A spatio-temporal combined modulation technique for CO_2 on GSO

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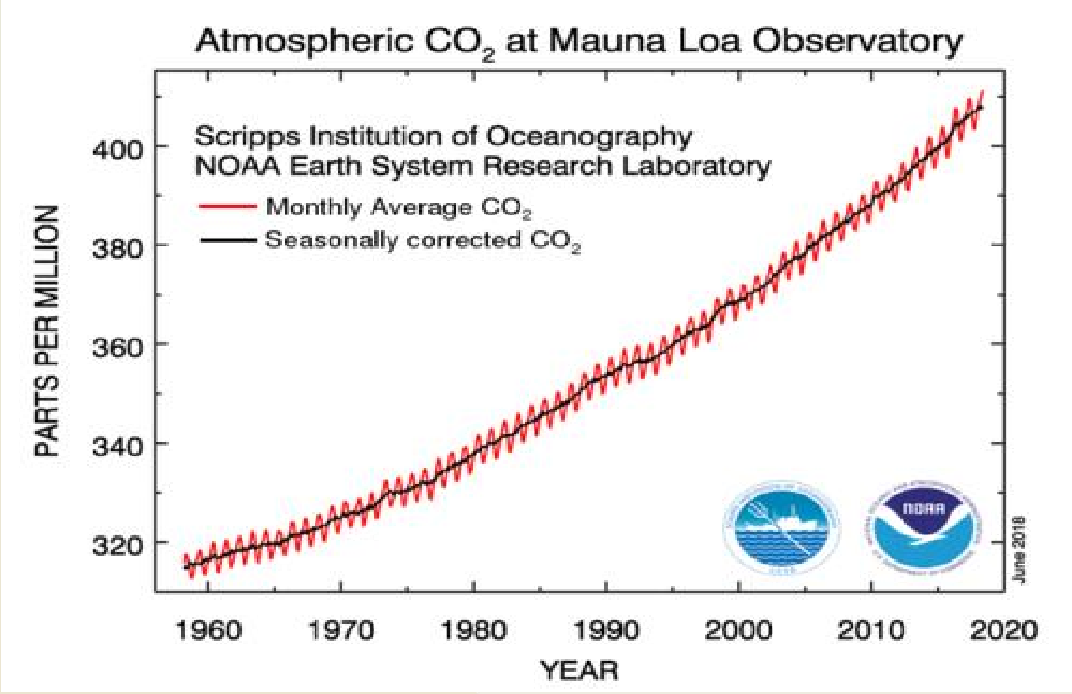
1 Introduction

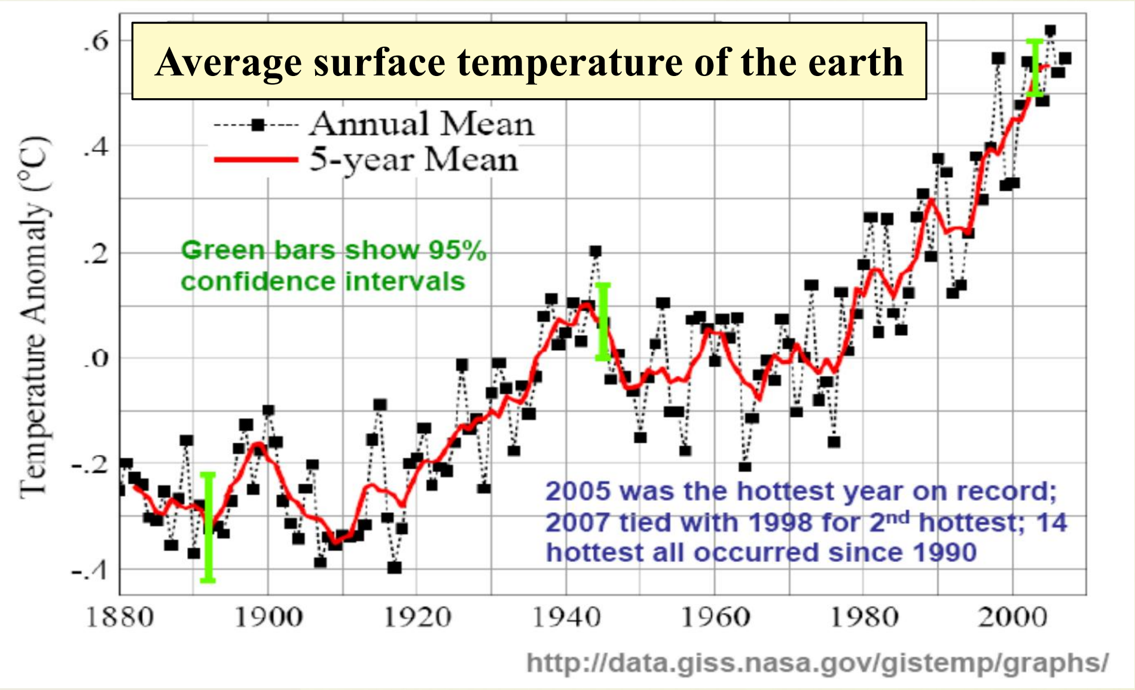
Research background

Greenhouse gases play a major role in global climate change:

1）Over the past 100 years, CO_2 concentrations have increased from **280ppm to 400ppm** with an average temperature increase of **0.85 ℃** (IPCC 2013)

2）Greenhouse gases from the burning of large amounts of **fossil fuels** are the main drivers of climate change (IPCC 2014)





Existing problem

According to the Paris Agreement, the global average temperature should be controlled within 2 ℃ by 2100 (the target is 1.5 ℃). Through **satellite remote sensing(IPCC 2019)**, global scale greenhouse gas concentration data and carbon emission data can be obtained, which can be used to **check national and regional greenhouse gas inventories and statistical emissions**. However, the existing satellite remote sensing monitoring technology still has the following problems and deficiencies

a. Existing CO_2 monitoring satellites achieve monthly global coverage at most, which is far from **daily coverage** applications.

b. Accurate location of GHG emission sources requires monitoring loads with **spatial resolution** of better than 1~2km or even higher.

c. The DQ-2 satellite being developed by China has high spatial resolution (3km), but insufficient **wide coverage** (86km).

3 Design and calibration

Design of STIIS prototype

The STIIS prototype design requirements are shown in Table 1. The spectral SNR of each detection channel under typical radiance is better than 300 and 200 respectively, which meets the requirement of CO_2 detection accuracy better than 4ppm.

Table. 1. Design requirements of STIIS prototype.

Channels	O2	W-CO2	S-CO2
Spectral range/μm	0.759-0.769	1.568-1583	2.043-2.058
Spectral resolution	0.035nm	0.080nm	0.120nm
SNR	300		200
Spatial resolution	＜3.0km@36000km		

The F number of the optical system is better than 5, and the SNR can be further improved by increasing the integration time (~500ms/ frame) and the number of acquired frames (≥5 frames).

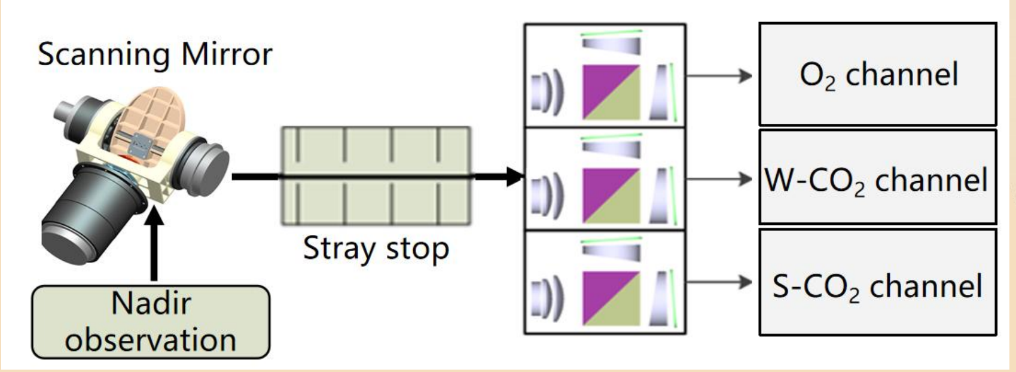


Fig. 3. Channel layout of STIIS prototype.

For the detection of CO_2, the main greenhouse gas in the atmosphere, the STIIS prototype is **divided** into three channels according to the design requirements of Table 1.Considering the effect of optical system efficiency, S-CO_2 is the first channel, followed by W-CO_2 and O_2 channels. There are also narrow band filters in each channel to avoid aliasing of low and high frequency interference spectra.

Fig. 4 shows the allowable defocusing range of the image plane of the W-CO_2 fore optics. and because the channel is the most important for inversion. Other dispersion modules and rear zoom imaging systems are designed on the same principle as the GF-5 GMI. On GSO(36,000 km), the W-CO_2 channel has a spatial resolution of 2.0 km and a spatial width of 1,024 km.

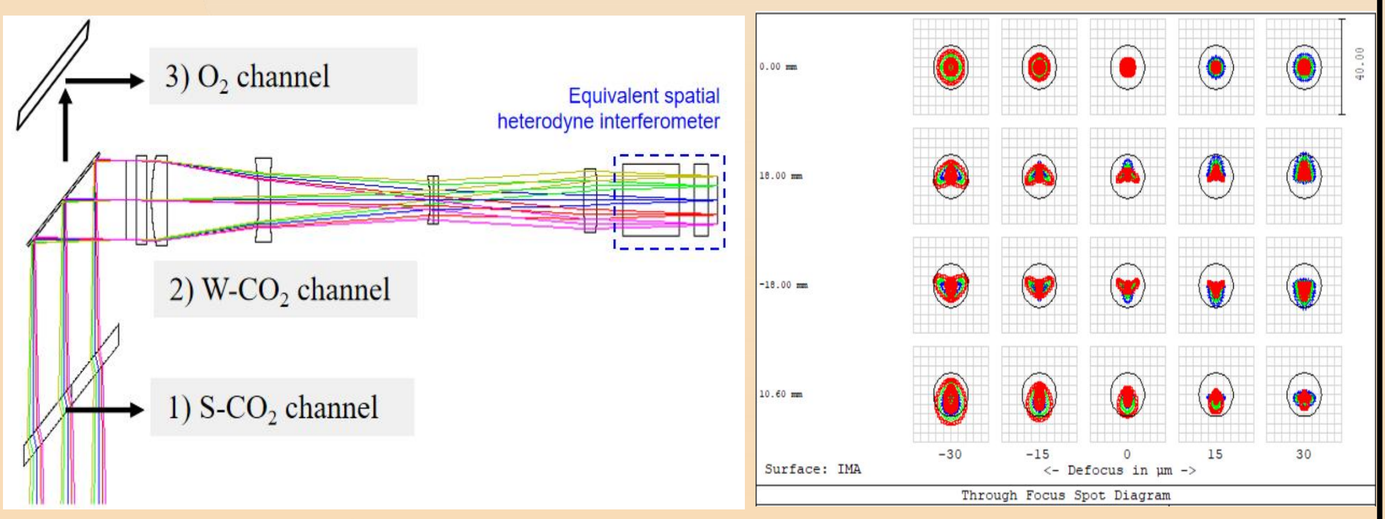


Fig. 4. Fore Optics of the STIIS W-CO_2 channel and the change of image point defocusing.

Field of view registration between channels of STIIS prototype

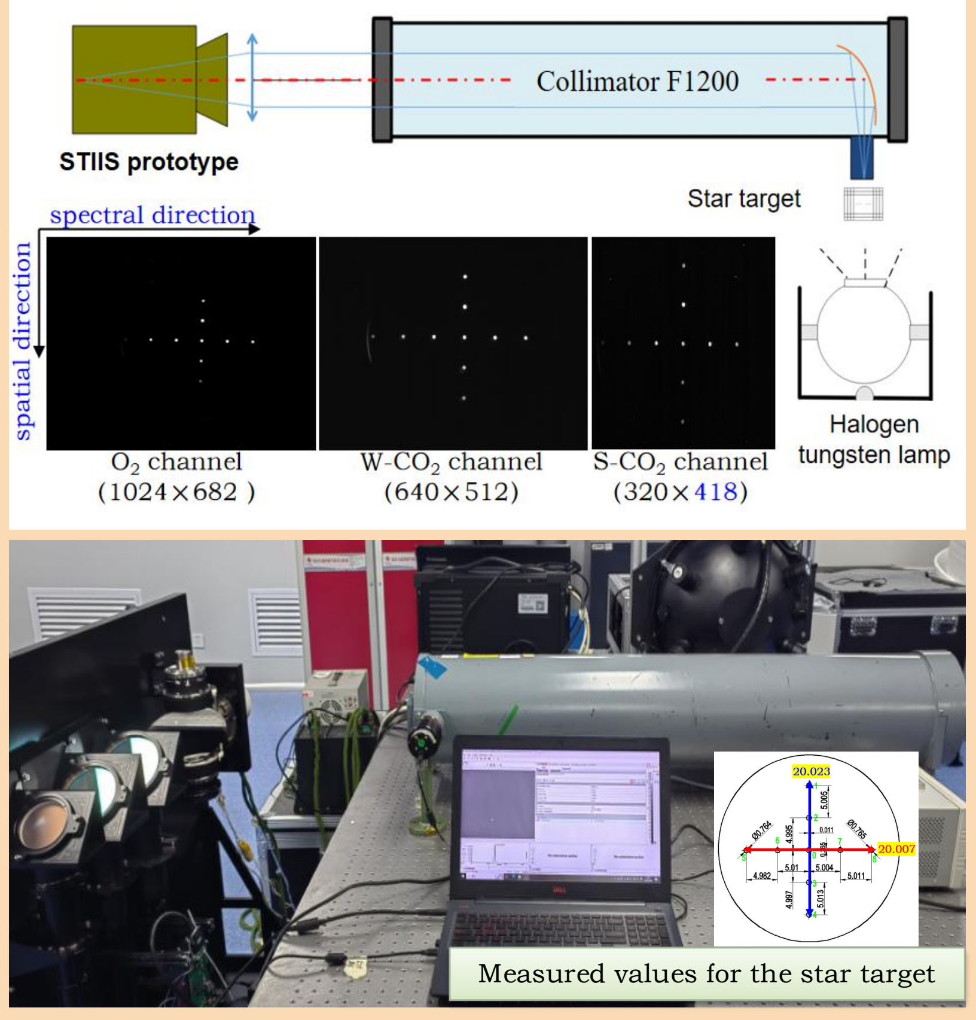


Fig. 5. Three channel field of view registration principle and test site

Different from GF-5 GMI, the STIIS prototype requires field of view registration and spatial resolution testing, and its method is shown in Figure 5. The STIIS prototype datum plane transfer process is as follows:
1) Core interferometer component beam splitter
2) Froe optics optical axis and its mechanical datum
3) Optical axis and its mechanical datum of dichroic mirror or reflector
4) two-dimensional scanning mirror substar point

Table. 2. FOV registration requirements and test results.

Channels	O_2	W-CO_2	S-CO_2
Designed spatial resolution /km	1.50	2.00	2.50
Measured spatial resolution /km	1.55	2.07	2.53
Measured spatial width /km	1587	1060	1042
Registration Requirements / Pixel	±192	±15	±12
Registration result / pixel	-1.2	-0.9	0.1

2 Technical principle of STIIS

The United States originally planned to launch **GeoCarb** geostationary orbit satellite in 2022, with a spatial resolution of 5~10km, an observation width of 5800km, with CH_4, CO_2 and CO detection channels, of which CO_2 detection accuracy of 2.7ppm. But for financial reasons, the program was discontinued.

In the manuscript, a **S**patio-**T**emporal combined modulation spatial heterodyne **I**nterferometric **I**maging **S**pectroscopy technique(**STIIS**) was proposed for the CO_2 detection. Based on STIIS, a high spatio-temporal resolution atmospheric greenhouse gas monitor is developed, with **a spatial resolution of 2.5 km**, **an observation width of more than 1000 km** limited by the number of detector pixels, and a detection channel of O_2, W-CO_2 and S-CO_2, which can meet the requirements of **revisiting the coverage area (5000km×3000km) in hours on GSO**.

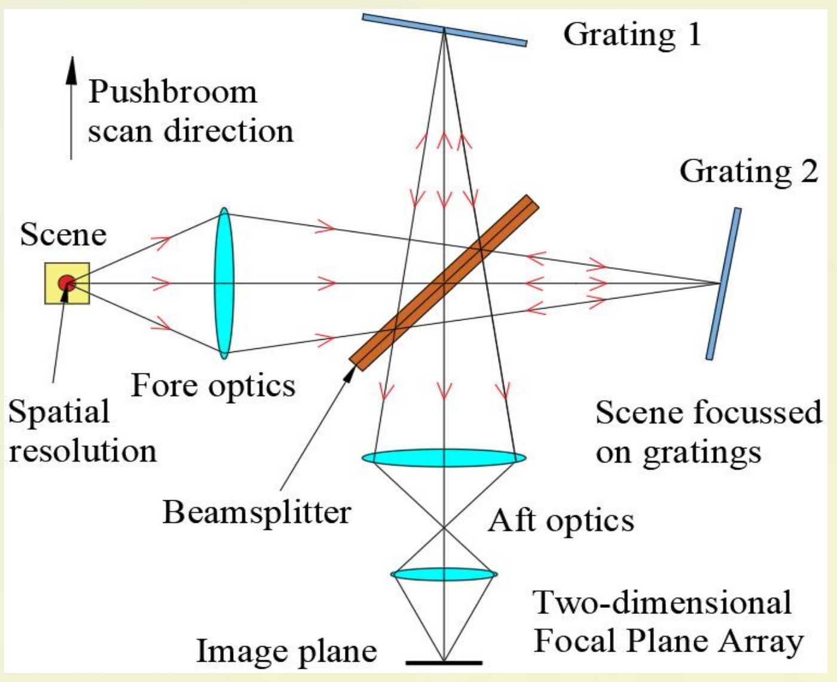


Fig. 1. Schematic diagram of the optical principle of STIIS

The fore optics is designed as a collimating objective system, on the one hand, in order to ensure that the measured target is imaged on the local surface of the interference fringes; on the other hand, it is required that the main light incident to the interferometer is consistent with the optical axis, that is, **telecentric imaging**, so as to maximize the modulation efficiency of the interference image. Among them, the spatial interference module is the core component of the instrument, in which the plane reflector in the two arms of the **Michelson interferometer** is replaced by a diffraction grating respectively.

Through push-sweep along the spectral dimension, in the direction perpendicular to the interference fringes, the optical path differences of different target units in the same field of view are different. After **continuous acquisition**, the interference information of **different optical path differences of the same object target** is obtained.

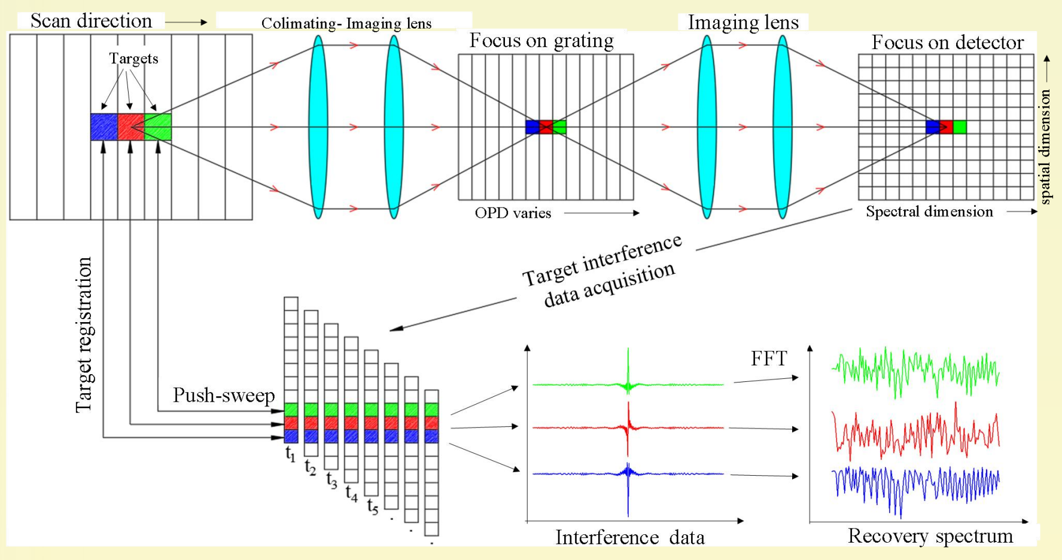


Fig. 2. Interference spectrum acquisition process based on push-scan imaging

4 Flight experiment

The actual optical path difference collected by the prototype on the aviation platform is about 1300 times that of the GSO platform, which does not meet the sampling conditions of Nyquist-Shannon, so it will cause serious distortion of the recovered spectrum.

The existing aerial flight platform is difficult to meet the design parameters of the satellite platform, so the field aerial flight test mainly considers imaging the uniform surface target to ensure the availability of the STIIS prototype measurement data.

Fig. 6. Interference spectrum acquisition process based on push-scan imaging

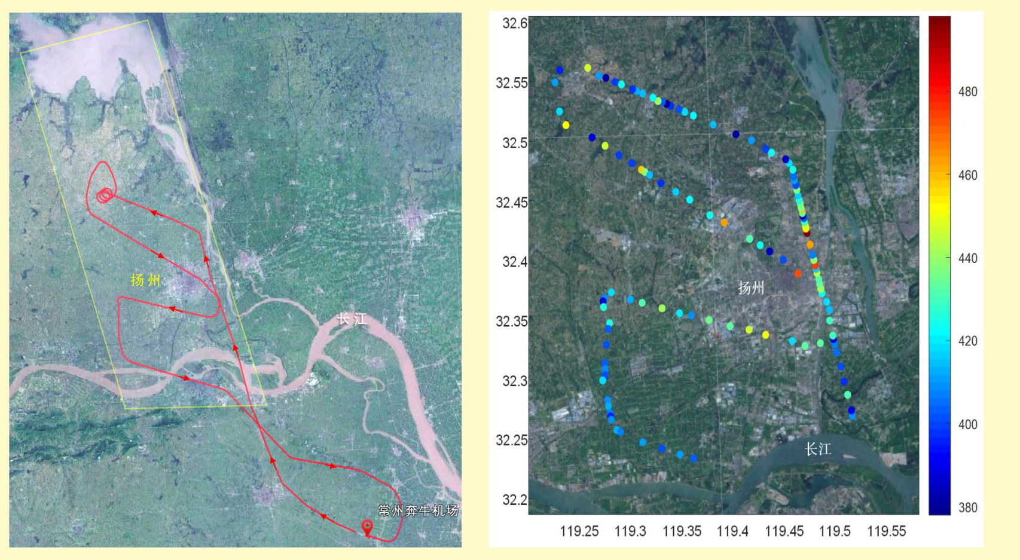


Fig. 7. Flight path map and CO_2 column concentration inversion results

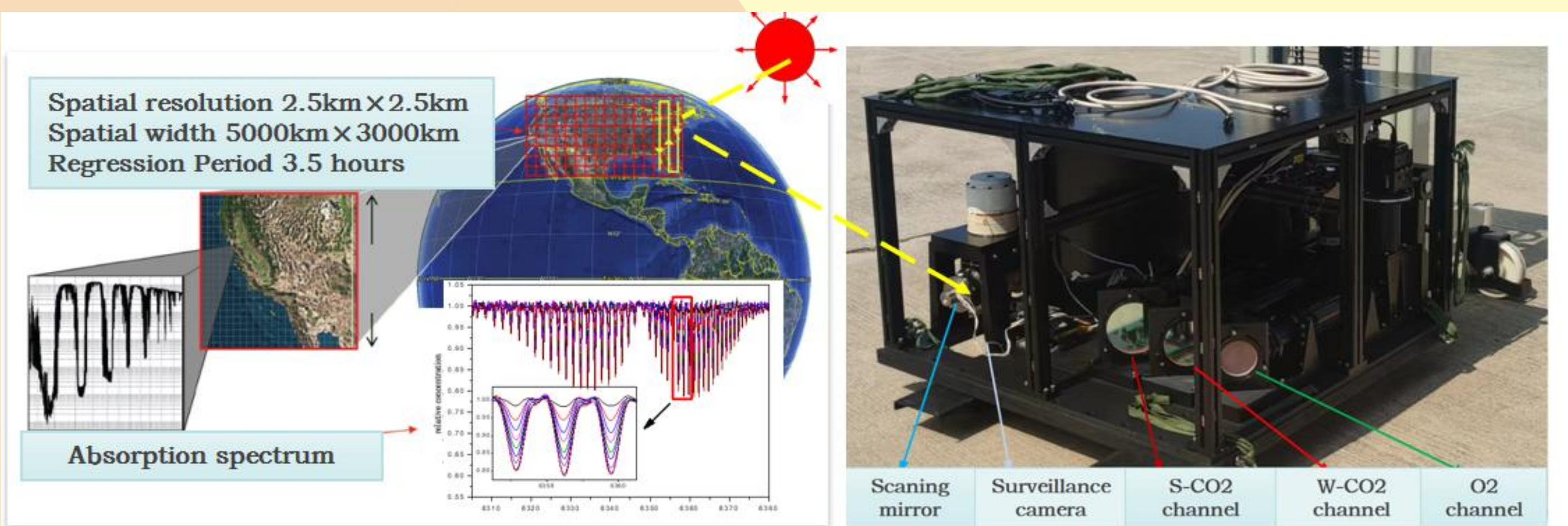


Fig. 8. Detection efficiency of the STIIS prototype on GSO

5 Conclusion

- The optical system of the three detection channels of the STIIS prototype is designed in detail.
- The assembly and development of the STIIS prototype are completed.
- The preliminary test results show that the inversion accuracy of CO_2 meets the requirement of better than 4ppm.

According to the above work of the STIIS prototype, it provides the technical basis for the next generation of high spatiotemporal resolution detection of greenhouse gases.