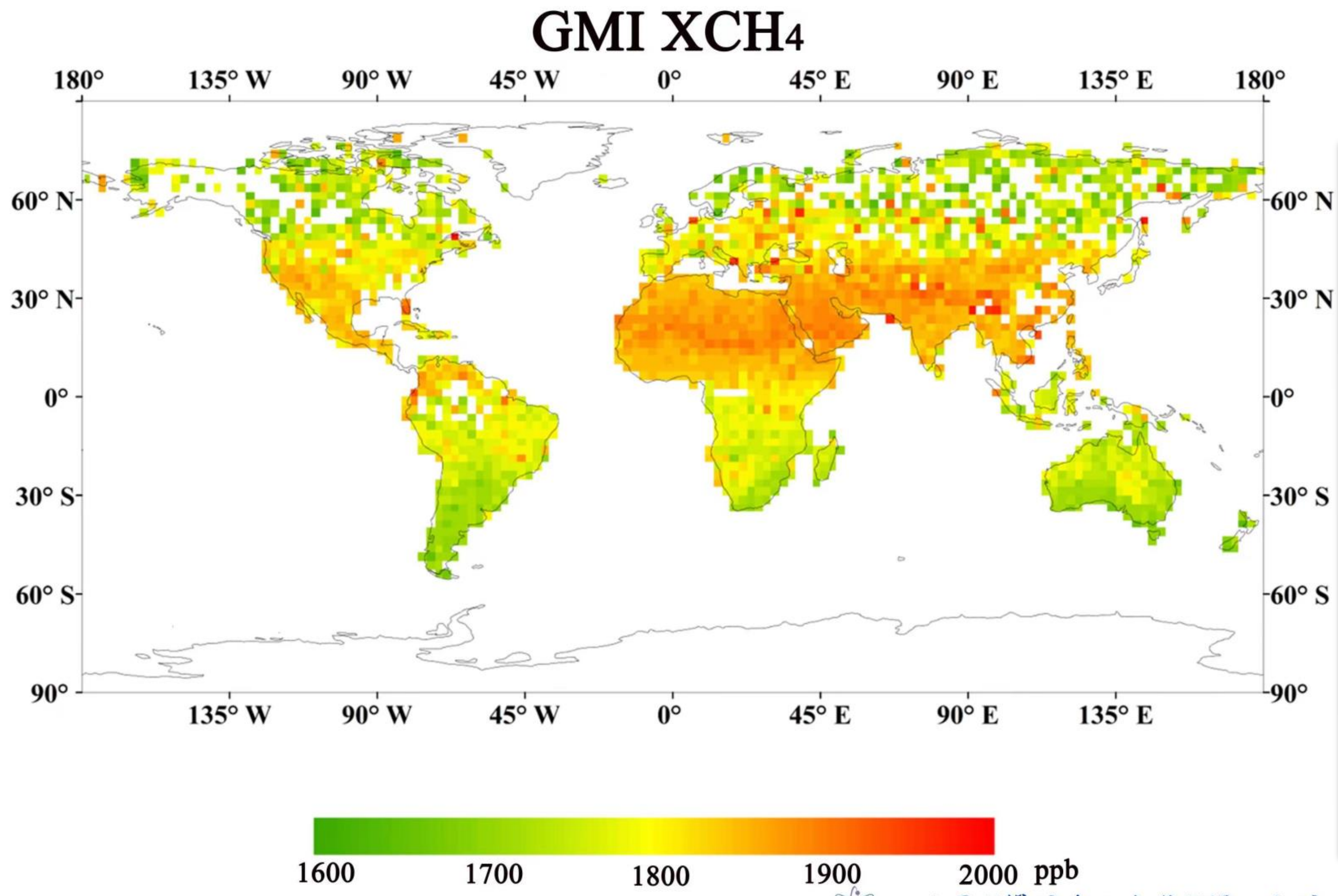
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks



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.

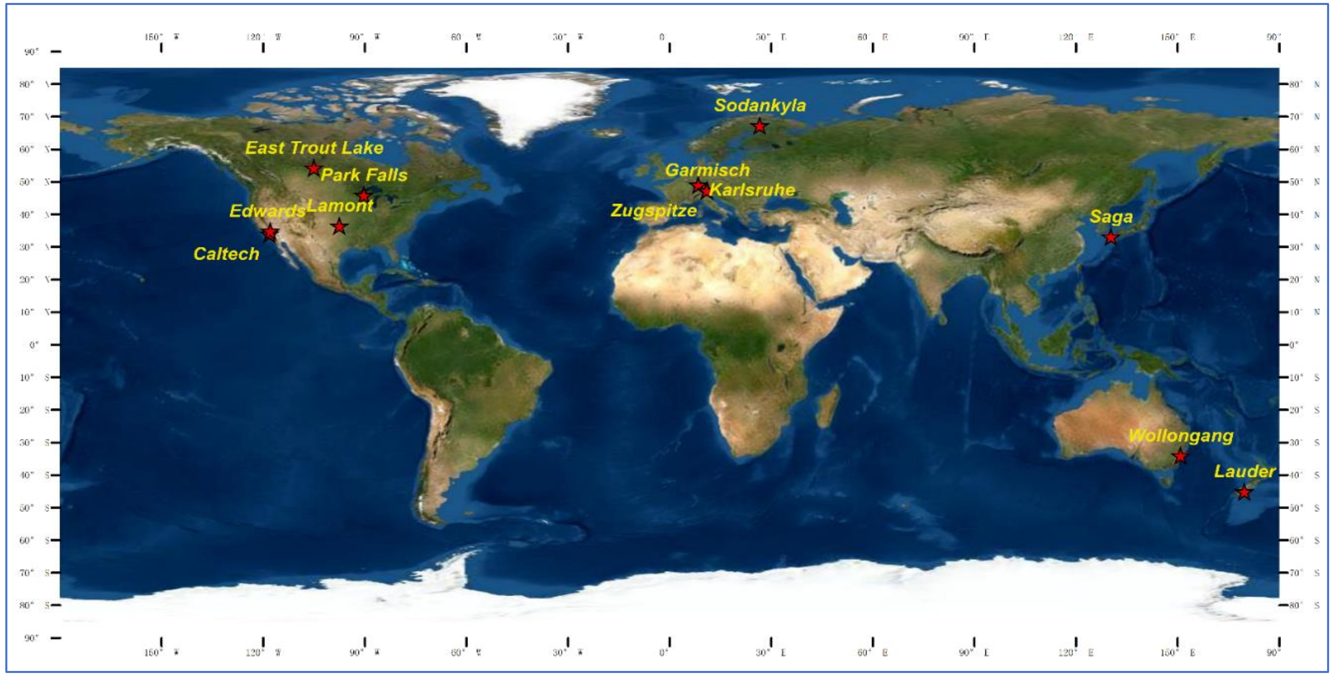
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks



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.

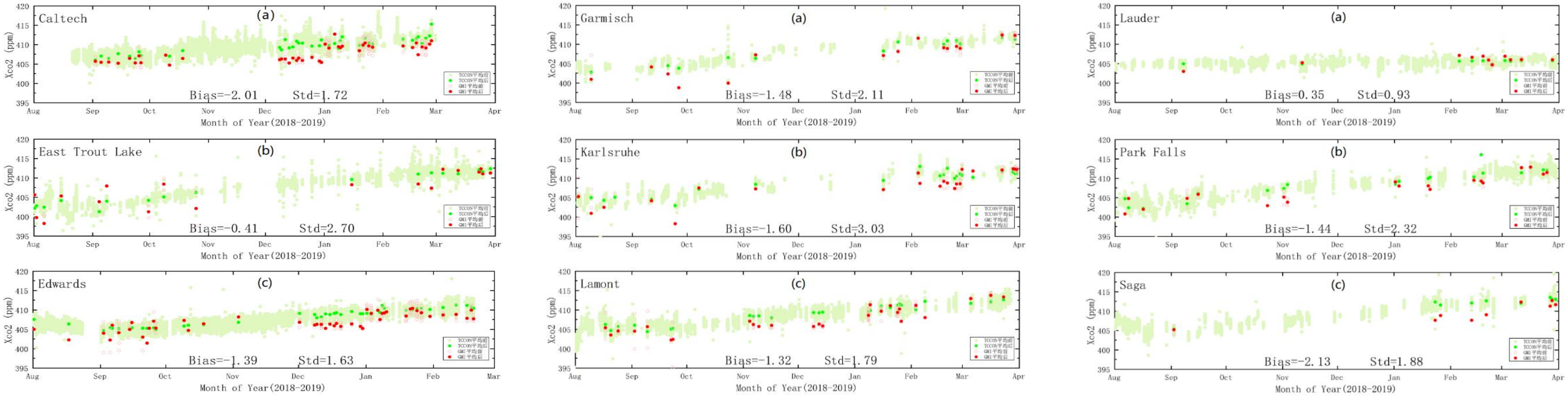
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks



- **Accuracy Validation of GMI CO2 with TCCON;**
- **Nine TCCON sites covering major global regions are used for comparison;**
- **Data is matched within ±5° 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

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

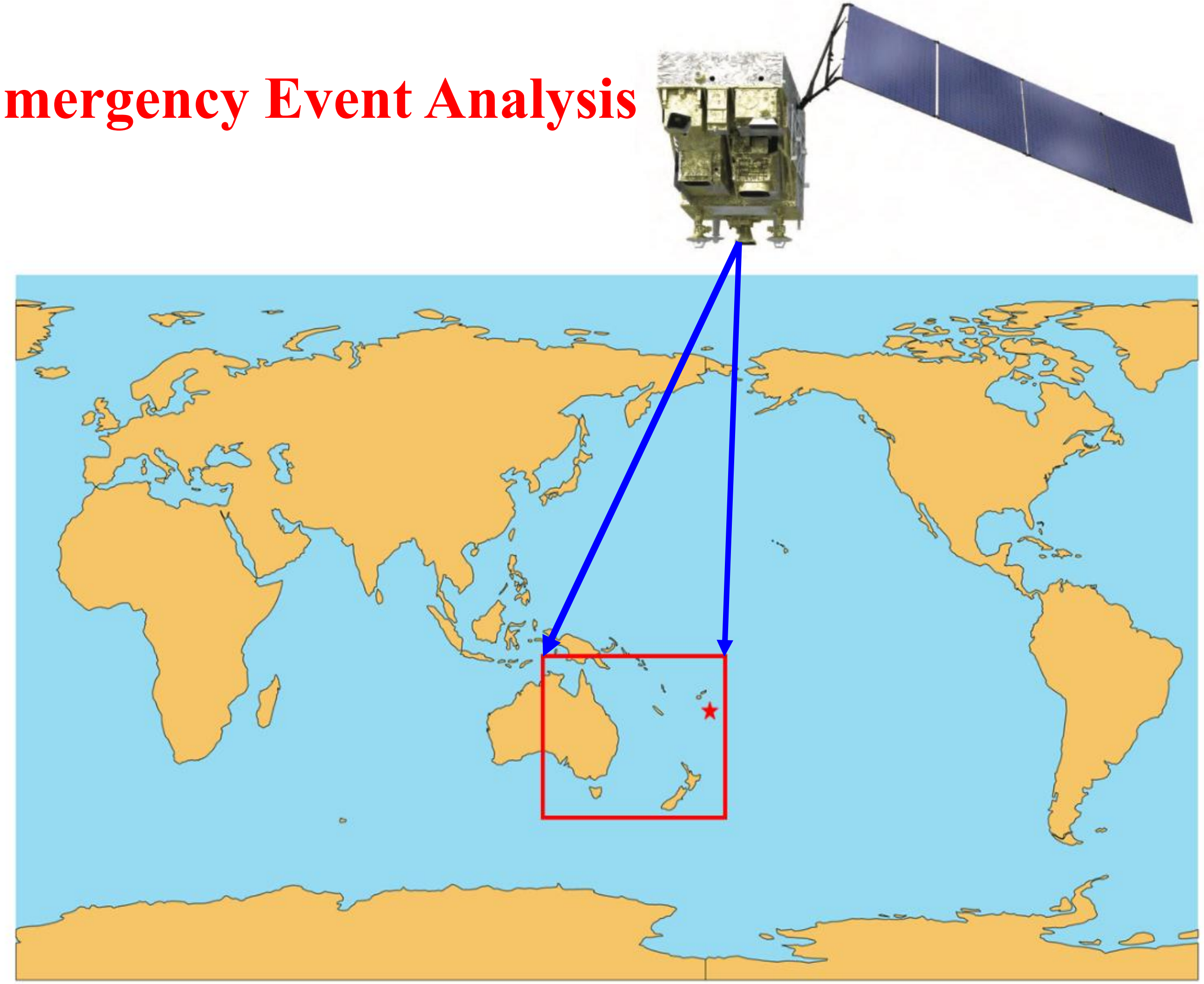


Sites	Lat	($GMI\ SWIR\ XCO_2$)-(g-$b\ FTS\ XCO_2$)			($GMI\ SWIR\ XCO_2$)-(g-$b\ FTS\ XCO_2$) / g-$b\ FTS\ XCO_2$	
		Number of data	Average (ppm)	1σ (ppm)	Average (%)	1σ (%)
Saga	33.24	10	-1.93	1.96	-0.47	0.48
Caltech	34.14	136	-1.71	1.91	-0.42	0.47
Edwards	34.96	167	-1.21	1.94	-0.29	0.48
Lamont	36.6	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.**

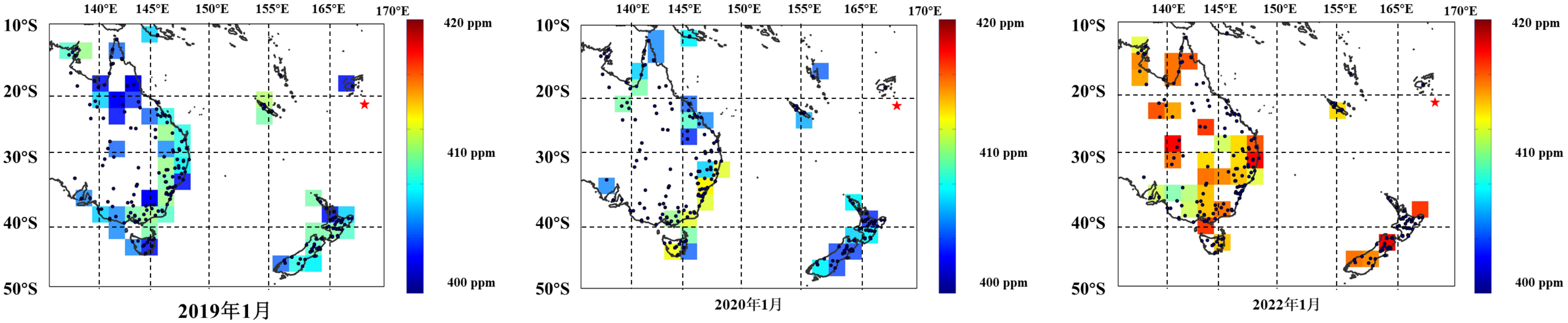
Satellite-Based Detection and Validation of Greenhouse Gas Sources and Sinks

Emergency Event Analysis



（submarine volcano in the Kingdom of Tonga ）

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



- 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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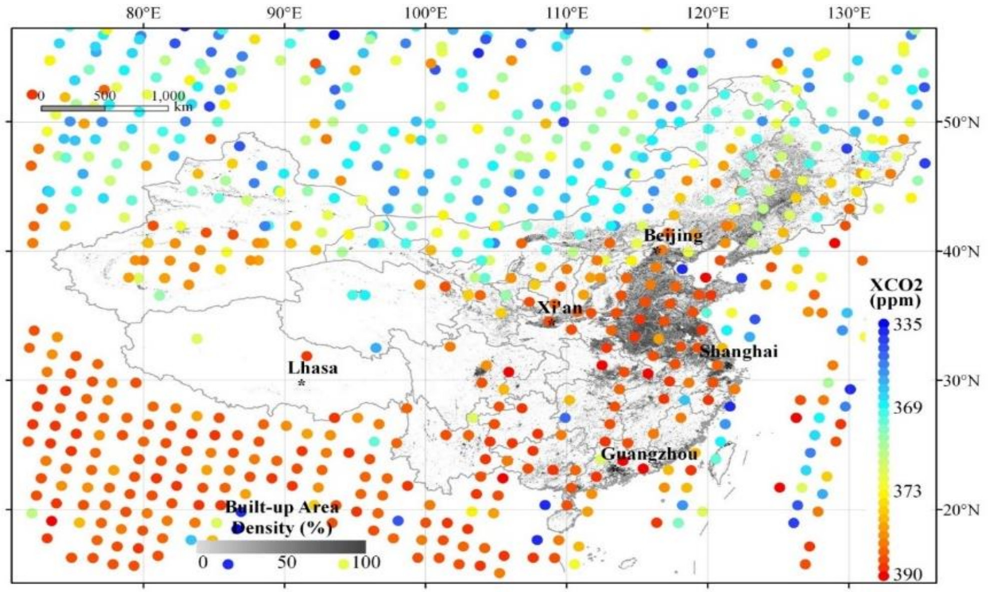
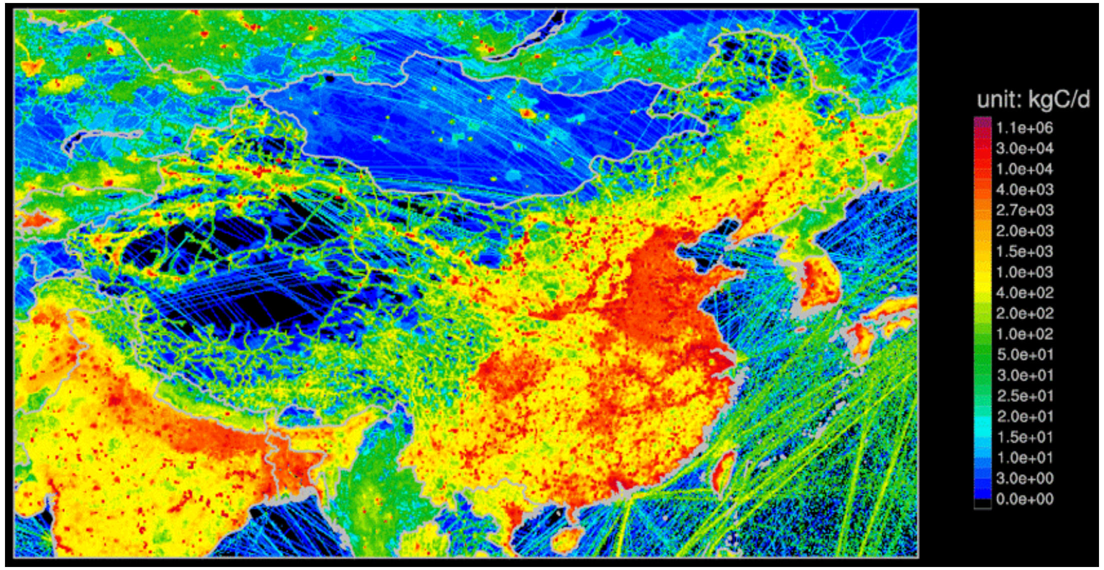
Satellite-based "Point Source" Greenhouse Gas Detection Technology / Medium Orbit

■ Non-Imaging Detection (Global Scale)

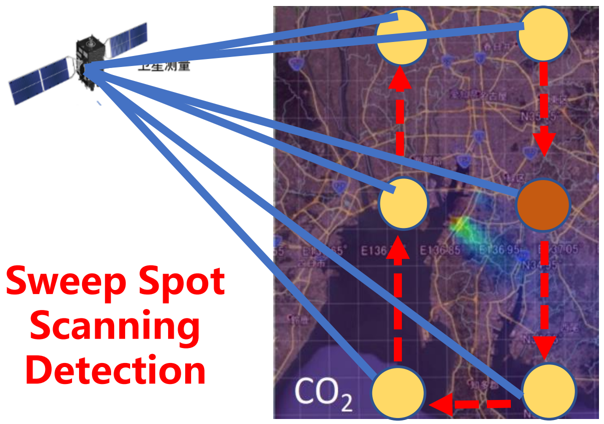


■ Imaging Detection (Urban/Point Sources)

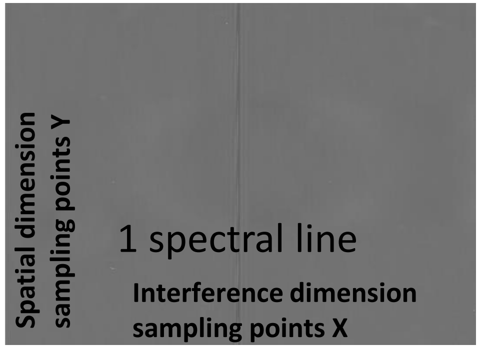


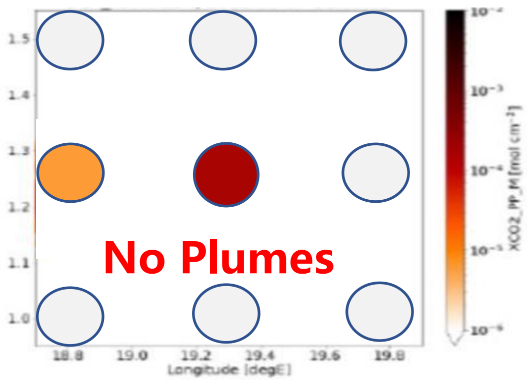
- Existing technologies focus on **non-imaging large-scale detection** (global greenhouse gas dynamics);
- Next-generation technologies prioritize **imaging regional-scale detection** (urban/point-source emissions);
- **Urgent need** : Development and data processing for **high-resolution imaging carbon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

Satellite-based "Point Source" Greenhouse Gas Detection Technology / Medium Orbit

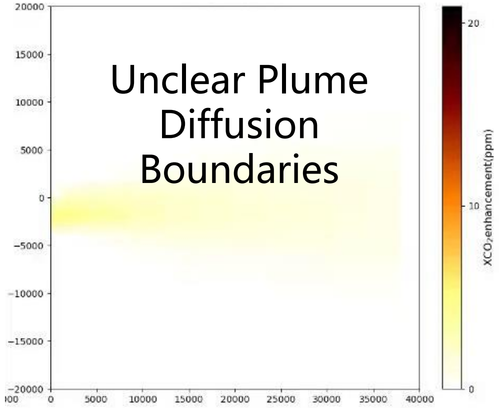


GF-5 Satellite : Greenhouse Gas Monitoring Payload

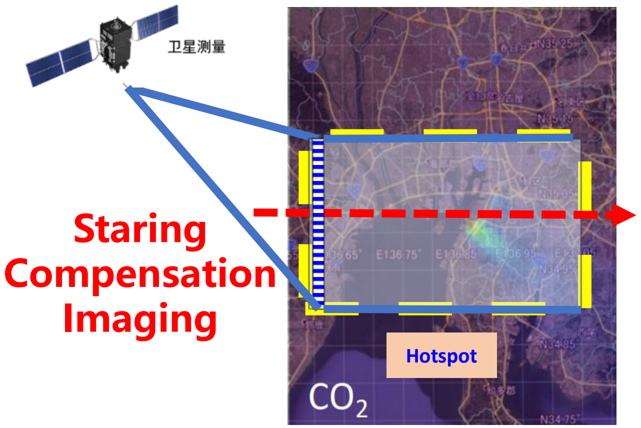


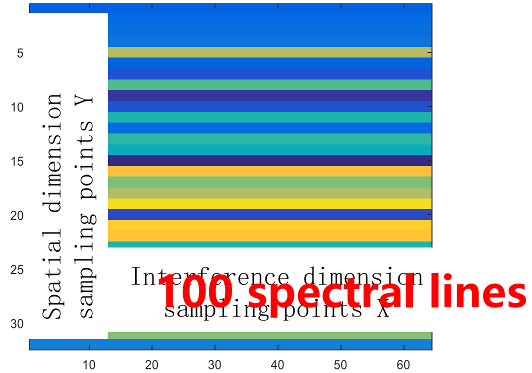


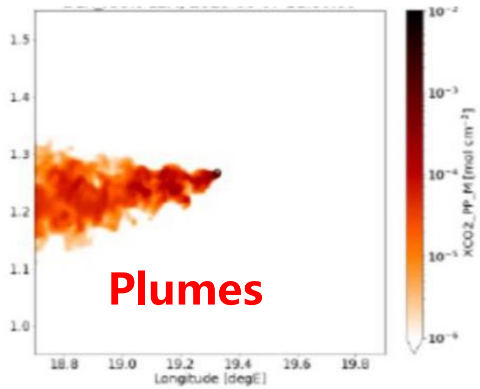
High-Resolution Support for Hotspot Carbon Emission Calculation

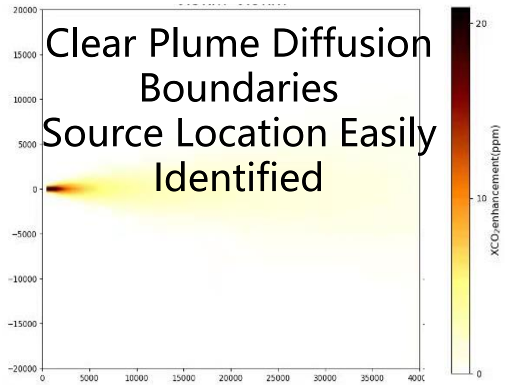


TanSat-2 Satellite : High-Resolution Hotspot Monitoring Payload







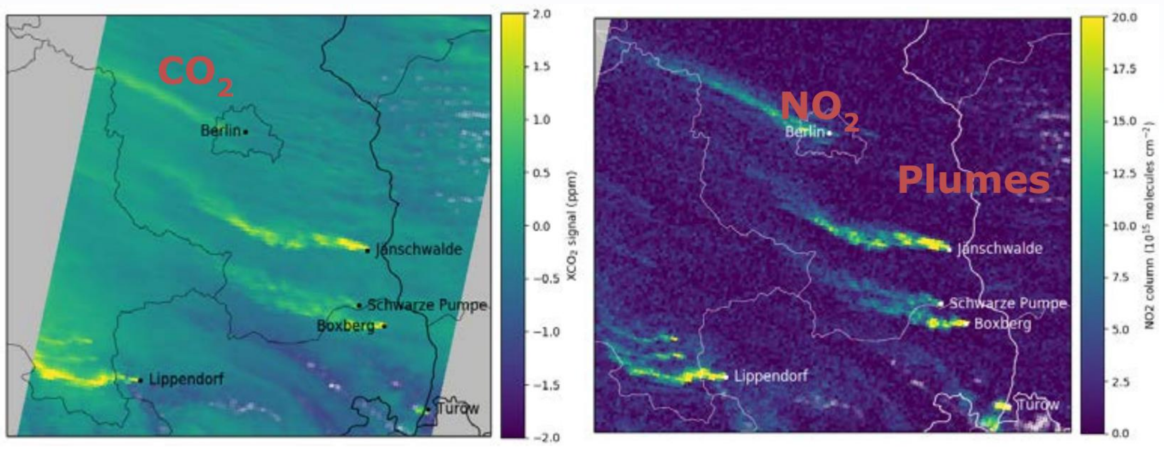


Achieve a spatial resolution of 0.5 km or higher, improving detection and increasing data volume by two orders of magnitude.

Satellite-based "Point Source" Greenhouse Gas Detection Technology / Medium Orbit

Tansat-2 Application Efficacy:

- High-resolution monitoring of CO_2, CH_4 greenhouse gases and NO_2 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 @ 7.85×1019 photons/sec/m2/Sr/μm *CH*4:250 @ 7.85×1019 photons/sec/m2/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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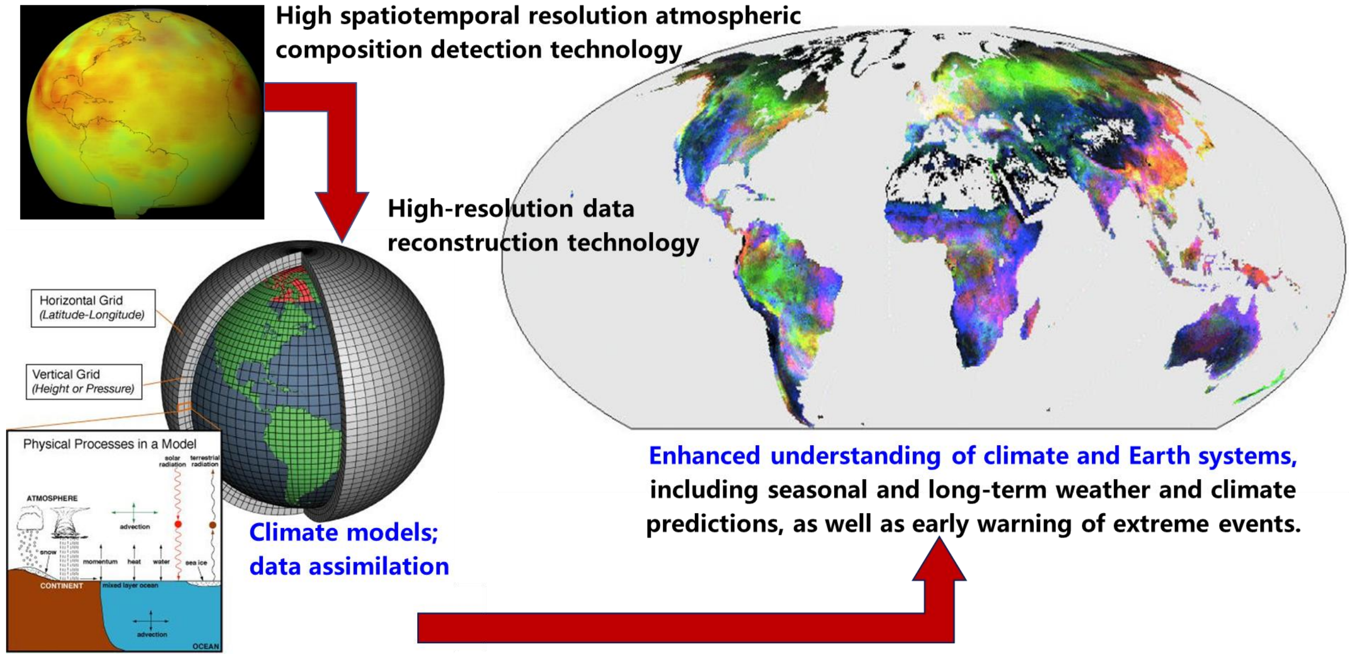
Related Achievements and Future Prospects

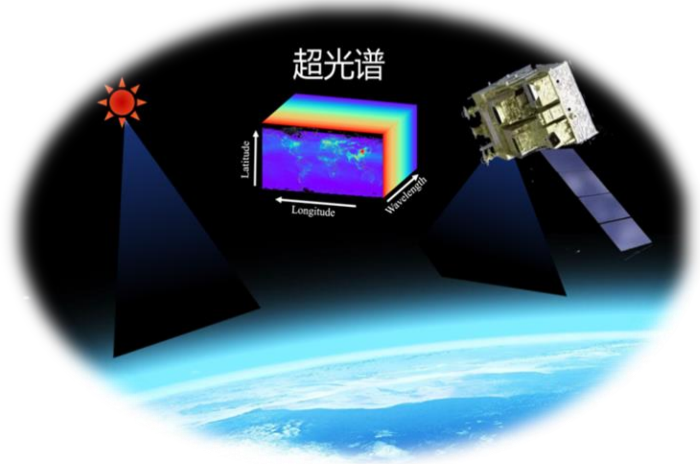


➢ **Our research goes beyond payload-level innovations to encompass the full chain of carbon monitoring and climate system simulations:**

- 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 CO_2 and CH_4;
- 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.**

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