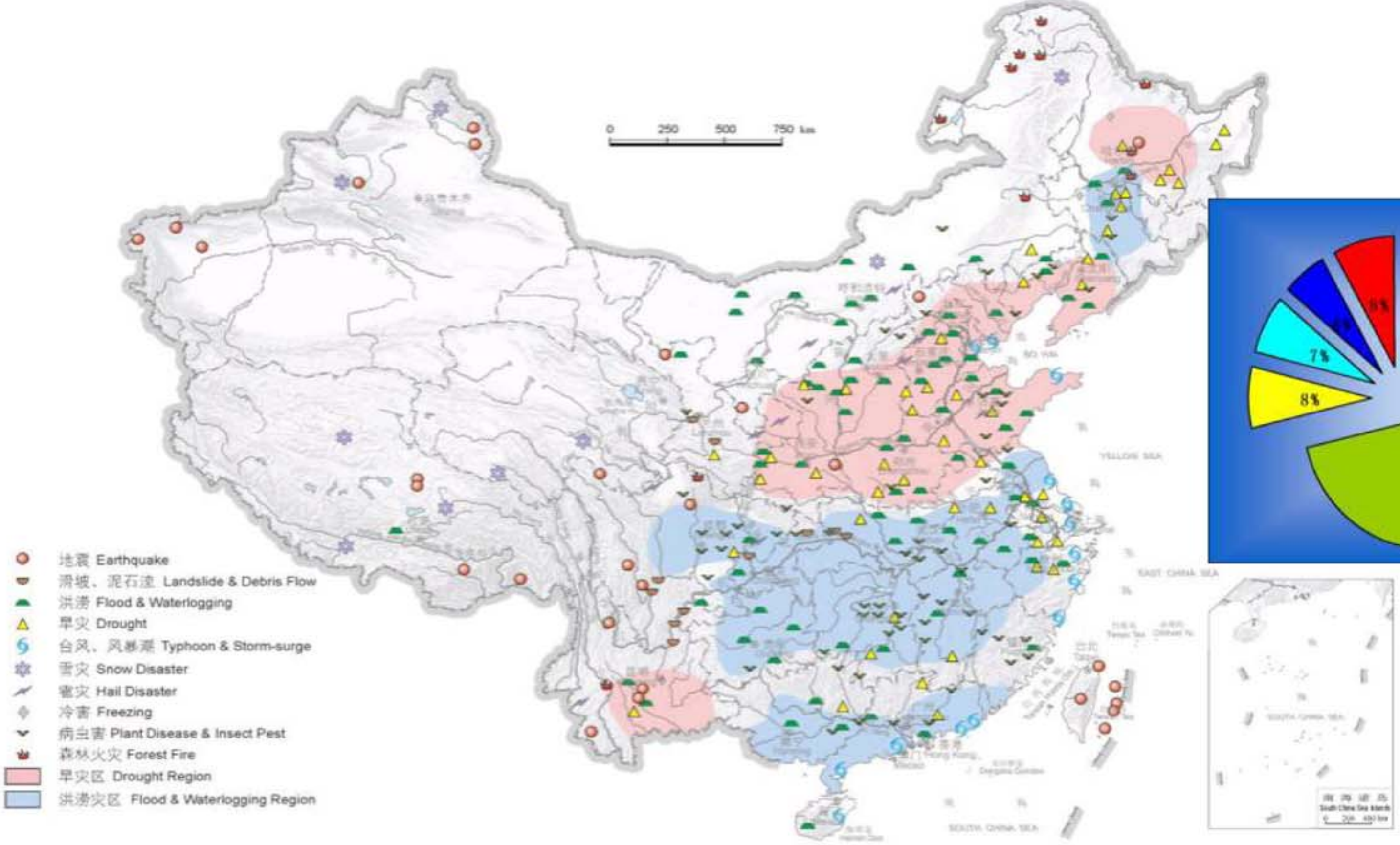
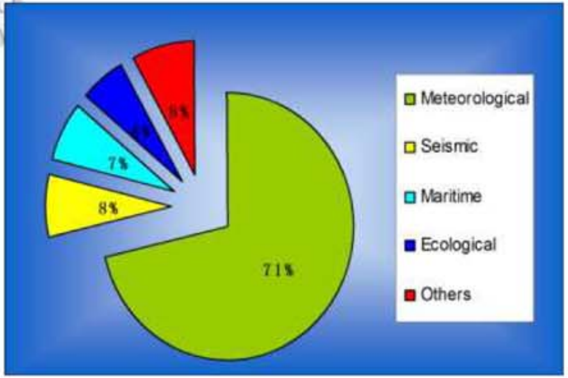
Interferometric Infrared Sounder technology based on satellite platform: towards the era of real-time detection of atmospheric characteristics

—— Infrared Remote Sensors for Meteorological Satellites

Shanghai Institute of Technical Physics, CAS
National Laboratory of Infrared Physics
CAS Key Laboratory of Infrared System Detection and Imaging Technology

October, 2021, Shanghai

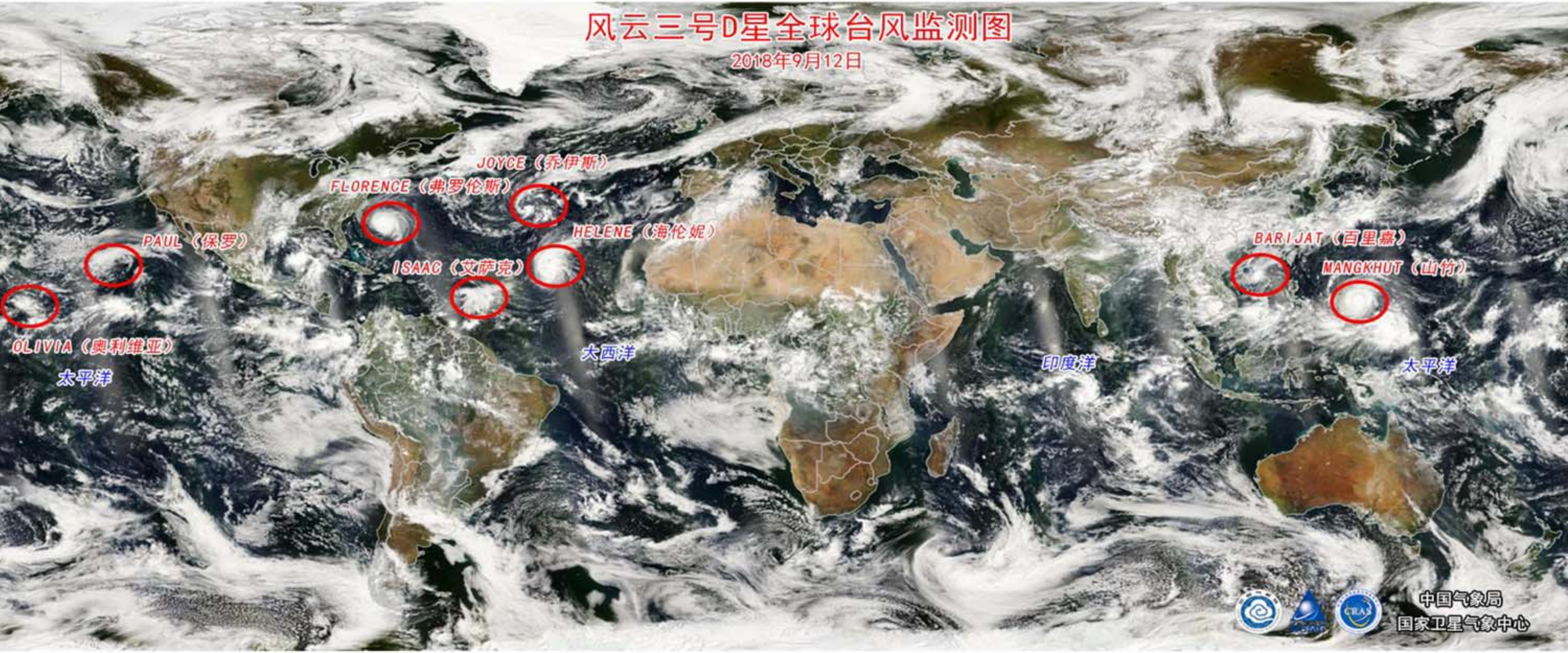




Economic loss of different disasters

Major Natural disasters Map in China

Observation from space



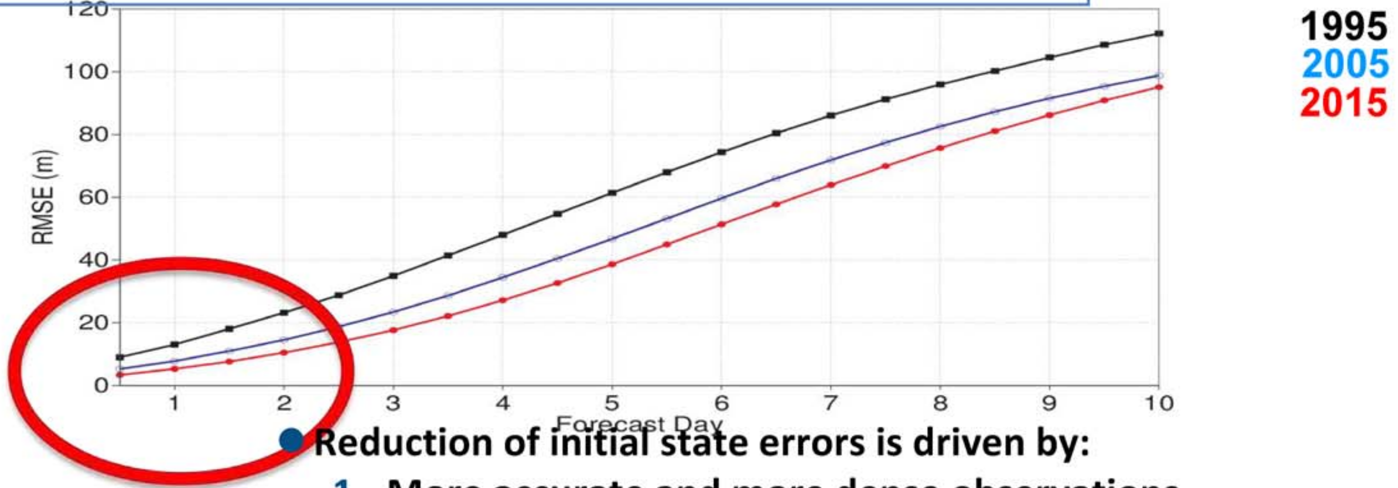
Global Earth Observation

NWP: An initial value problem

Current data assimilation is able to better constrain the growing error modes

$$J(\mathbf{x}) = J_b + J_o = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}(\mathbf{y}^o - \mathbf{H}\mathbf{x})^T \mathbf{R}^{-1}(\mathbf{y}^o - \mathbf{H}\mathbf{x})$$

mGeopotential RMSE – 500 hPa – Northern Hemisphere

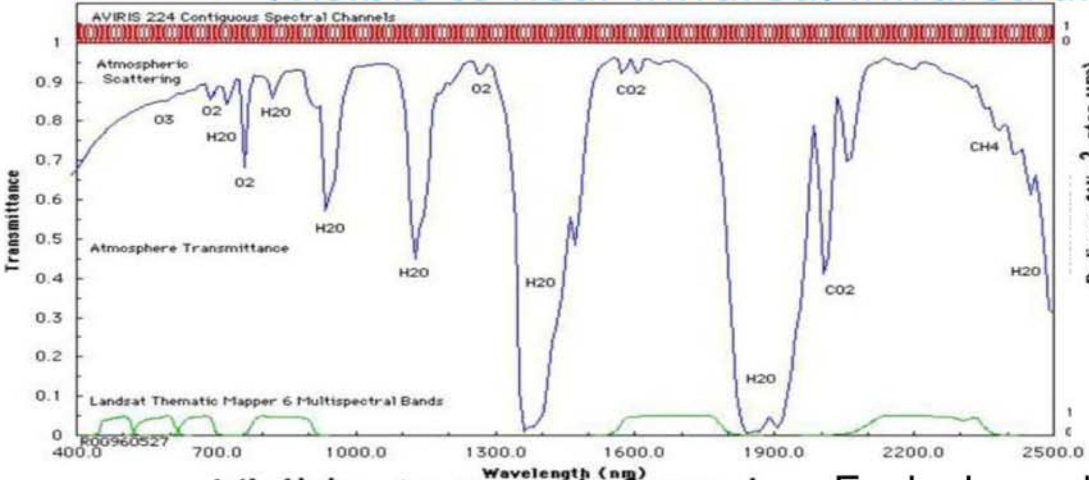


- **Reduction of initial state errors is driven by:**
  1. **More accurate and more dense observations**
  2. **Improved accuracy and resolution of forecast model**
  3. **Better Data Assimilation methods**

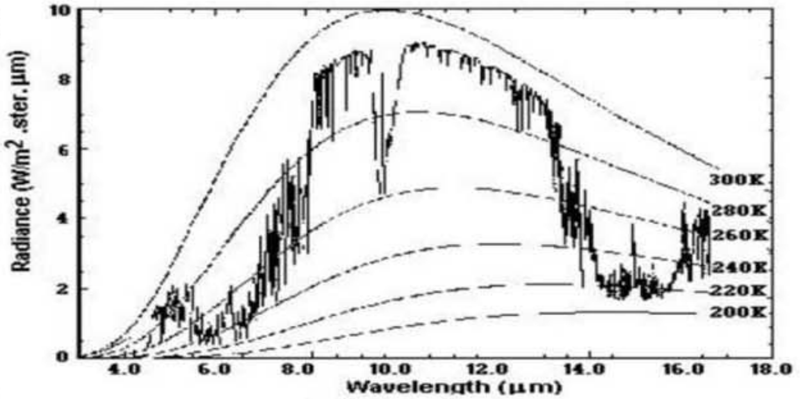
From: **Wei HAN,** NWPC,CMA

Spectral Resolution

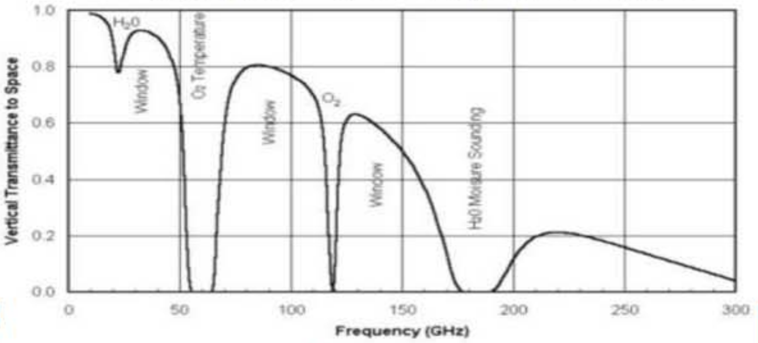
(visible to near infrared, infrared and microwave)



Visible- to near infrared



infrared

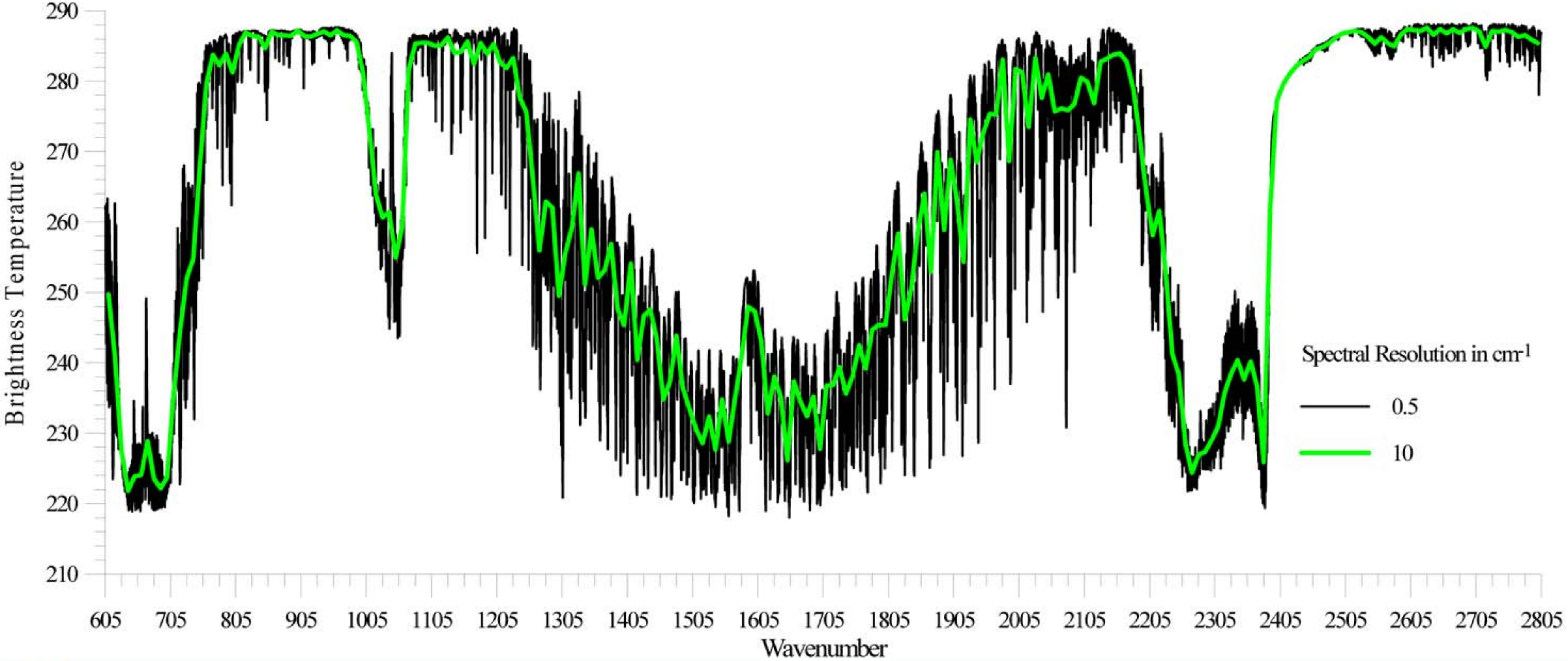


microwave

Each channel has its specific wavelength range and in the certain spectral band. the same target has different features in different channel, from this, we can discern a target, like cloud, snow, fog and dust storm.

The more narrow the wavelength is the more accurate spectrum features we can get from the target.

More details with hyperspectral observation



SITP

Satellite Ultraspectral Sounder Evolution

Nimbus-3 & -4
IRIS/SIRS
(1969-1972)

First Satellite Sounder Experiments

Nimbus-5 ITPR
ITOS/VTPR
Nimbus-6/NOAA HIRS;
GOES-VAS & HIRS
(1972-2010)

High Horizontal Resolution

High Resolution Interferometer Sounder (HIS)
(1985 – 1999)

Ultra-spectral Resolution

Aircraft
Nast-I/SHIS
(1998-)

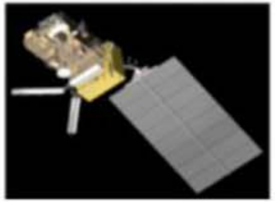
Ultra-spectral Resolution Imagers

ADEOS IMG [LEO] (1996-1997)

Aqua-AIRS (2002) [LEO]

First Satellite Ultra-spectral Resolution Sounding Spectrometers

METOP-IASI (2006/2012) [LEO]

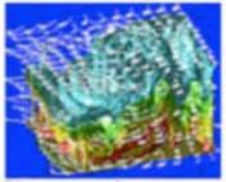


1st Operational Ultra-spectral Resolution Sounder

NPP/JPSS/CrIS (2011)
FY3D/HIRAS (2017)
[LEO]

1st US Operational Ultra-spectral Resolution Sounder

GIIRS/IRS (2016/2021)/2023 [GEO]

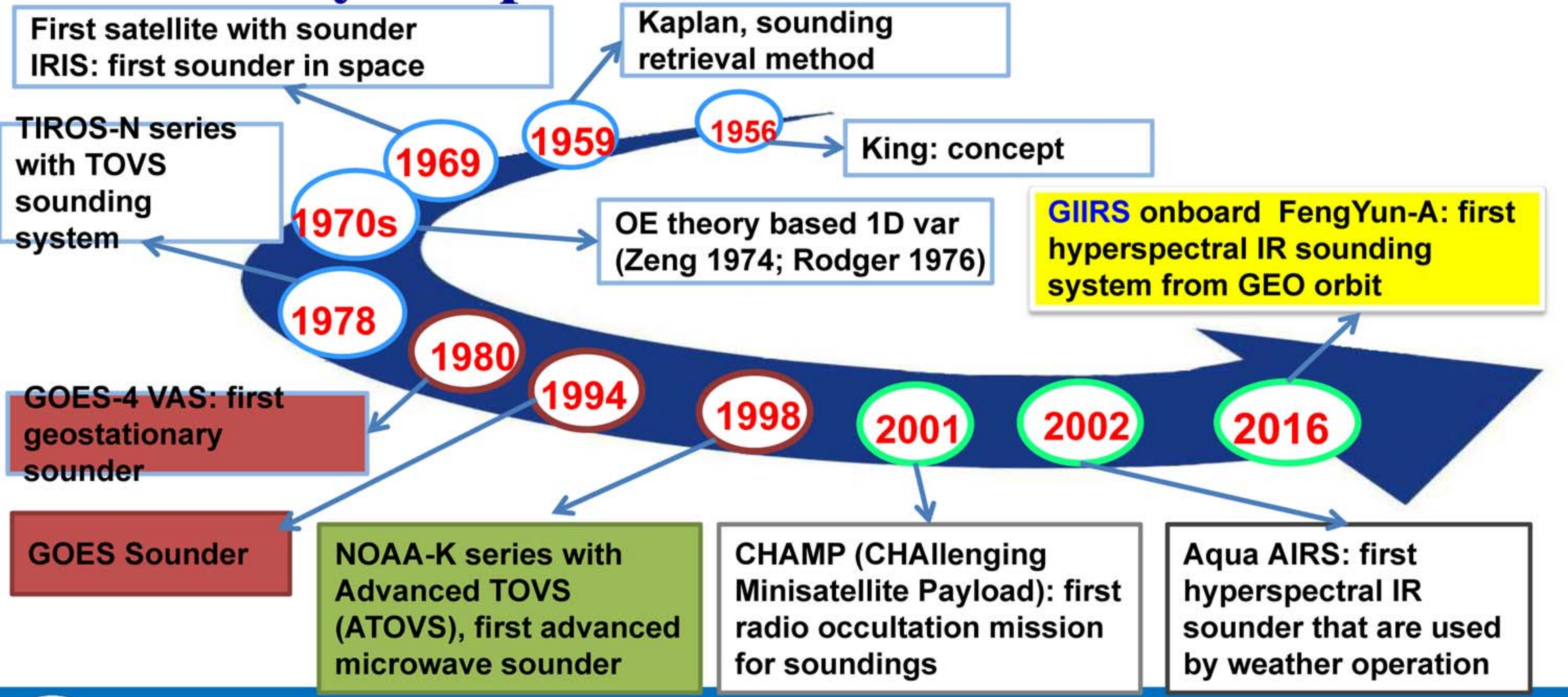


Geostationary 4-d Imaging Ultra-spectral Sounders

Experimental
Air-borne
LEO，
GEO， unique

from：W. L. Smith Sr.
Hampton University

History of Space-born Sounder and models



From: **Wei HAN,** NWPC,CMA

AIRS
Atmospheric InfraRed Sounder
Grating spectrometer
166 kg, 256 W
13.5 km FOV at nadir, contiguous
Launched on NASA Aqua in 2002

AIRS with 2378 infrared channels

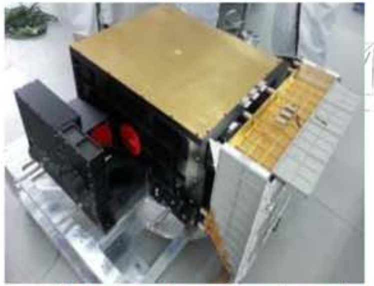
IASI
Infrared Atmospheric Sounding Interferometer
Michelson interferometer
236 kg, 210 W
2x2 12 km FOVs at nadir, non-contiguous
Launched on Metop-A in 2006

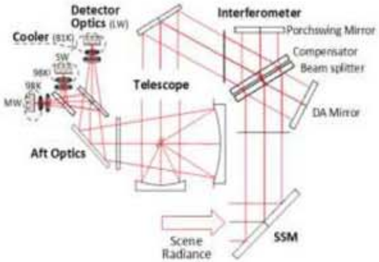
Full scale model at 2010 IASI meeting

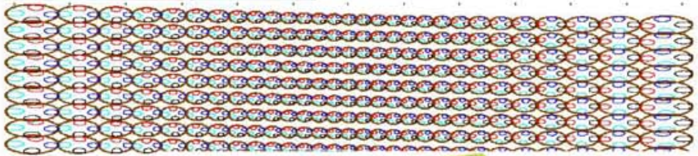
IASI with 8461 infrared channels

CrIS
Cross-track Infrared Sounder
Michelson interferometer
146 kg, 110 W
3x3 14 km FOVs at nadir, contiguous
Launched on Suomi NPP, 28 Oct 2011

CrIS with 2211/1305 infrared channels



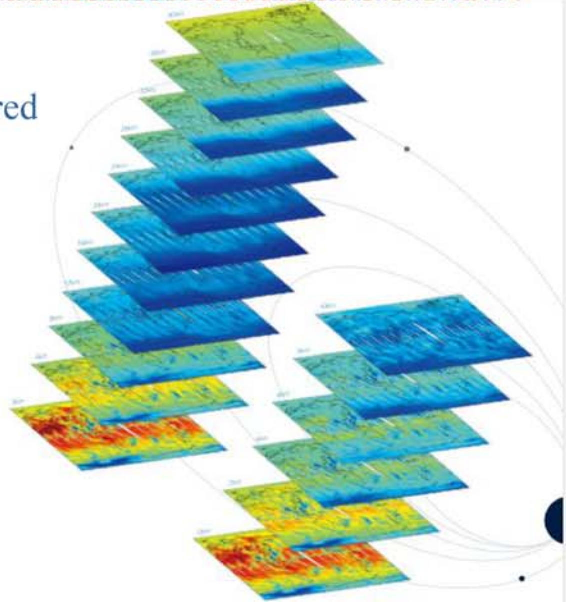




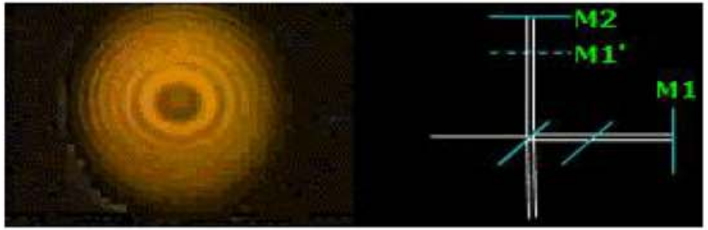
HIRAS

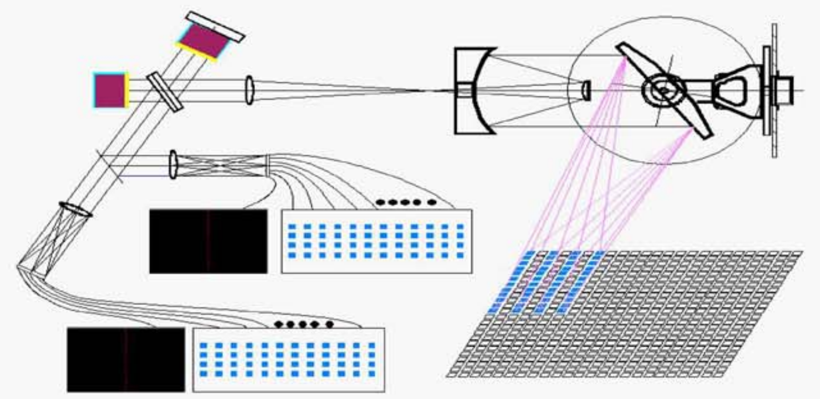
with 2275 infrared channels

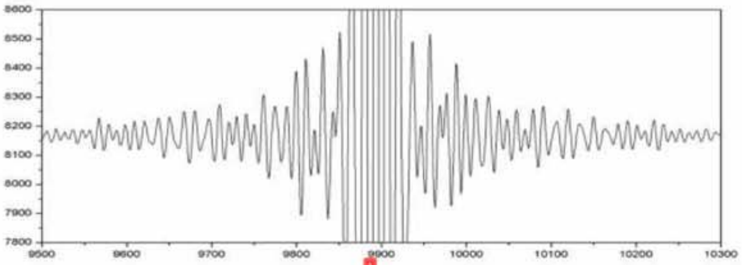
Early SNO comparisons with IASI and CrIS are very promising

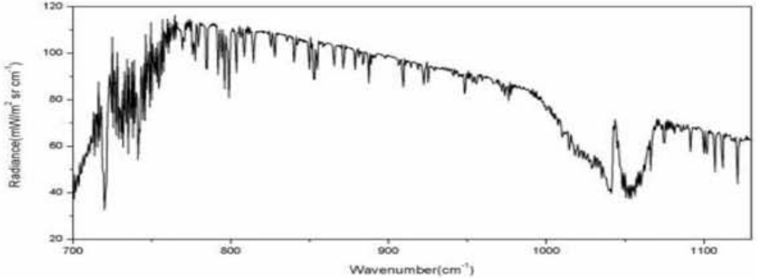


Example of very uniform SNO shows good performance





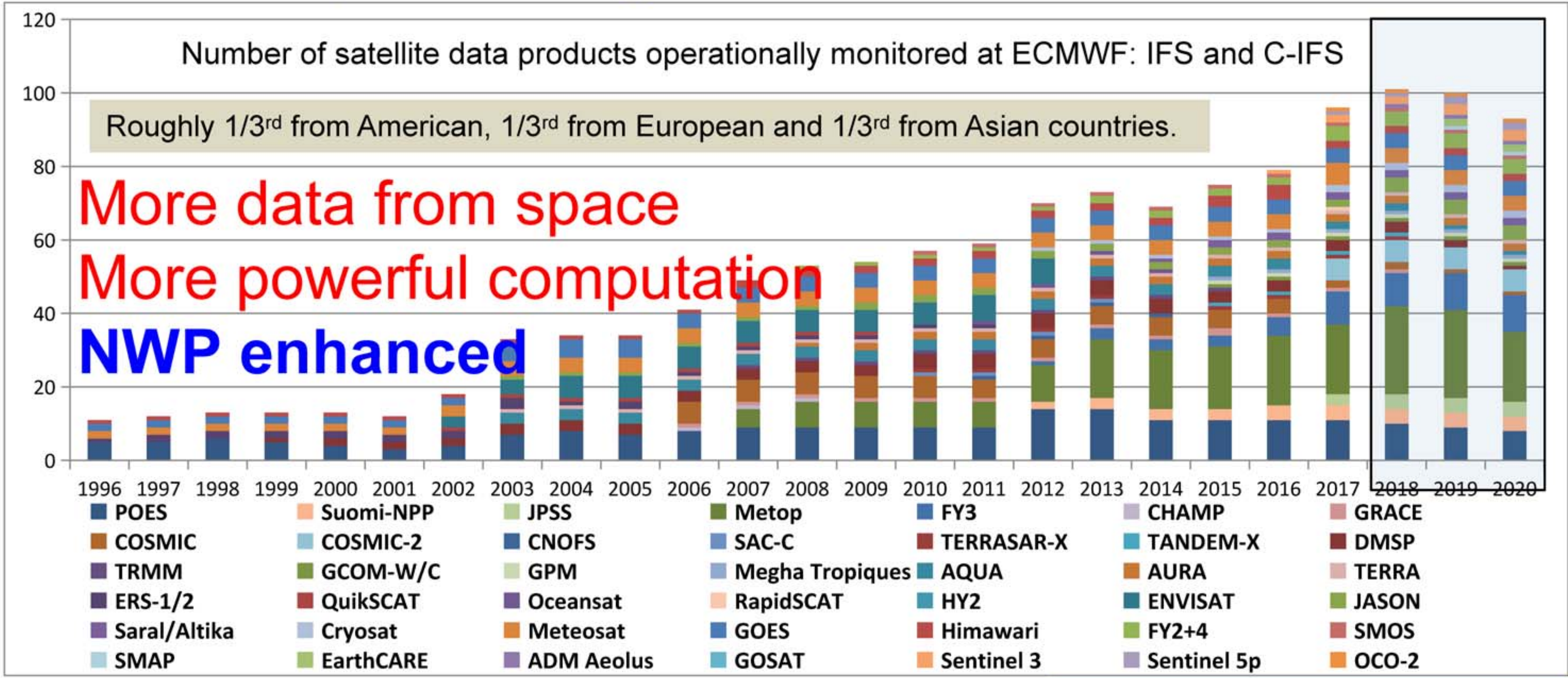




To increase the spectral and spatial resolution of satellite based atmospheric sounding instruments
To provide the high spatial density temperature, moisture and trace gas profiles with the high vertical and temporal resolution from geosynchronous orbit.

Michelson interferometer

New era,Increasing Use of Satellite Data in NWP



From: **Wei HAN**, NWPC,CMA

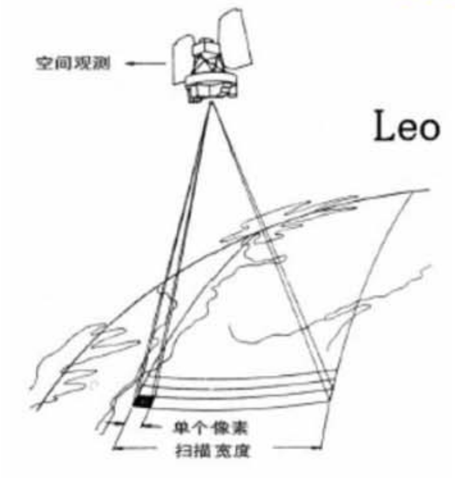
DATA from Chinese satellites increase obviously

Observation Resolution

What we want ? → **Satellite Capability**

- **Improve Image** ← **High Spatial Resolution**
- **Continued Monitoring** ← **High Temporal Resolution**
- **Quantitative Remote Sensing** ← **High Radiometric Resolution**
- **Difference Targets** ← **High Spectral Resolution**

More satellite platforms



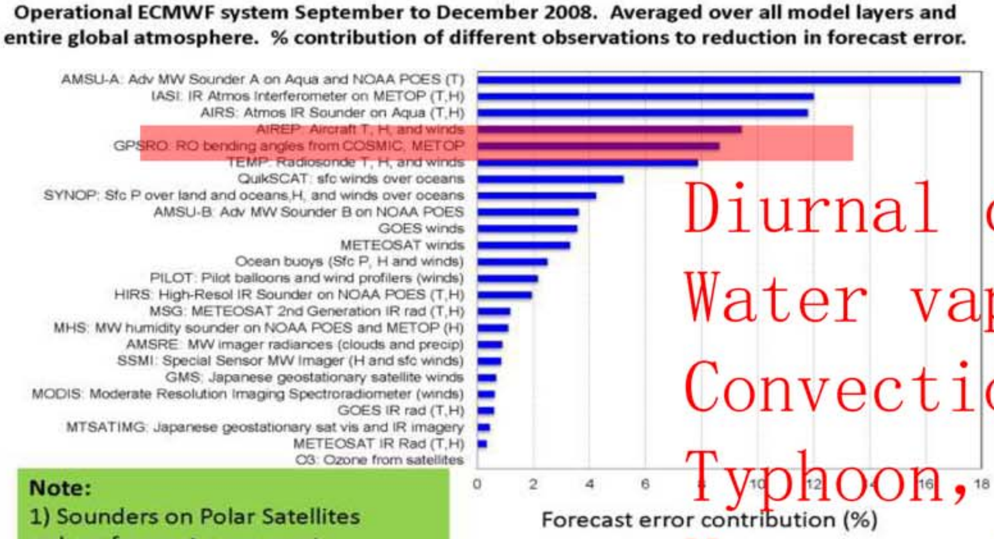
Polar orbiting platform

Advantage: global coverage, multiple instruments, good spatial resolution, good spectral resolution
Disadvantage: bad temporal frequency

Geostationary orbiting platform，FY-4

- Three-axis stability, active attitude control, low stability
- High observation efficiency, can always face the earth
- Atmospheric vertical detection and lightning detection
- Technical implementation is difficult: pointing accuracy,stability

Why do we need GEO hyperspectral IR sounders?

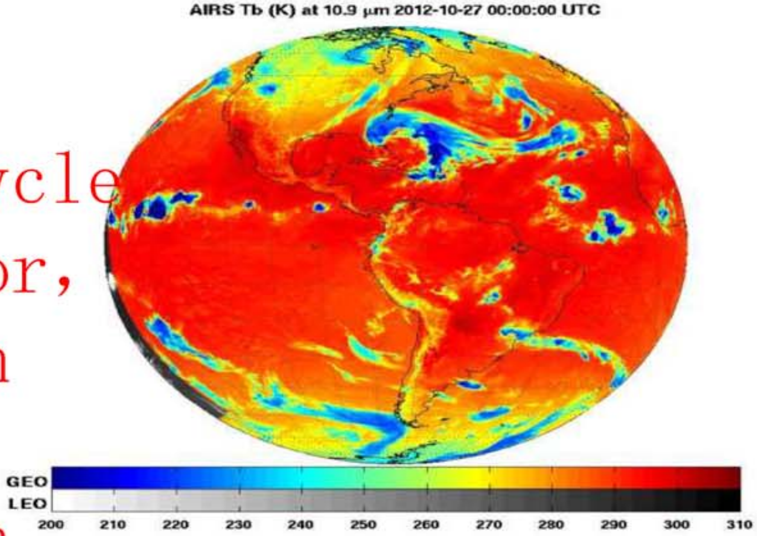


Note:
1) Sounders on Polar Satellites reduce forecast error most
2) Results are relevant for other NWP Centers, including NWS/NCEP

Courtesy: Carla Cardinali and Sean Healy, ECMWF

39

Diurnal cycle
Water vapor,
Convection
Typhoon,
Heavy rain
……

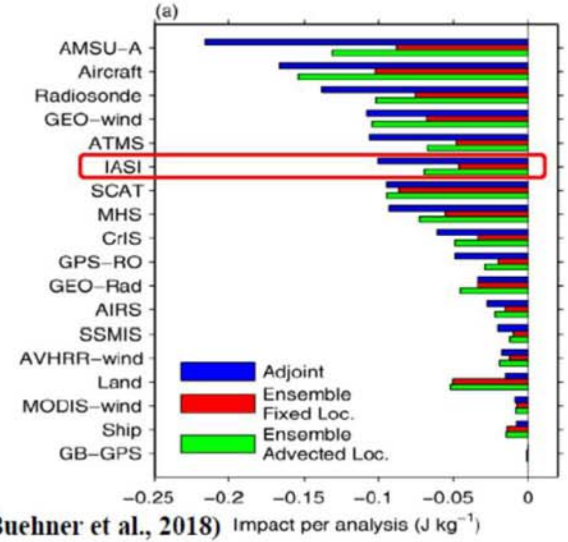


- Compared with LEO: **Larger spatial coverage** and **higher temporal resolution** for regional models
- Compared with microwave sounders: finer vertical resolution

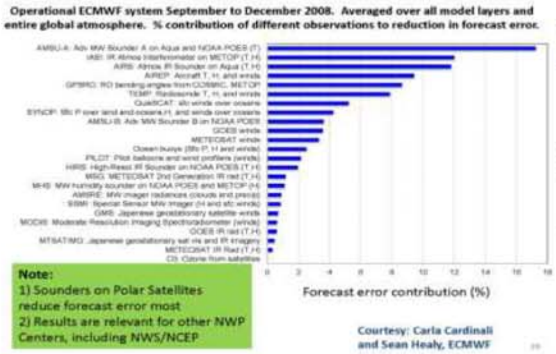
Q: GEO high temporal resolution observations GEO provide critical information for nowcasting, what is the impact in NWP models, for example, on storm forec

Courtesy of Dr. Jun Li

Why do we need GEO hyperspectral IR sounders ?

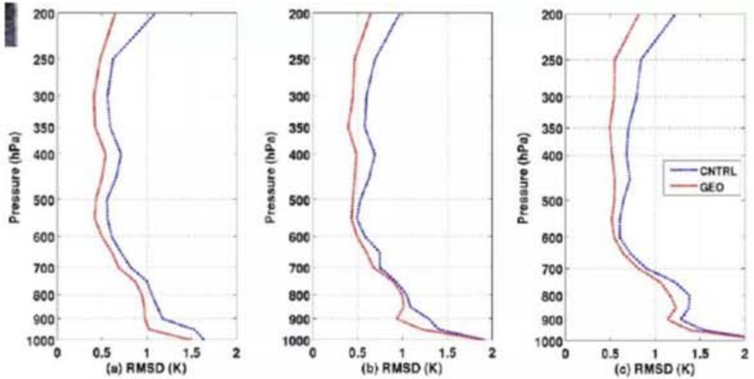


(Buehner et al., 2018)



Diurnal cycle，
Water vapor，
Convection
Typhoon，

Heavy rain
……



Li, Z. L., and Coauthors, 2018: Value-added impact of geostationary hyperspectral infrared sounders on local severe storm forecasts—via a quick regional OSSE. Adv. Atmos. Sci., 35(10), 1217- 1230

- Compared with microwave sounders: finer vertical resolution
- Compared with LEO: **Larger spatial coverage** and **higher temporal resolution** for regional models

Q: GEO high temporal resolution observations GEO provide critical information for nowcasting, what is the impact in NWP models, for example, on storm forecasts?

From: **Jun LI,** NSMC,CMA

FengYun Platform

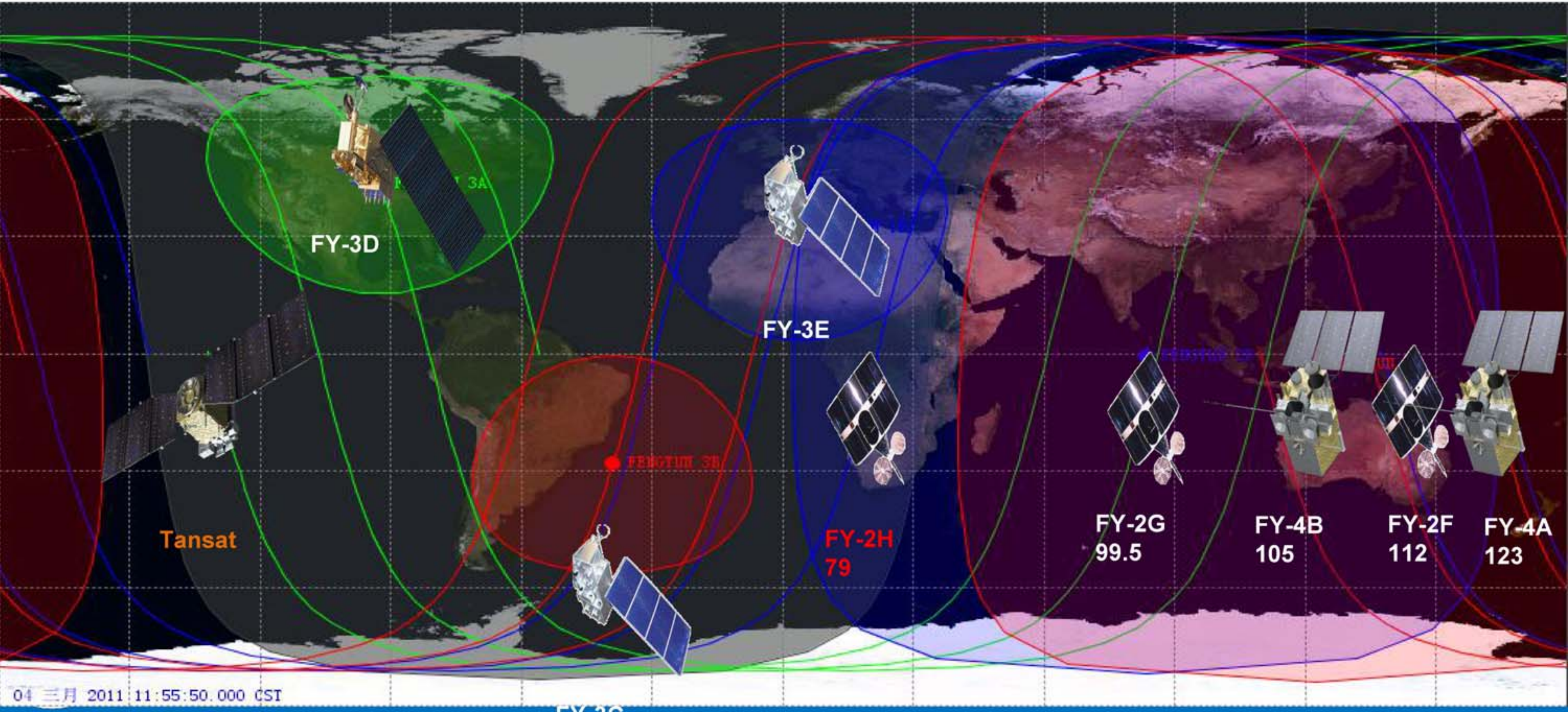


TABLE 2. Spectral parameters of current and planned satellite-based hyperspectral IR sounders.

Satellite	Sounder	Spectroscopic method	Spectral range cm⁻¹ (μm)	Spectral resolution (cm⁻¹)	Channel No.	Subpoint resolution (km)	Sensitivity (NEΔT)	Scan width (km)
ADEOS	IMG	Interferometer	715–3,030 (3.3–15.0)	0.1	~60,000	8	0.1 K	827
EOS *Aqua*	AIRS	Grating	LW 649–1,136 (15.4–8.80) MW 1,212–1,612 (8.22–6.2) SW 2,169–2,673 (4.61–3.74)	0.55 1.2 2.0	2,378	13	0.15–0.35 K (at 280 K)	1,650
MetOp	IASI	Interferometer	LW 640.2–1,210 (15.5–8.26) MW 1,210–2,100 (8.26–5.0) SW 2,100–2,700 (5.0–3.62)	0.25	8,460	12	0.2–0.35 K (at 280 K)	2,052
Suomi NPP (and JPSS)	CrIS	Interferometer	LW 650–1,095 (15.38–9.13) MW 1,210–1,750 (8.26–5.71) SW 2,155–2,550 (4.64–3.92)	0.625 1.25 2.5	1,385	14	0.1–0.5 K (at 250 K)	2,200
FY-3	HIRAS	Interferometer	LW 667–1,136 (15.00–8.80) MW 1,210–1,750 (8.26–5.71) SW 2,155–2,550 (4.64–3.92)	0.625 1.25 2.5	1,343	16	0.15 K (at 250 K) 0.2 K (at 250 K) 0.3 K (at 250 K)	2,300
FY-4	GIIRS	Interferometer	LW 700–1,130 (14.28–8.85) SW/MW 1,650–2,250 (6.06–4.45)	0.8 (trial) 0.625 (op) 1.6 (trial) 1.2 (op)	912 (trial) 1,188 (op)	16 (trial) 8 (op)	0.3 K 0.1 K	Regional/ meso- and microscale
MTG	IRS	Interferometer	LW 700–1,210 (14.28–8.26) MW 1,600–2,175 (6.25–4.60)	0.625	1,740	4	0.2 K (at 280 K)	Full disk

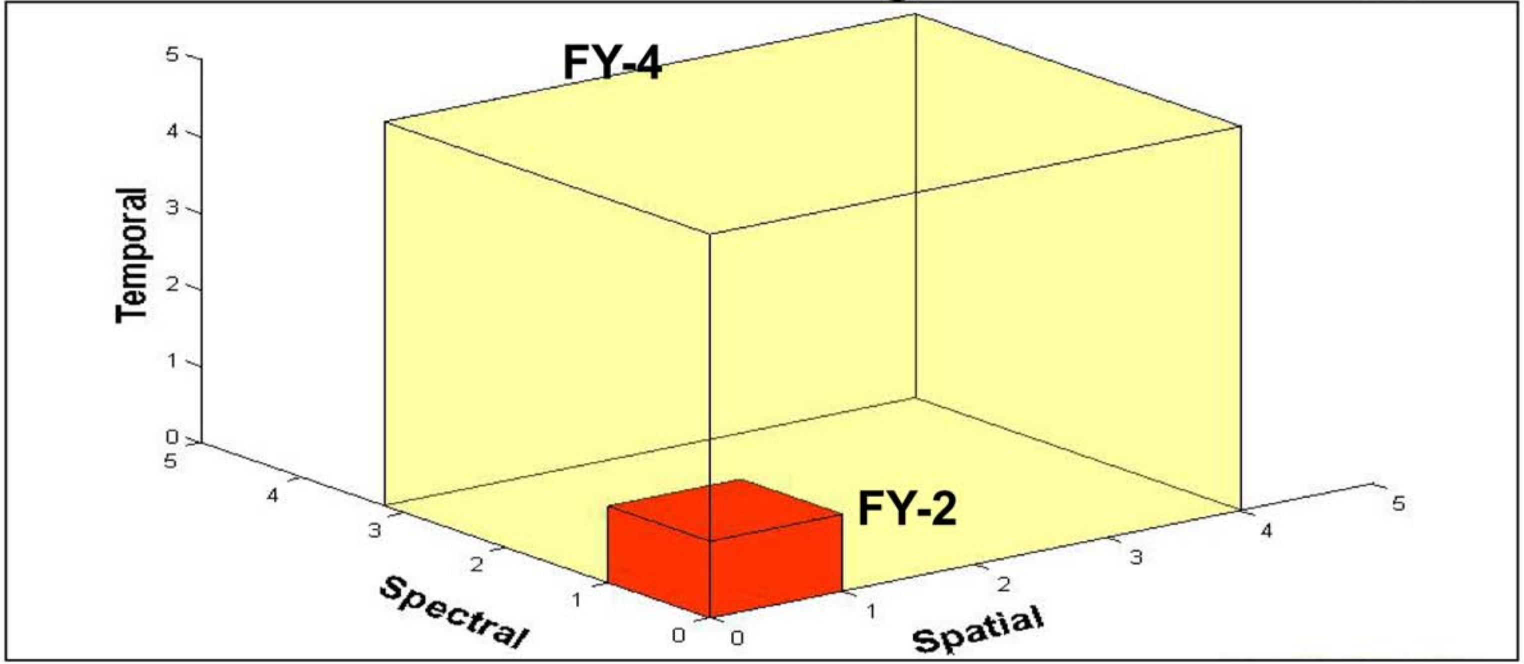
Menzel et al. 2018: Satellite based infrared sounder development and applications, Bulletin of American Meteorological Society, Vol.99, No.03, 583 – 603.

China has hyper-spectral atmospheric vertical detection capability in polar orbit and geostationary orbit simultaneously

FY-4 Technical Properties

Detectability		FY-4A (China)	FY-4B (China)	FY-2 (China)	GOES-R (USA)	Himawari-8/9 (Japan)
Imager	Spatial resolution	Visible/Near Infrared: 0.5-1Km Infrared： 2-4km	Visible/Near Infrared: 0.5-1Km ;**pan：250m** Infrared： 2-4km	Visible/Near Infrared: 1.25km Infrared： 5km	Visible/Near Infrared: 0.5-1km Infrared： 2km	Visible/Near Infrared: 0.5-1km Infrared： 2km
	Temporal resolution	15min	15min； **1min**@2000km×2000km	30min（6min）	5m	10m
	Band number	15	**16+7**	5	16	16
	Precision	**0.2K（Actual <0.1K）**	**0.2K（Actual <0.1K）**		0.1K	0.1K
Sounder	Spectral Range	8.85-14.29μm 4.44-6.06μm	**8.85-14.7μm** 4.44-6.06μm			
	Band number	1650	1650			
	Spectral resolution	$0.625cm^{-1}$	$0.625cm^{-1}$			
	Spatial resolution	16km	**12km**			
lightning mapping imager	Center wavelength	777.4nm			777.4nm	
	Temporal resolution	2ms			2ms	
Space	target	Particle/magnetic field /X ray	Particle/magnetic field /X ray		Particle/magnetic field /Imaging of the sun	

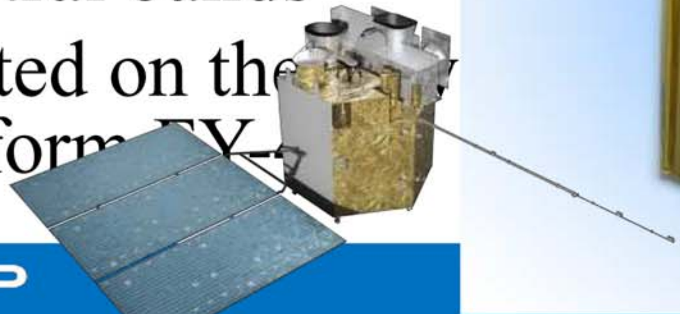
Era of Big Data



Compared with FY-2, FY-4 could provide more observation data and useful information in 3-D (spectral, spatial and temporal). It is a challenge to effectively dig out the useful information from the big data.

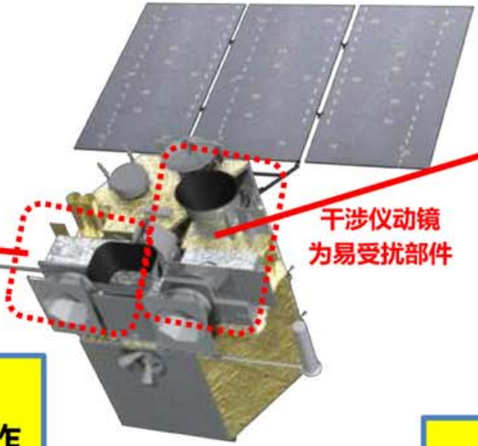
GIIRS, for new era of detection of atmospheric characteristics

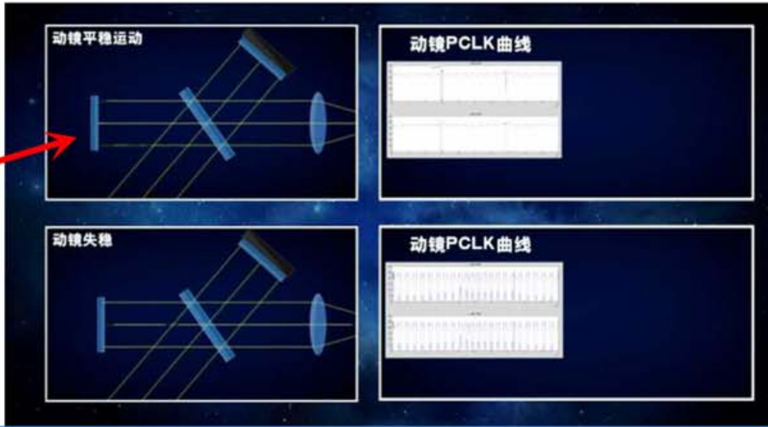
- Geostationary Interferometric InfraRed Sounder
- Michelson interferometer based on the principle of Fourier Transform
- designed to measu
radiation from the
spectral bands
- located on the
platfor



Requirements for platform

- **micro-vibration isolation**

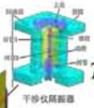




摆扫速度：10°/s
干扰力矩0.16Nm，影响干涉仪工作

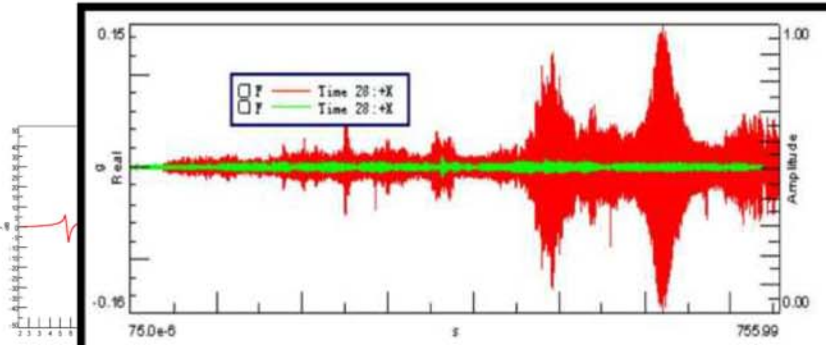
动镜位移要求：0.4微米，线振动要求：1mg
扰动大于50mg时，光谱误差由8ppm到25ppm

- **first platform loading hyper-spectral sounder and scanning imager**
- **dynamic interference**



$$T_r = \sqrt{\frac{1+4\zeta^2\left(\frac{\omega}{\omega_n}\right)^2}{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+4\left(\frac{\omega}{\omega_n}\right)^2\zeta^2}}$$

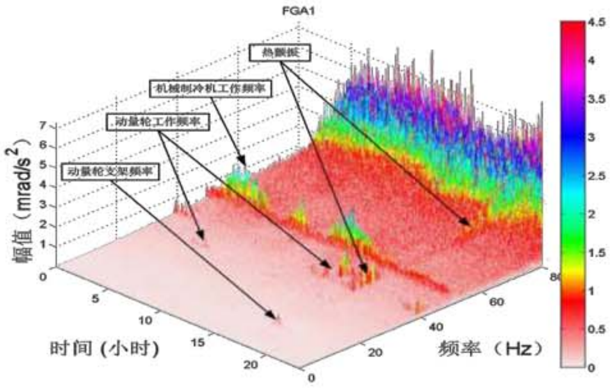
ω_n固有频率设计值
ζ阻尼比设计值



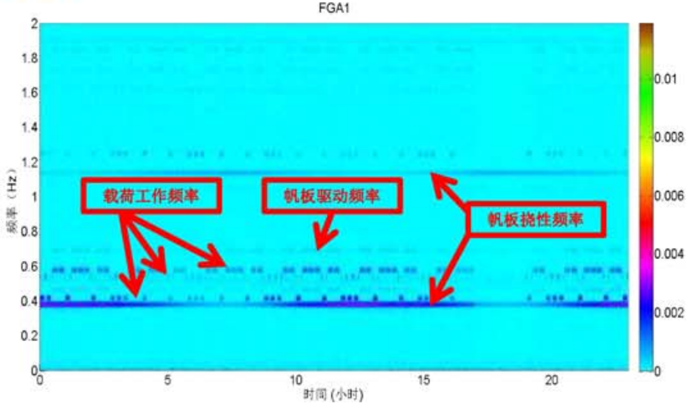
Requirements for platform

measured linear vibration < **0.1mg**， angular vibration< **5mrad/s²**

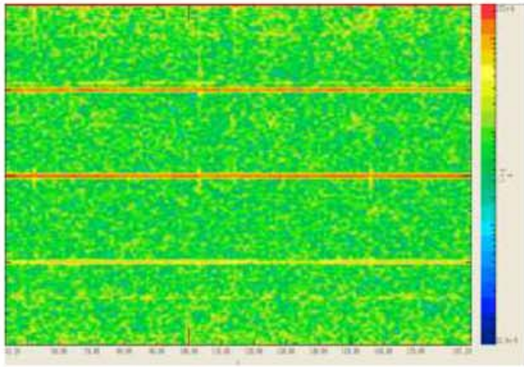
- **micro-vibration isolation**



full frequency band vibration all day three-dimensional spectrum data



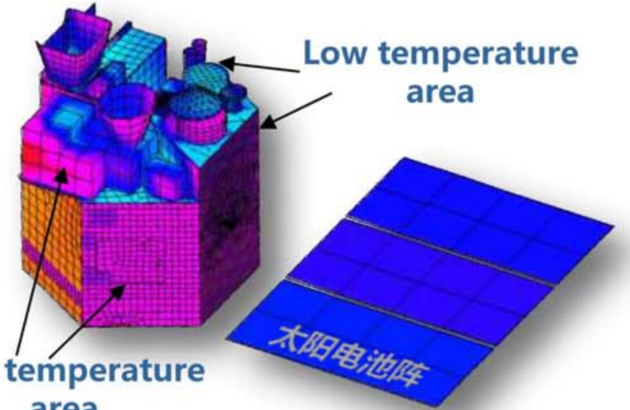
low frequency band vibration all day three-dimensional spectrum data



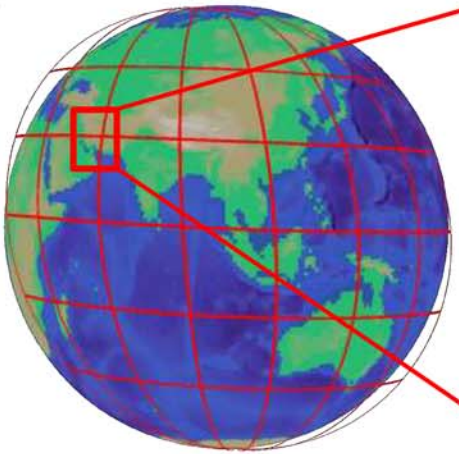
Micro-vibration response at interferometer installation interface (**good effect)**

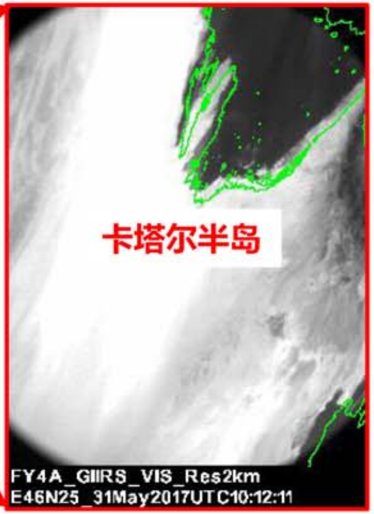
Requirements for platform

- Adapting severe heat alternating environment
- Satellite image navigation and registration



in the 24-hour cycle, the sun shines on different surfaces of the satellite in turn, and the temperature range is ± 150 ℃

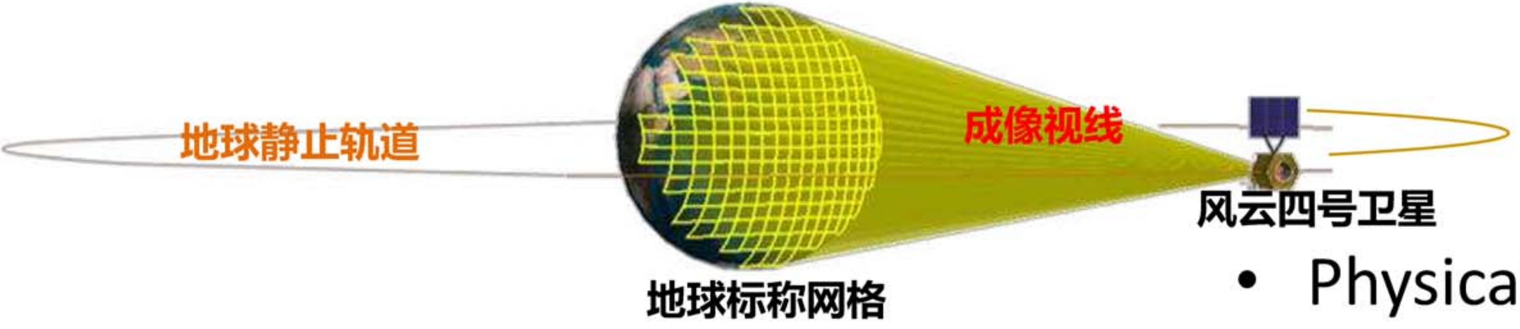


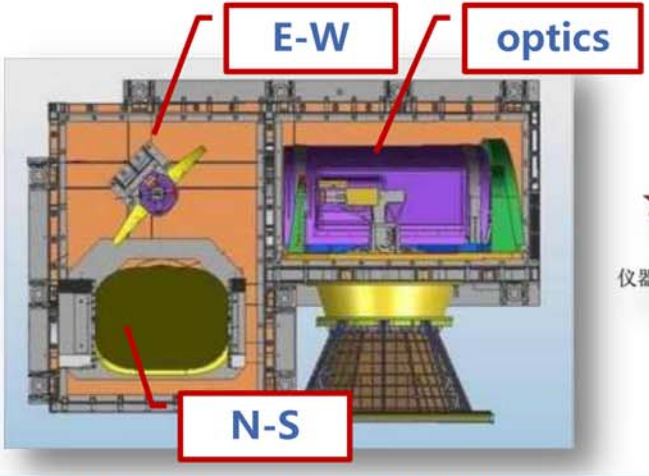


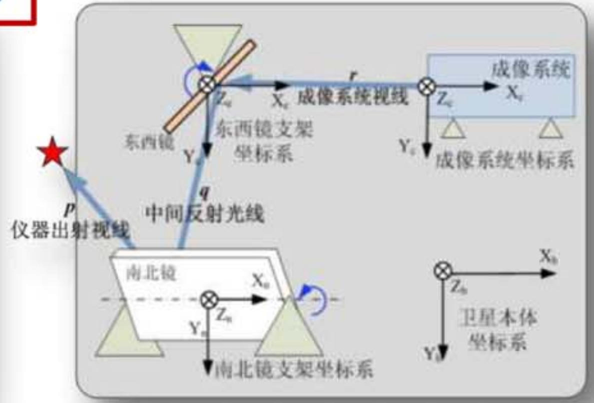
heat deformation leads to image distortion and distortion

pointing error ~100 km

Requirements for platform



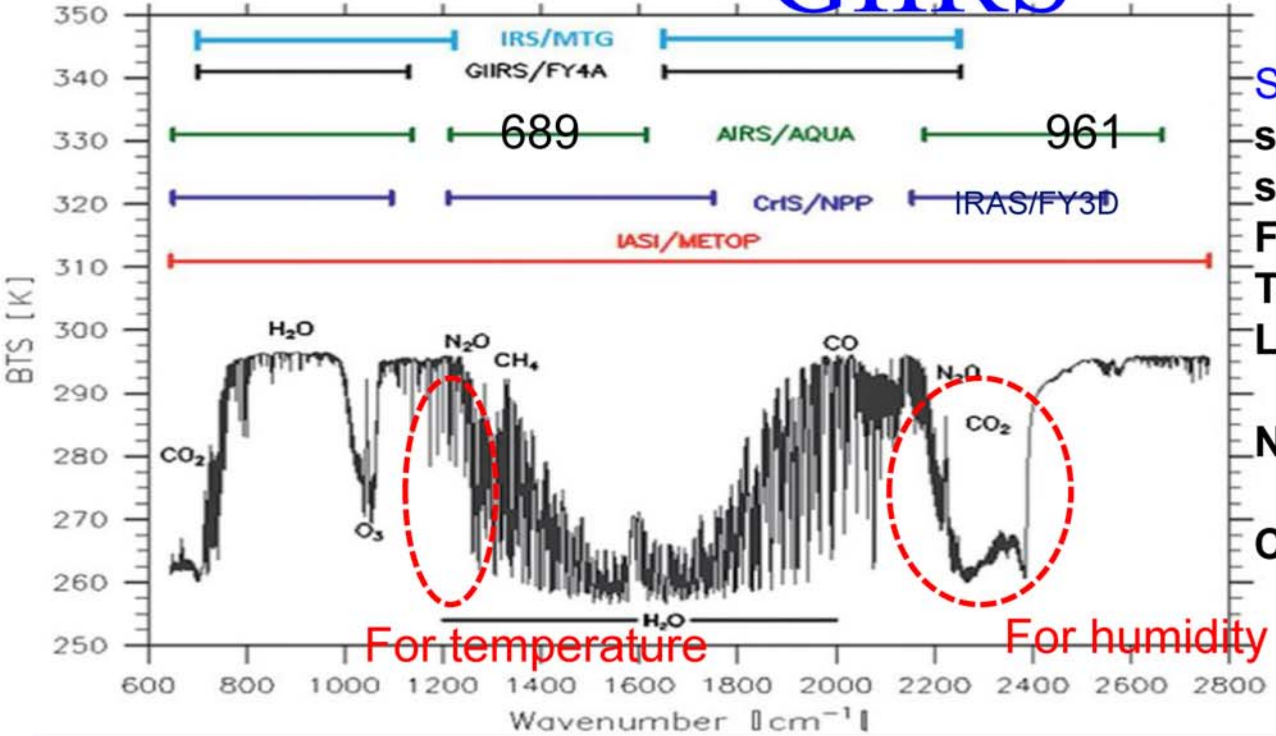




- Physical model: rigorous description of the optical path
- Equivalent model: satellite in orbit Identification

物理模型：严密描述光路　　等效模型：卫星在轨辨识

GIIRS



Specification:

spectral resolution：0.625cm^{-1}

spatial resolution：16km

FPA：4*32 pixels

Temporal resolution: 67min

Line position uncertainty : 10 ppm (3σ)

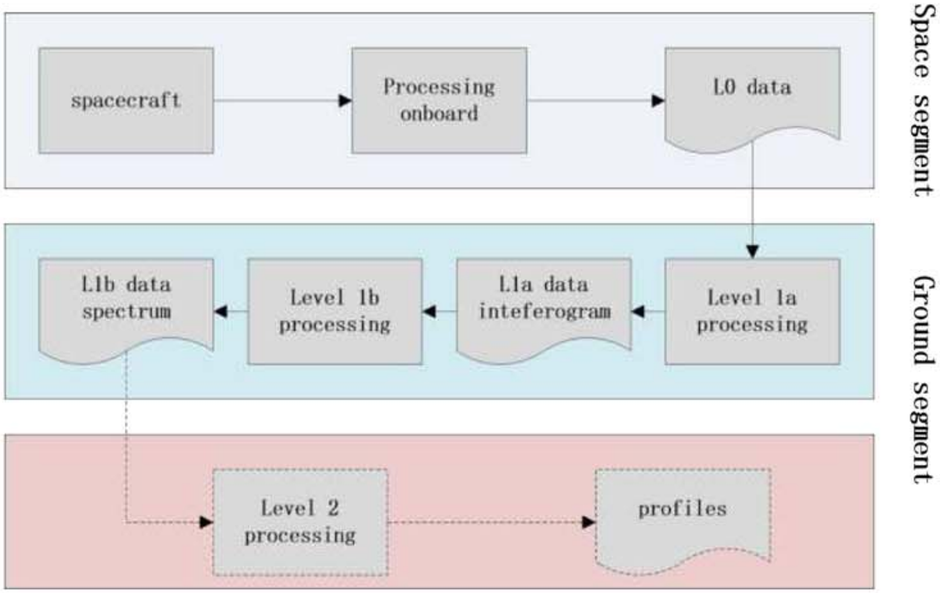
NESR (mW/m2 sr cm-1):LW，0.5; MW，0.1；

Calibration error :1.5 K (3σ)

Yang J, Zhang Z, Wei C, Guo Q. : 2017,
Introducing the new generation of Chinese geostationary weather satellites – FengYun 4 (FY-4) [J]. Bulletin of the American Meteorological Society. DOI:10.1175/BAMS-D-16-0065.1

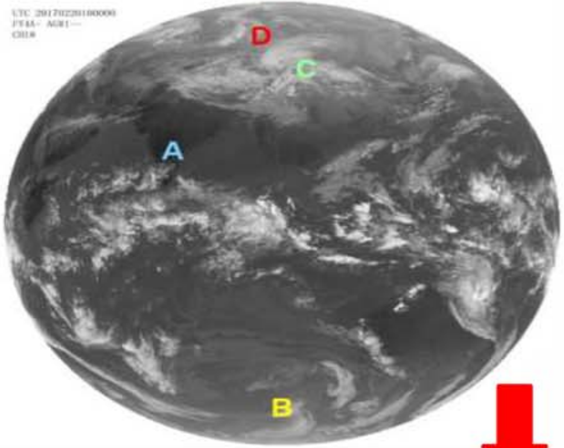
GIIRS Operational Concept

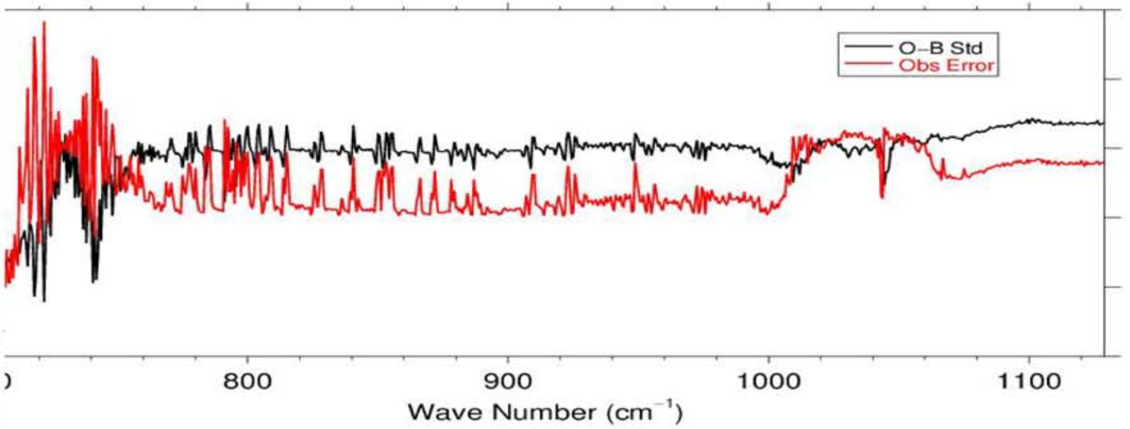
- Space segment：
  - At each dwell, GIIRS observes 8 Earth scenes with interferometer sweeps in forward and reverse direction
  - Every 15 mins, GIIRS observes 16 calibration targets (8 Deep Space + 8 hot body Target)
- Ground segment：
  - Transform GIIRS interferograms into fully calibrated and geolocated spectra
  - Transform spectra into temperature, pressure and moisture profiles

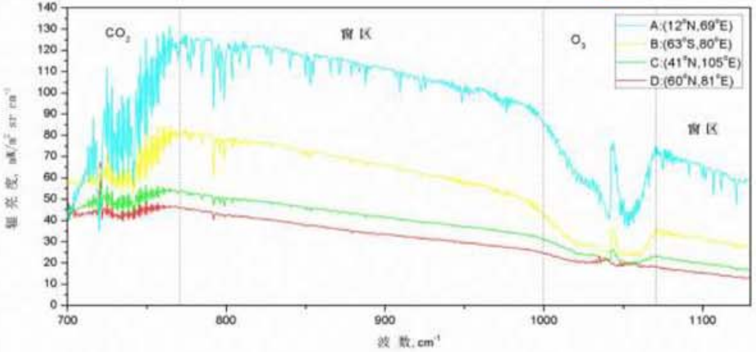


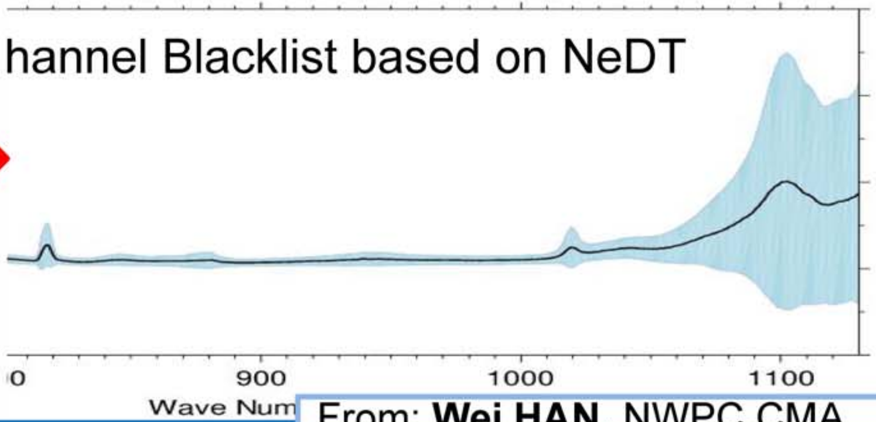
From: **Xuan FENG,** NSMC,CMA

Observation Error Estimation



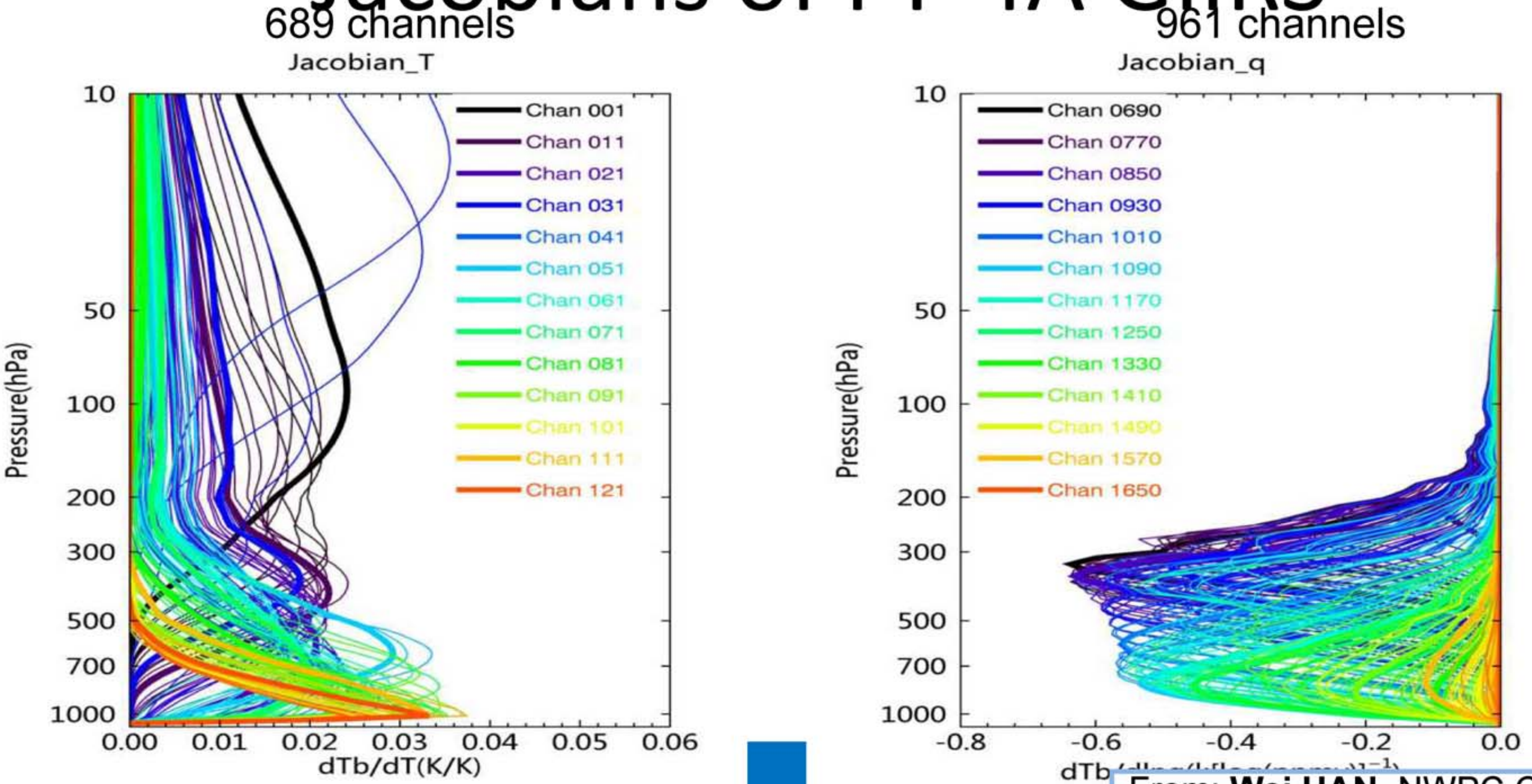






From: **Wei HAN,** NWPC,CMA

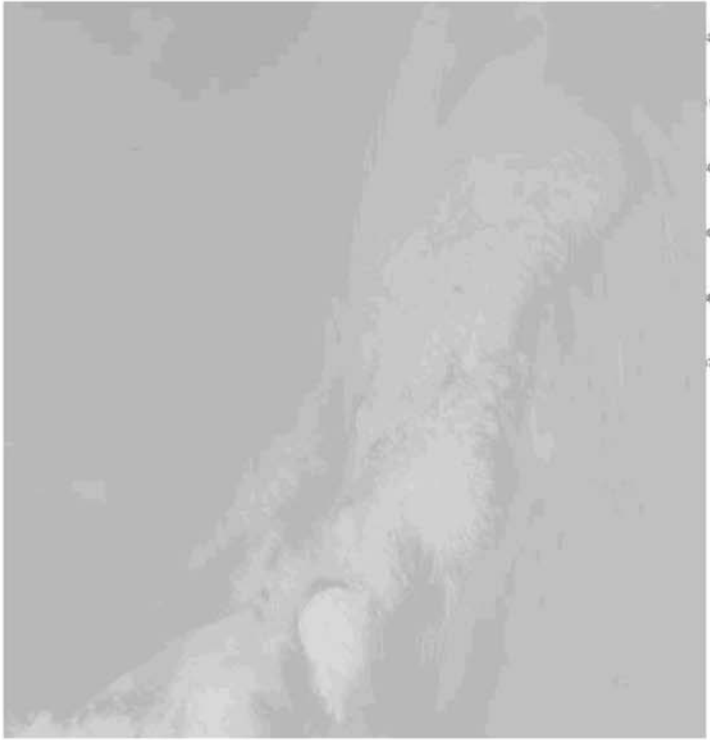
Jacobians of FY-4A GIIRS

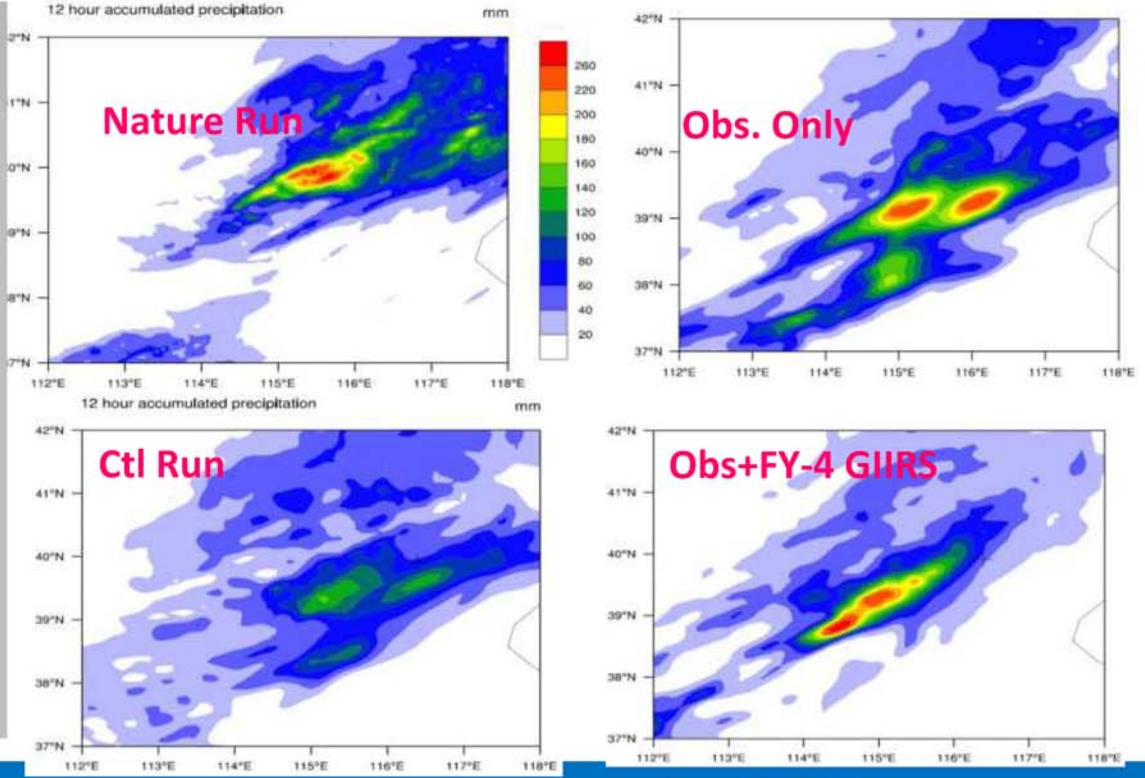


From: **Wei HAN**, NWPC,CMA

Potential for new application model innovation

as the first hyper-spectral sounder staring at the Earth

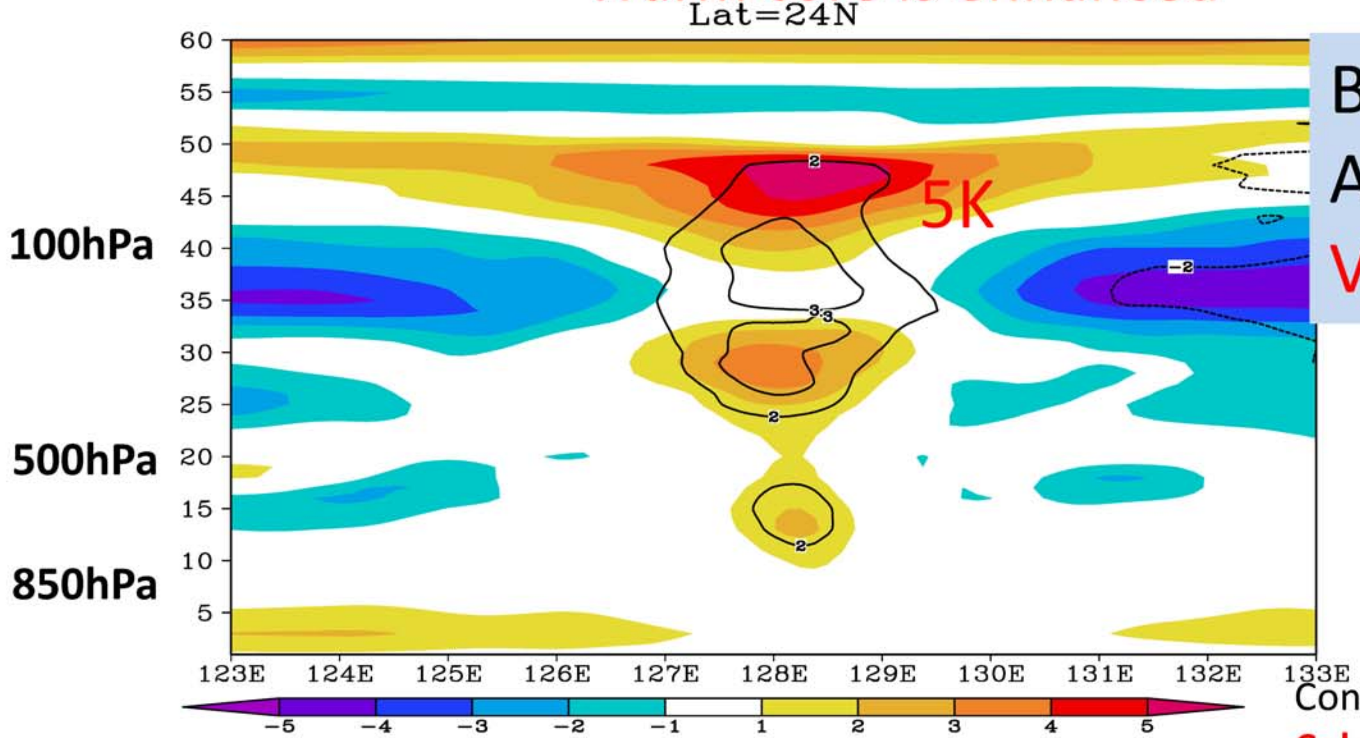




- From CMA杨军

Impact of assimilating high temporal GIIRS observations on analysis:

Warm core is enhanced



BG: 3 K

AN: 5 K

Vertical structure

24° N

Contour : Temp BG departure

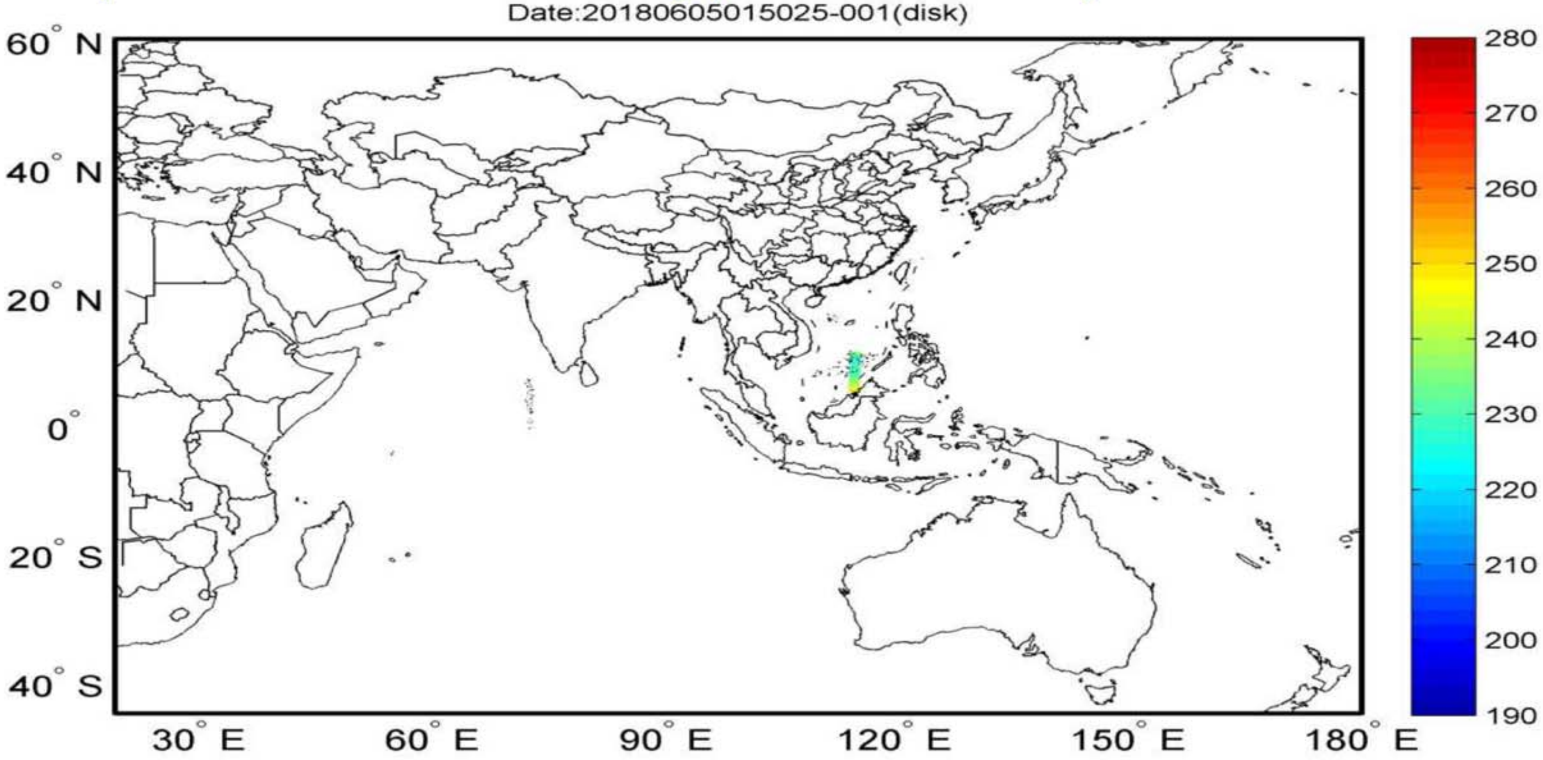
Color： Temp AN departure

0500 Z 10 July 2018 (Beijing Time)

From: **Wei HAN,** NWPC,CMA

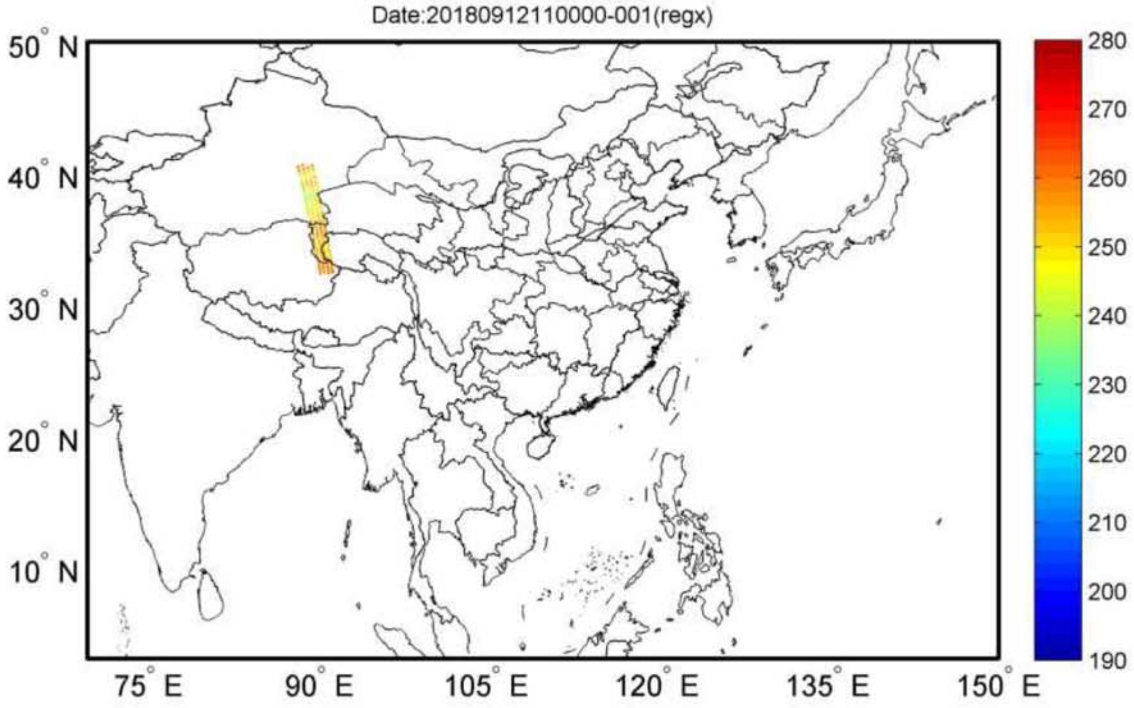
GIIRS been assimilated in GRAPES 4D-Var

– Impacts on recent Typhoon analysis and forecasts



From: **Wei HAN,** NWPC,CMA

30 minutes temporal resolutinon

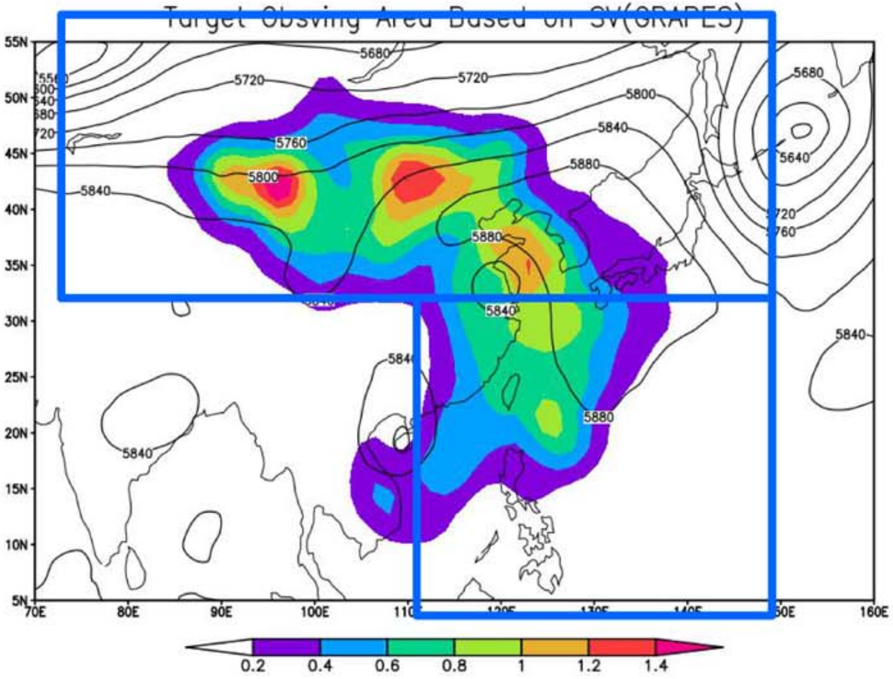


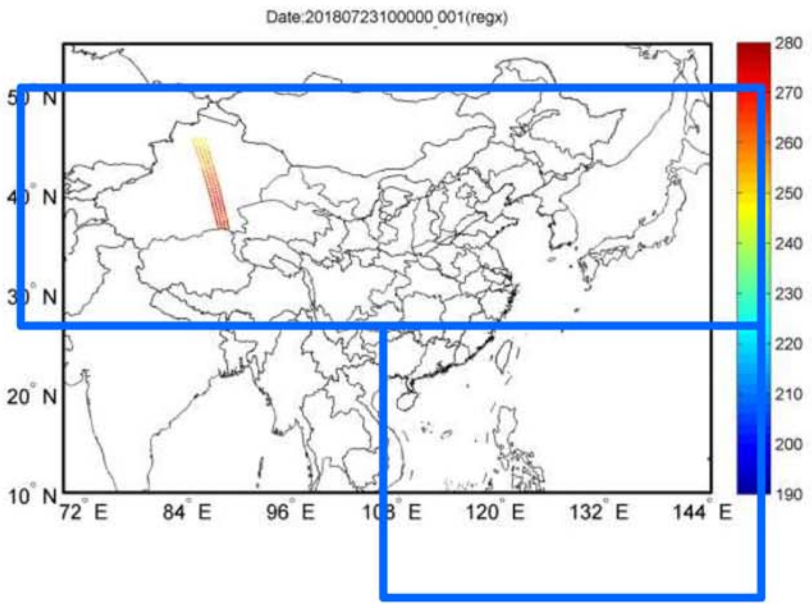
From: **Wei HAN**, NWPC,CMA

GRAPES 4D-Var +GIIRS, sensitive area

GIIRS, densified observation every 30 min

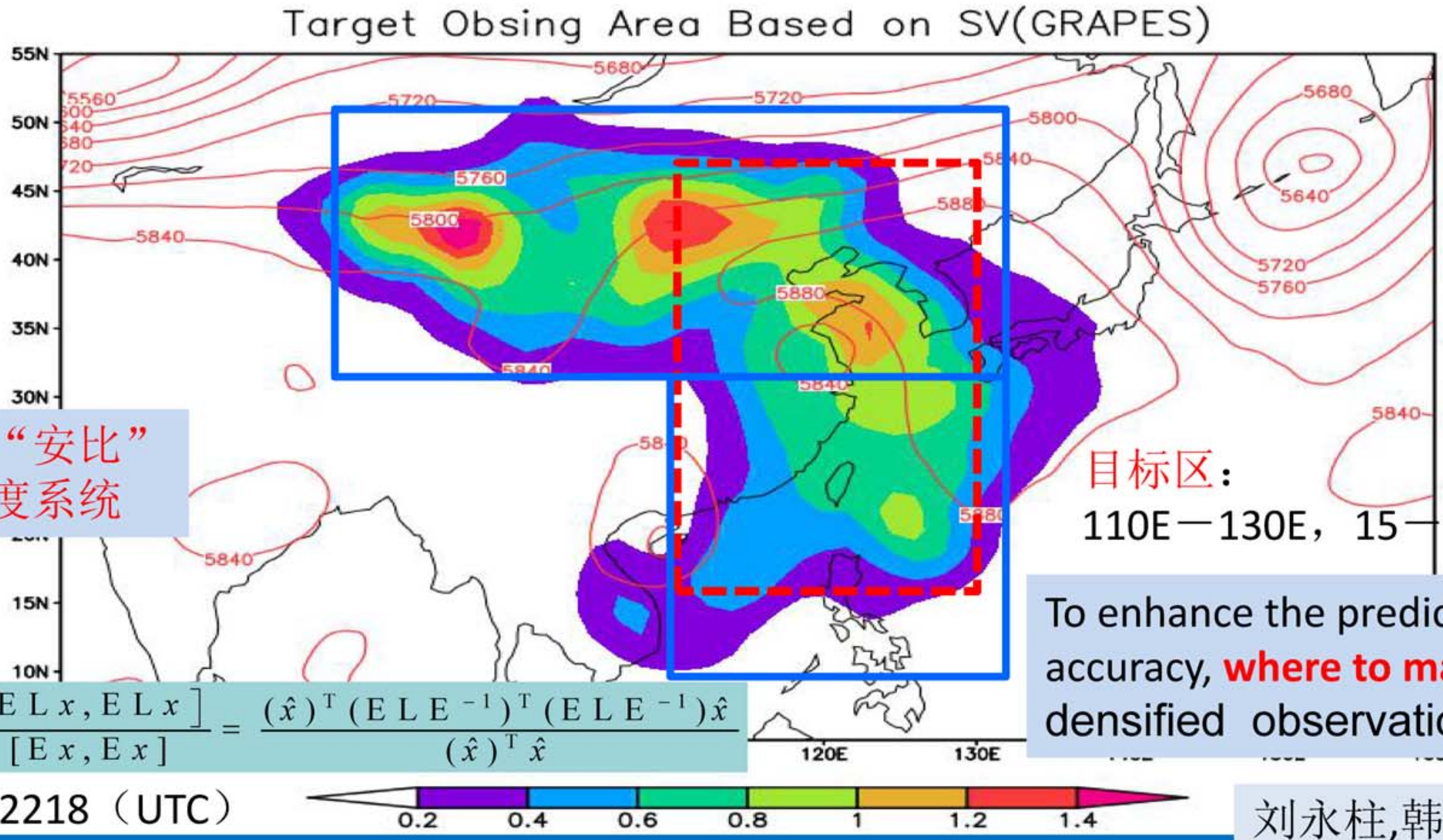
2018年7月23日10时（世界时）





30min temporal resolutinon， assimilated in GRAPES 4D-Var

(adaptive observation or target observation)



台风“安比”
中纬度系统

目标区：
110E－130E，15－45N

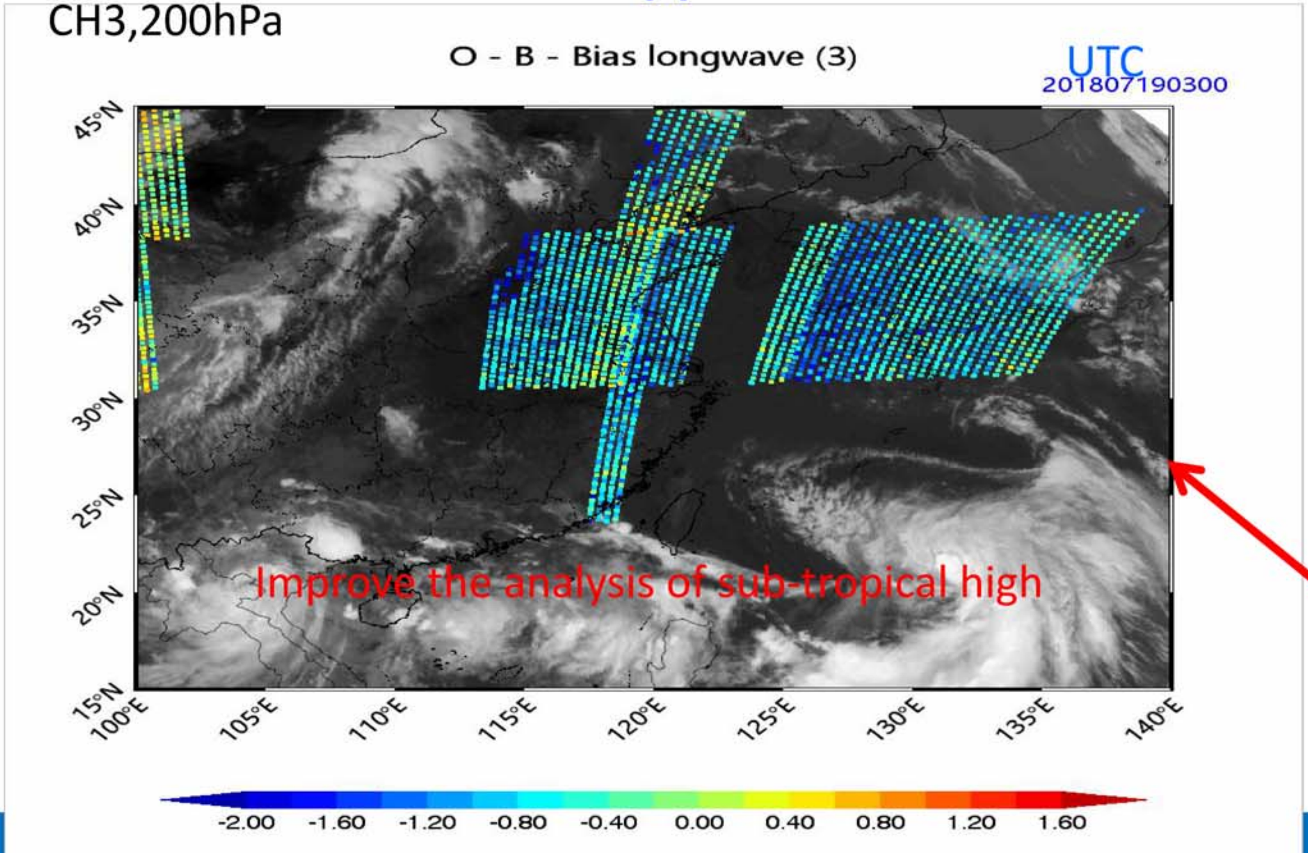
To enhance the prediction accuracy, **where to make** densified observation ？

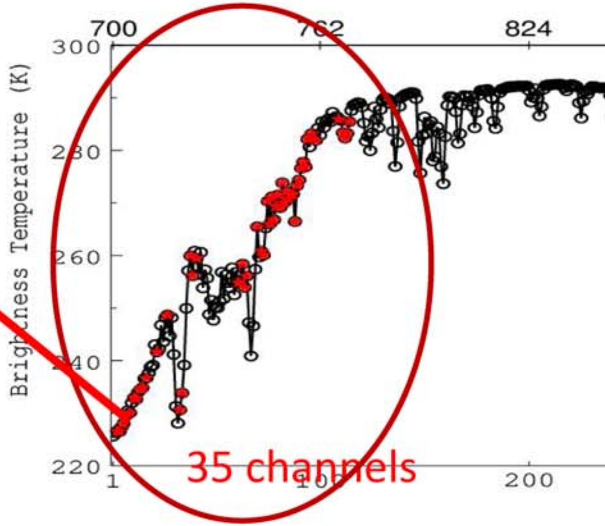
$$J(x)=\frac{[ELx, ELx]}{[Ex, Ex]}=\frac{(\hat{x})^T(ELE^{-1})^T(ELE^{-1})\hat{x}}{(\hat{x})^T\hat{x}}$$

2018072218（UTC）

刘永柱,韩威,2018

Assimilation of GIIRS in GRAPES 4D-Var: Typhoon Ambil case



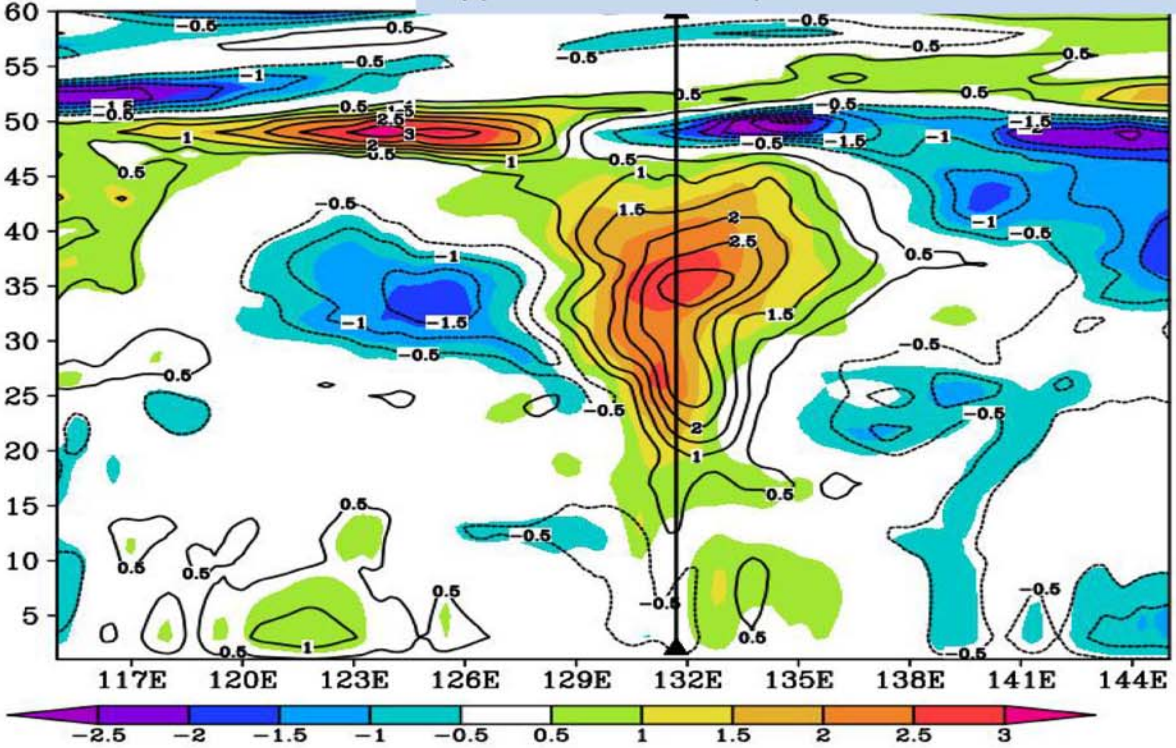


YIN Ruoying and HAN Wei,2018

Impact of assimilating high temporal GIIRS observations on AMBIL analysis: **Position is more closer to reality**

Typhoon center position:**20.6N，131.7E**

300 hPa



color：
GRAPES_4DVAR+GIIRS

Contour：
GRAPES_4DVAR

SITP

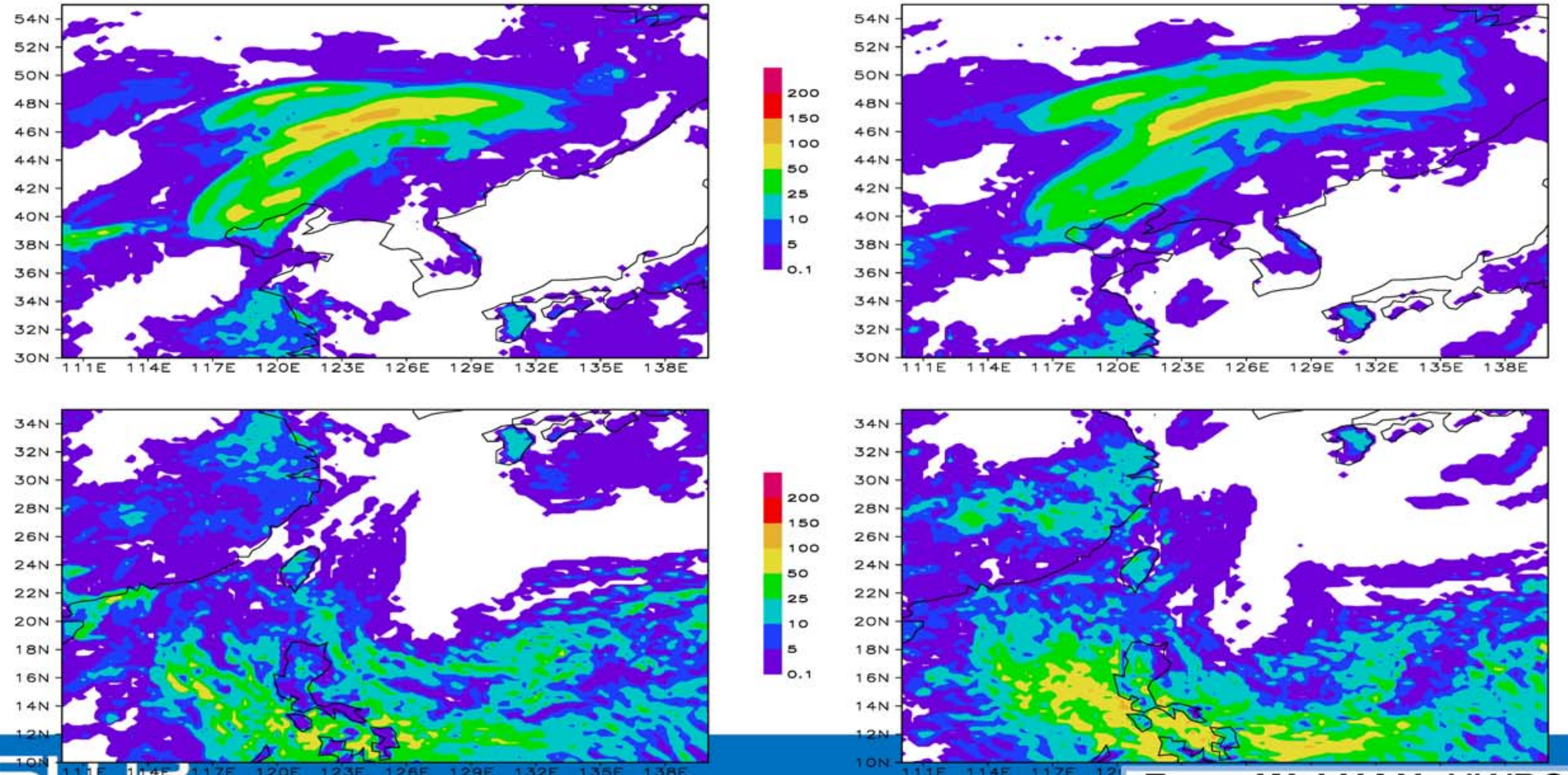
Vertical distribution of temperature depar

From: **Wei HAN**, NWPC,CMA

Impact on Precipitation Prediction

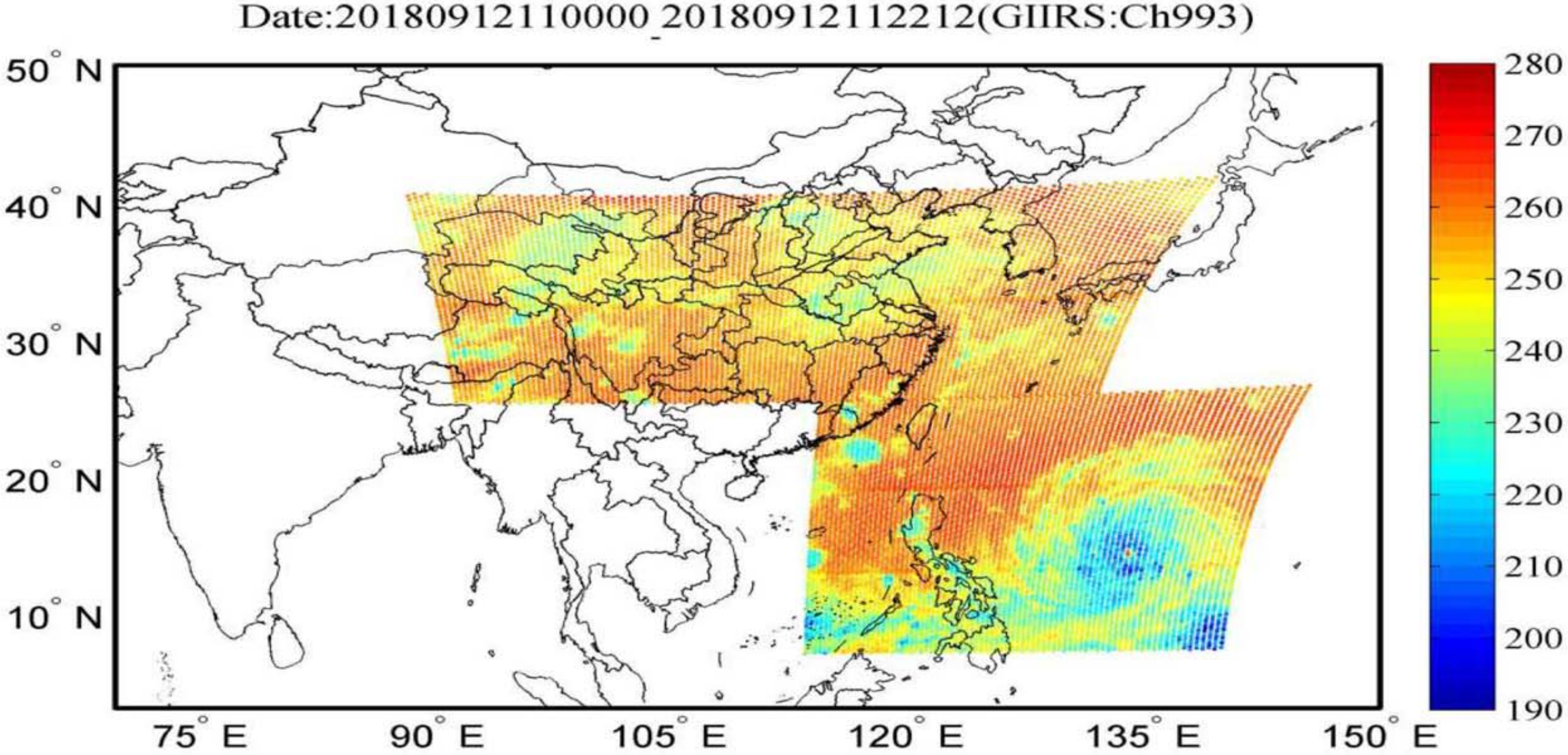
（24—25, July 2018 ）

Without GIIRS **With GIIRS**



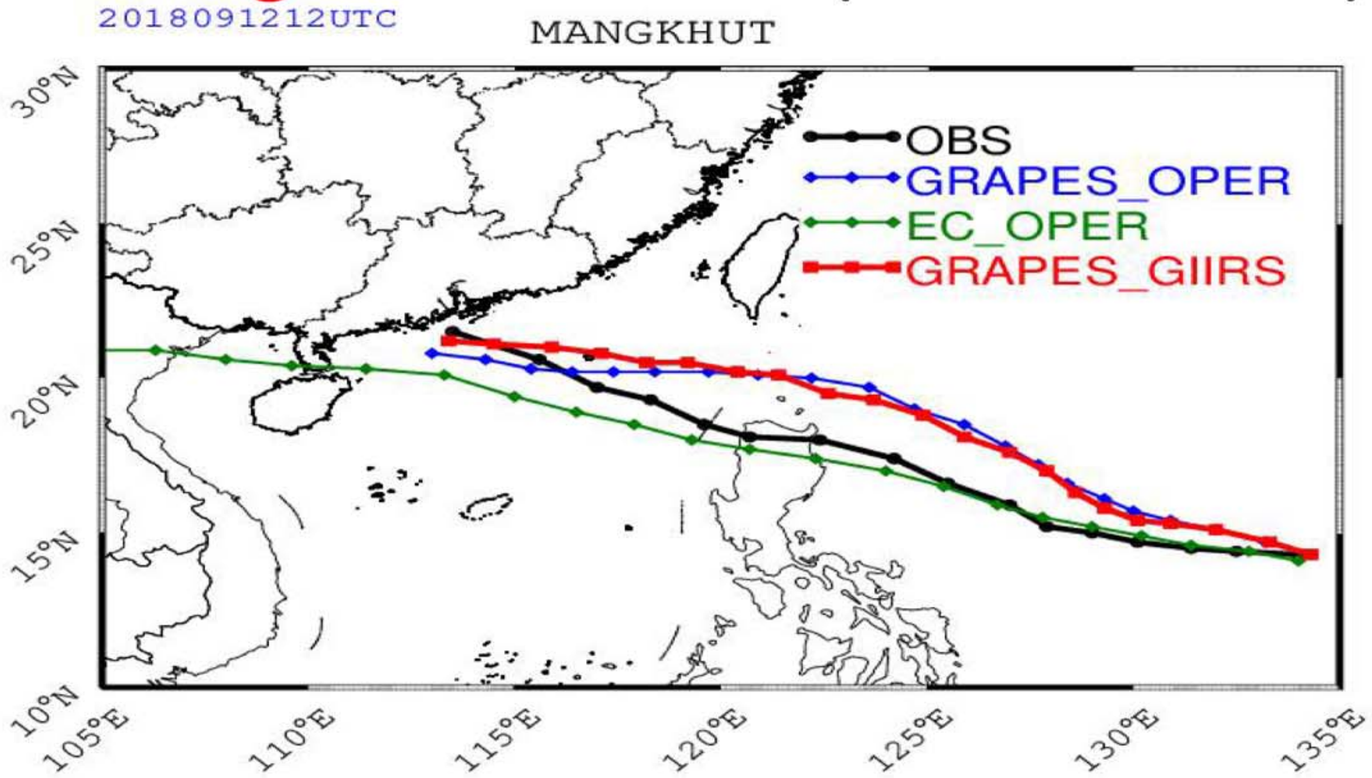
From: **Wei HAN**, NWPC,CMA

Target observing using GIIRS, Typhoon Mangkhut 2018



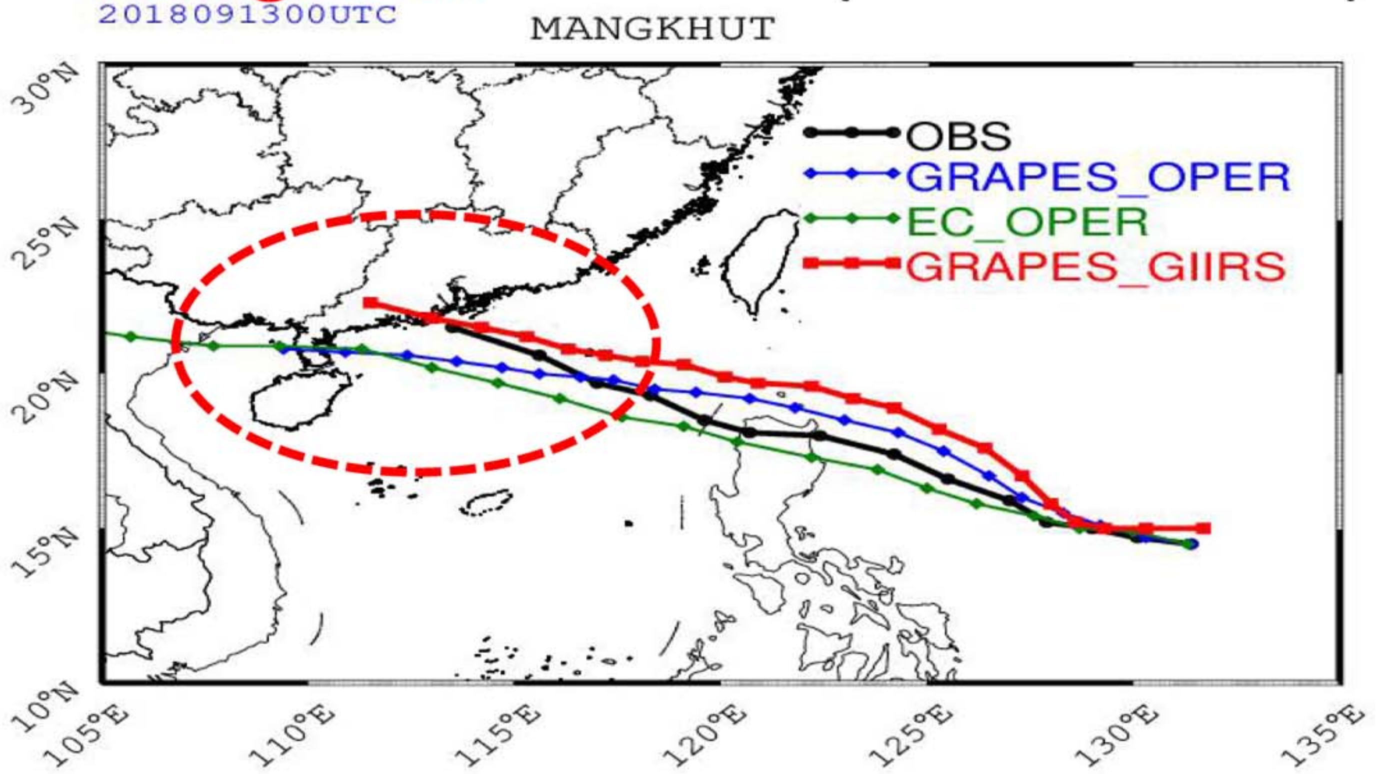
From: **Wei HAN,** NWPC,CMA

Real time Assimilation of GIIRS for Typhoon Mangkhut forecast (2018091212)



From: **Wei HAN,** NWPC,CMA

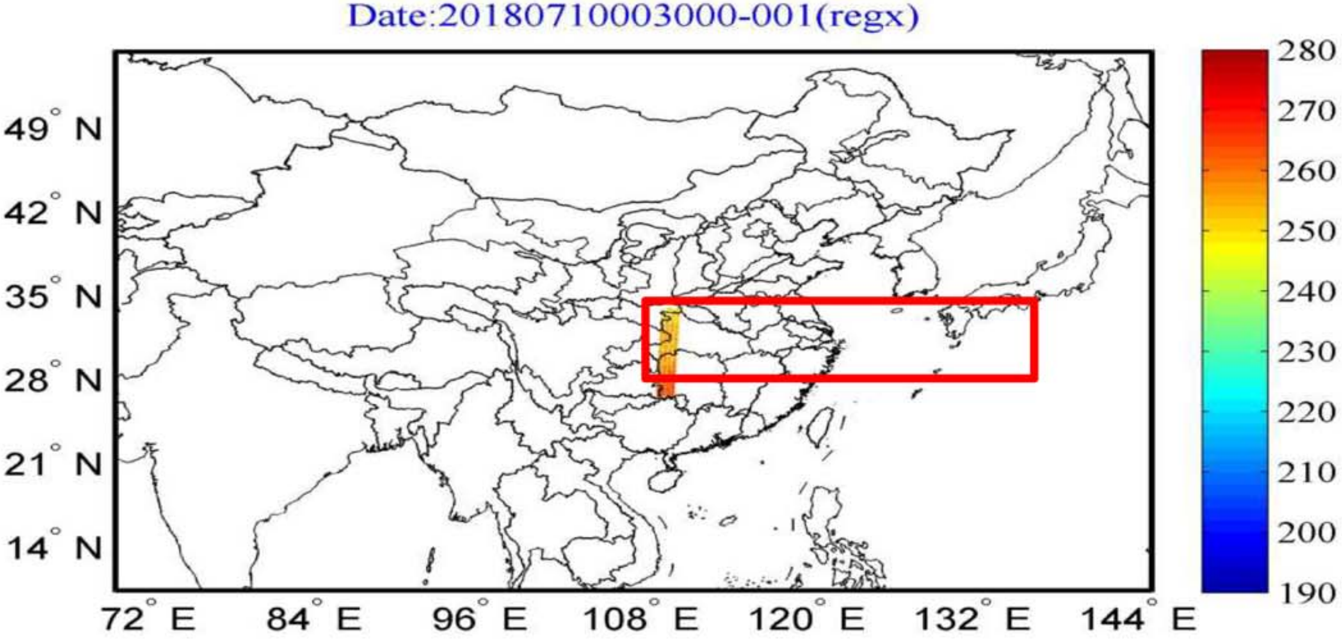
Real time Assimilation of GIIRS for Typhoon Mangkhut forecast (2018091300)

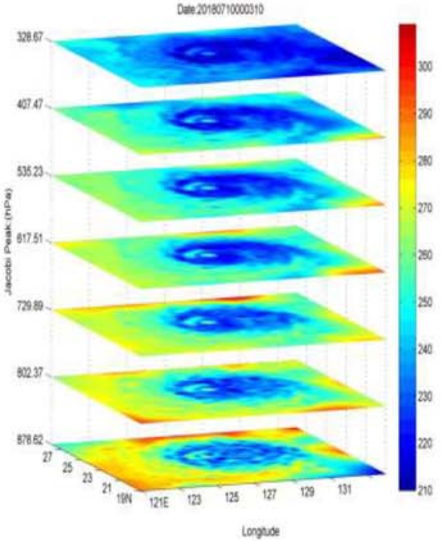


SITP

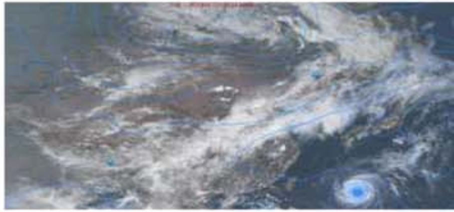
From: **Wei HAN,** NWPC,CMA

2018年7月10日08时(北京时)
启动针对台风Maria的目标区15分钟加密观测
FY-4A/GIIRS观测1分钟后到达风四数据资源池，
实现在GRAPES 4D-Var中的实时同化应用





densified observation every 15 min



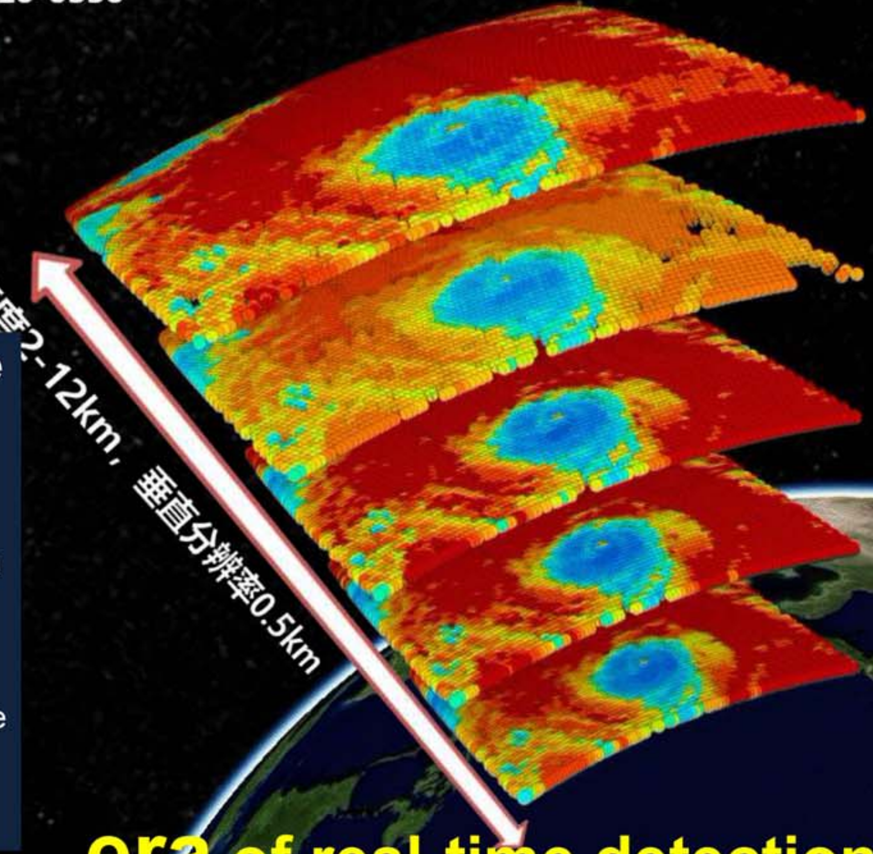
Typhoon Maria

From: **Wei HAN**, NWPC,CMA

GIIRS

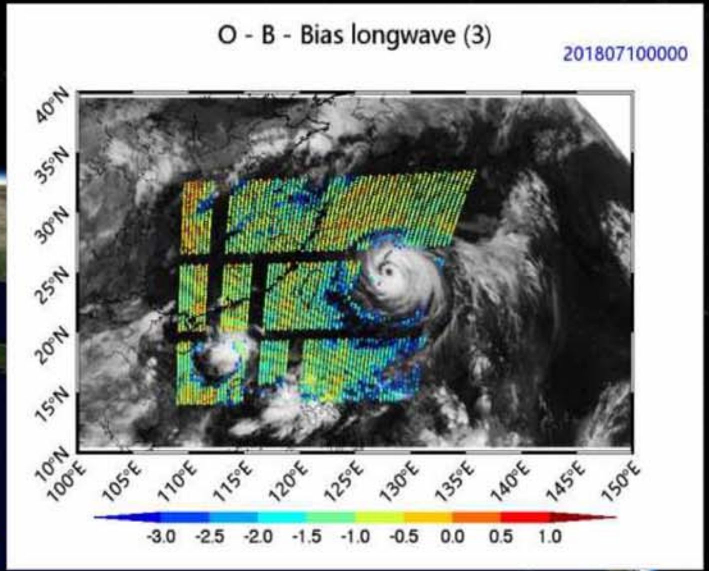
internal temperature and humidity information of typhoon Maria

2018-07-10-0330



3-D detection

For **the first time** in the world, the temperature and humidity data in the vertical direction of the subtropical high in the center of the typhoon eye and around the typhoon eye are detected once every 15 minutes



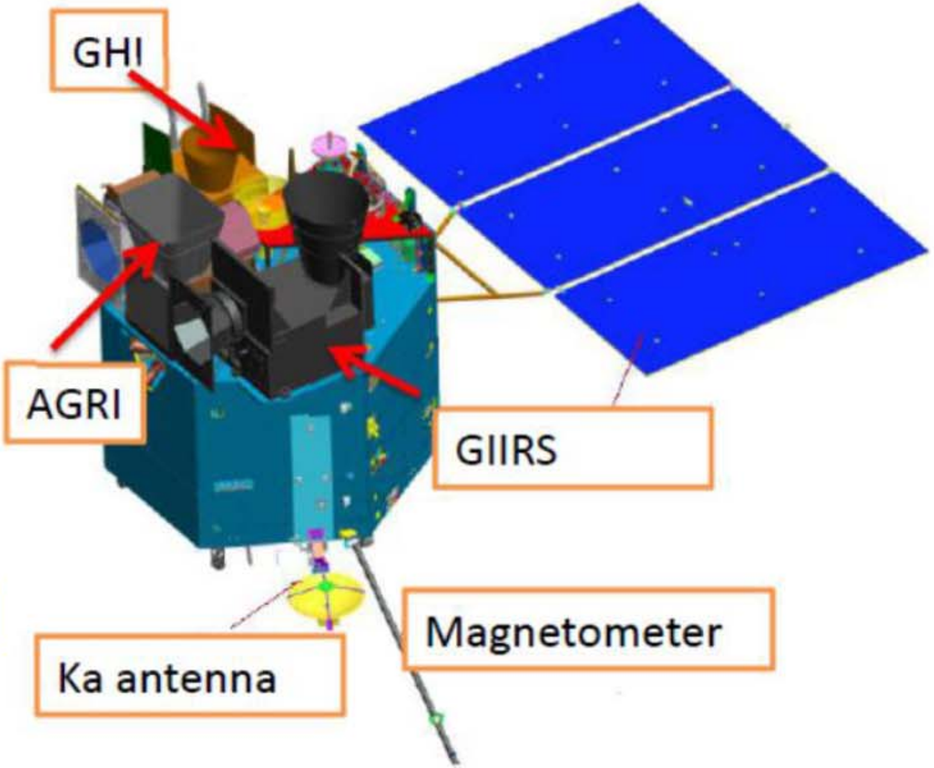
era of real-time detection

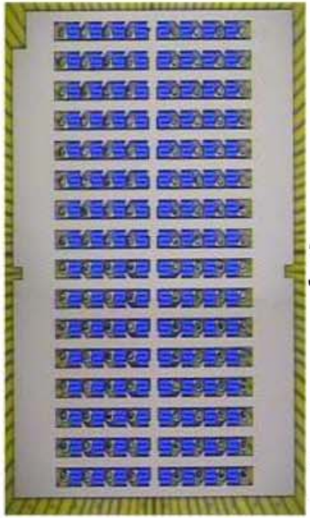
FY-4B launched on 3rd, June 2021

Modules enhanced of GIIRS in FY-4B

- MCT detector
- Interferometer
- Cooled aft-optics
- Heat control

- High Spacial &Temporal resolution



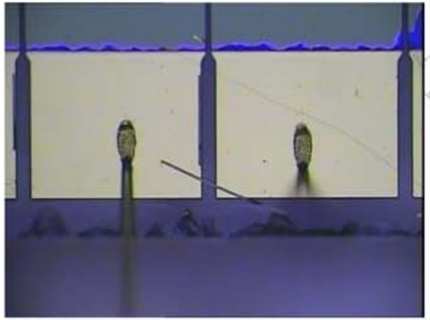


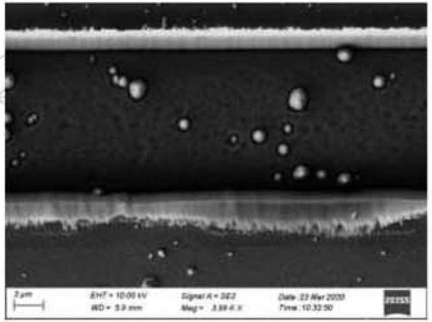
32×4 array

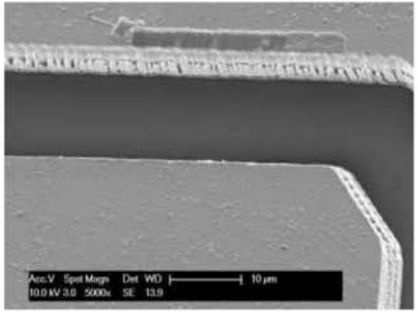
16×8 array

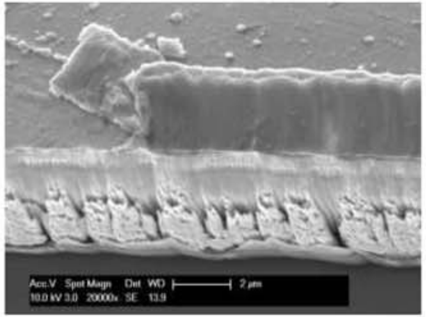
FY-4A FY-4B

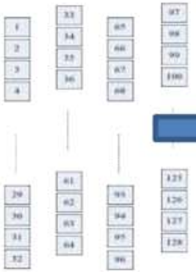
Detector

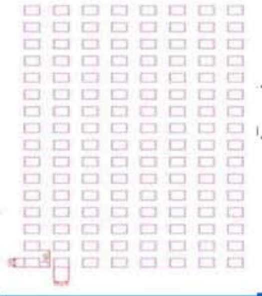






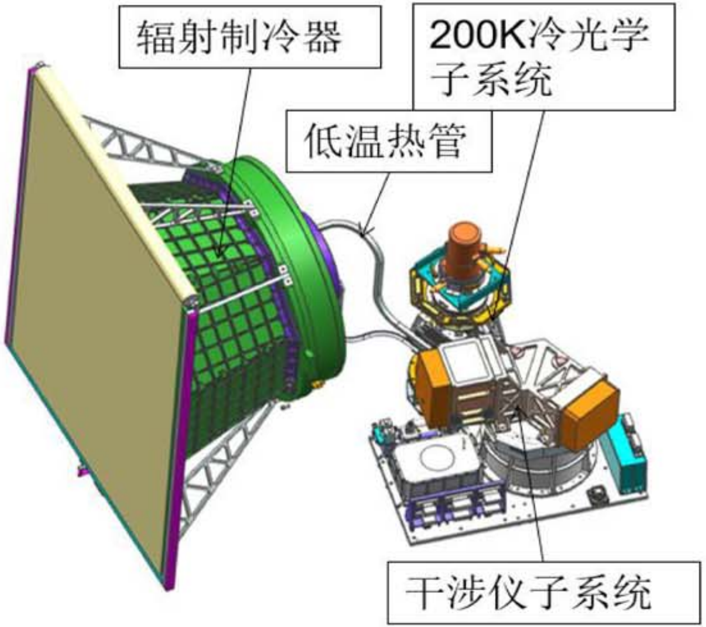


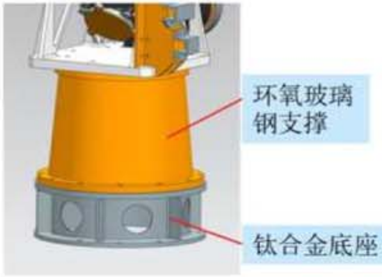


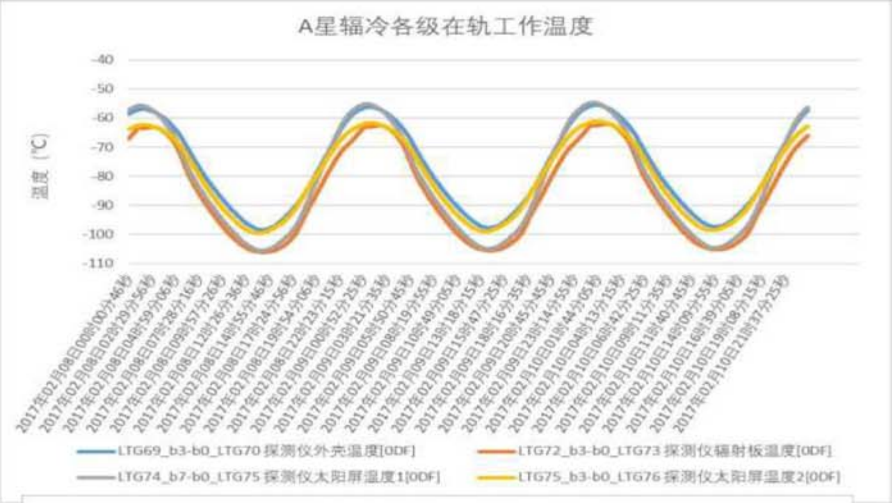


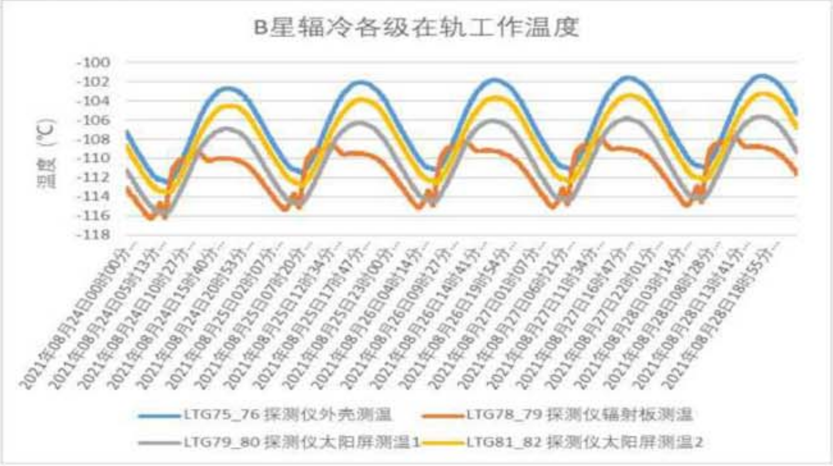
Sensitivity raises > 8%

Wave range >16.3μm

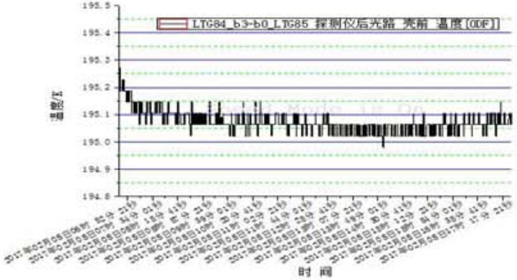








FY-4B, better temperature condition

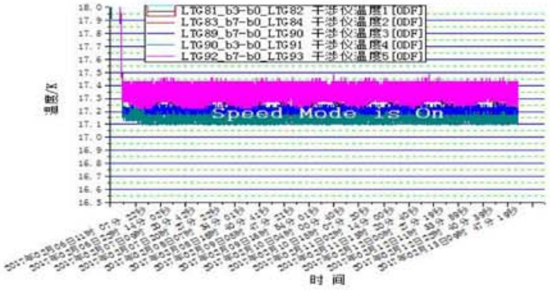


FY-4A

FY-4B

Temperature of cooled aft-optics, down to 195K

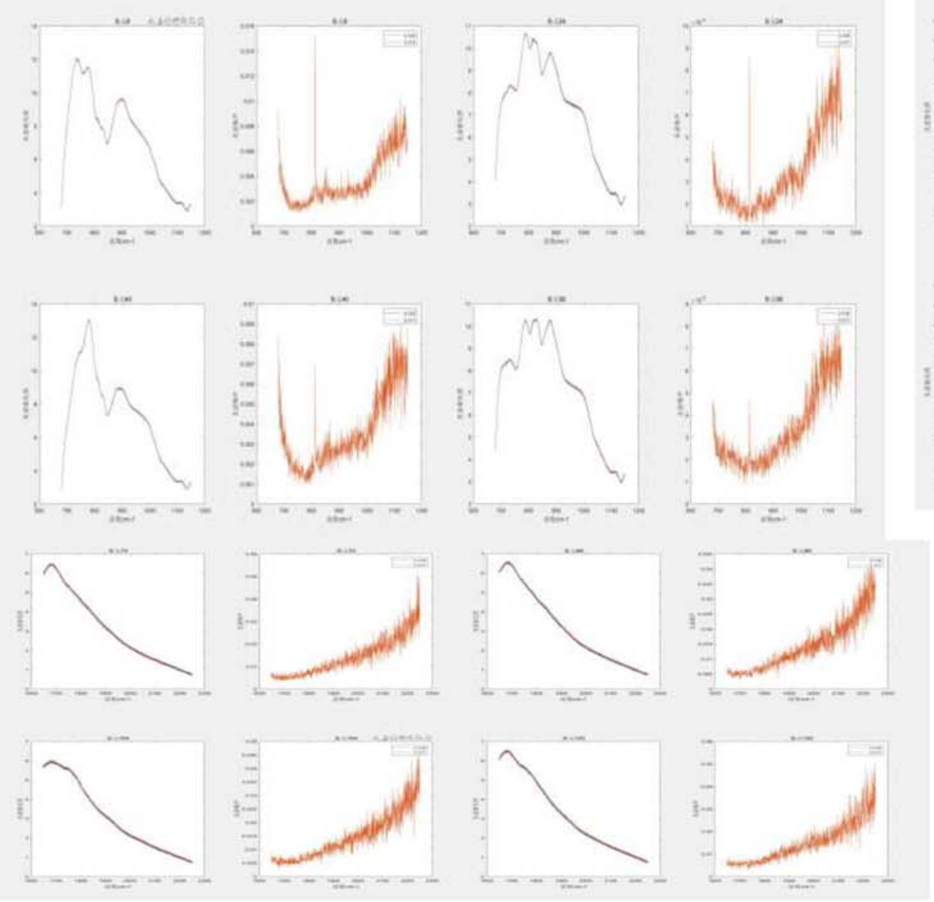
fluctuation of temperature control less than ±0.1K



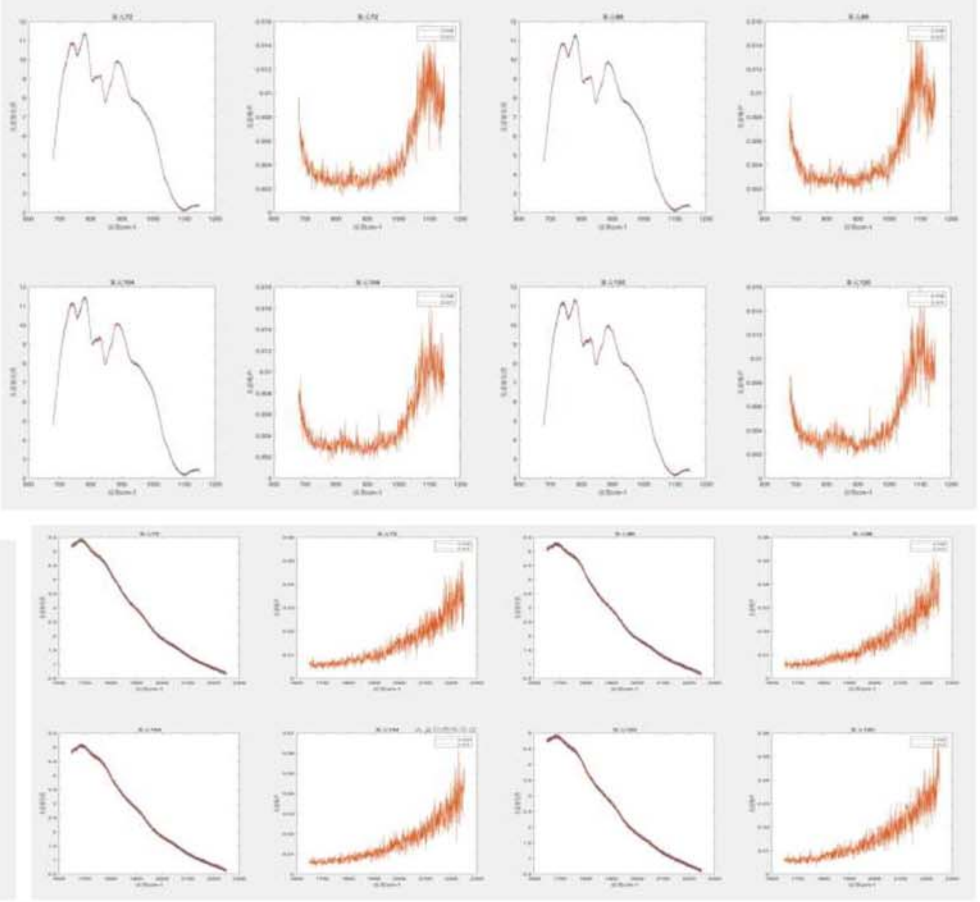
FY-4A, ±0.2K

FY-4B, ±0.15K

Temperature of interferometer

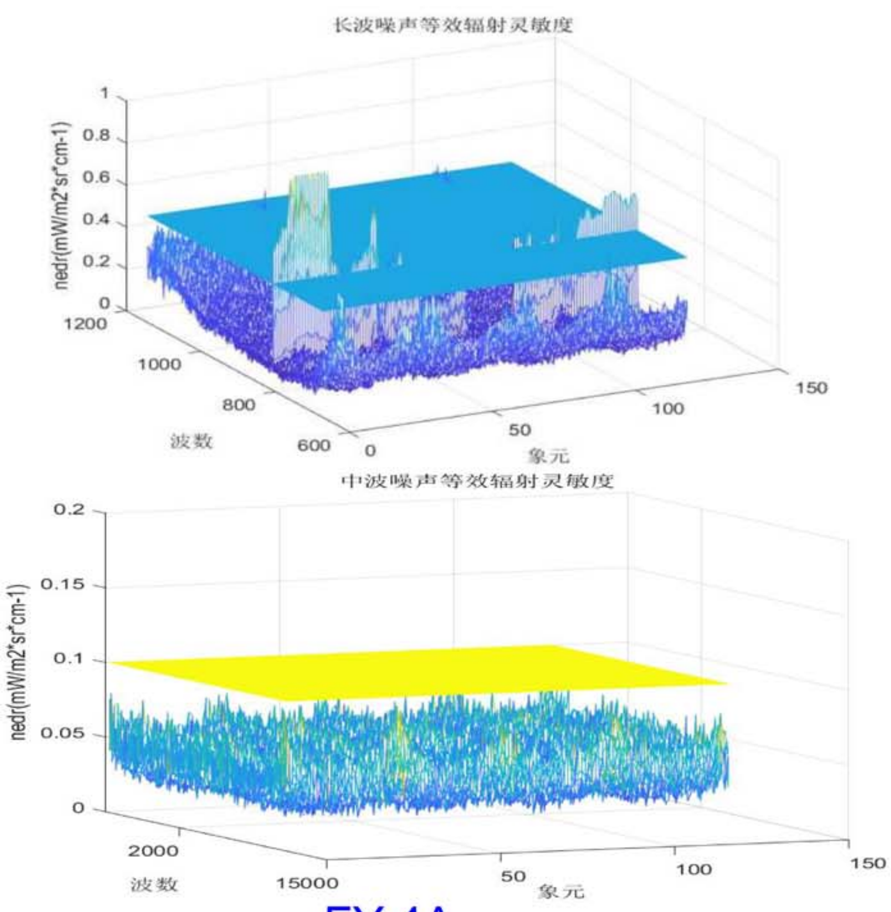


FY-4A

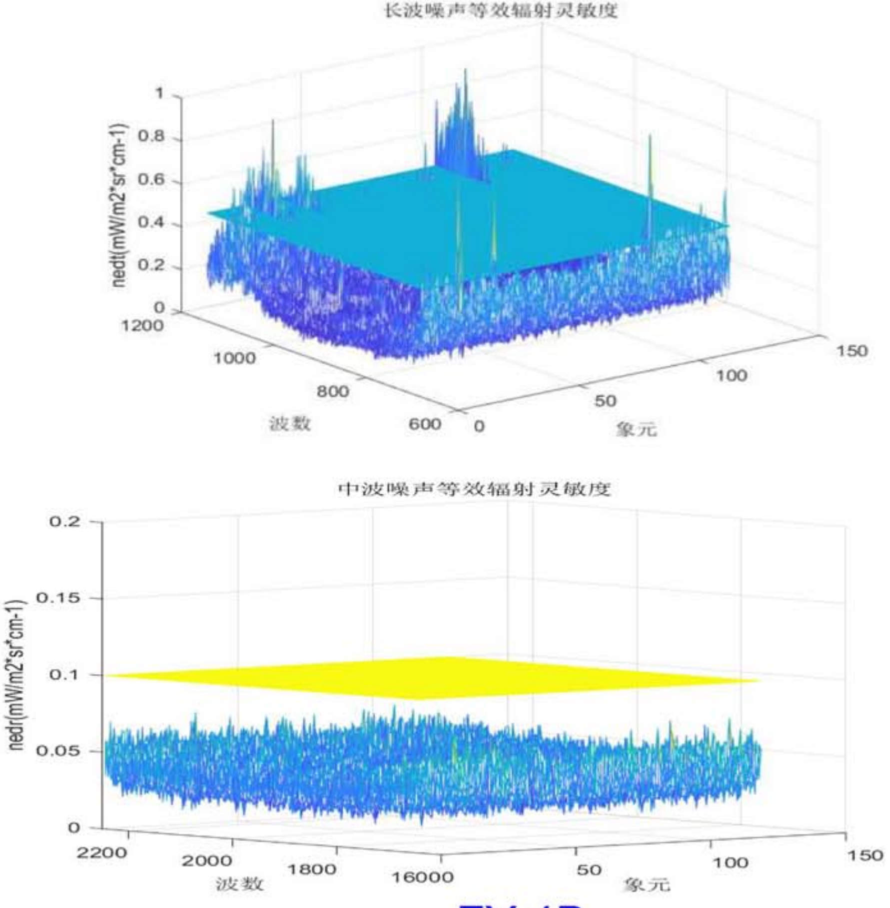


FY-4B

Better spectral response for LW band



FY-4A



FY-4B

SITP

same sensitivity ,better for MW band

GIIRS for FY-4C

	FY-4A	FY-4B	FY-4C
Spectral range (cm^{-1})	700 – 1130 1650 –2250	680 – 1130 1650 –2250	650 – 1130 1650 –2250
Spectral resolution (cm^{-1})	0.625 0.625	0.625 0.625	0.625 0.625
Sensitivity@280K (K)	0.4-0.8 0.8-1.2	0.4 0.8	0.2 0.1
Spatial resolution (km)	16	12	4-8
Temporal resolution (min)	67(China area)	45(China area)	45(China area)
Planned Launch	2016	2021	**2024**
Status	R&D / Op.	Op.	Op.

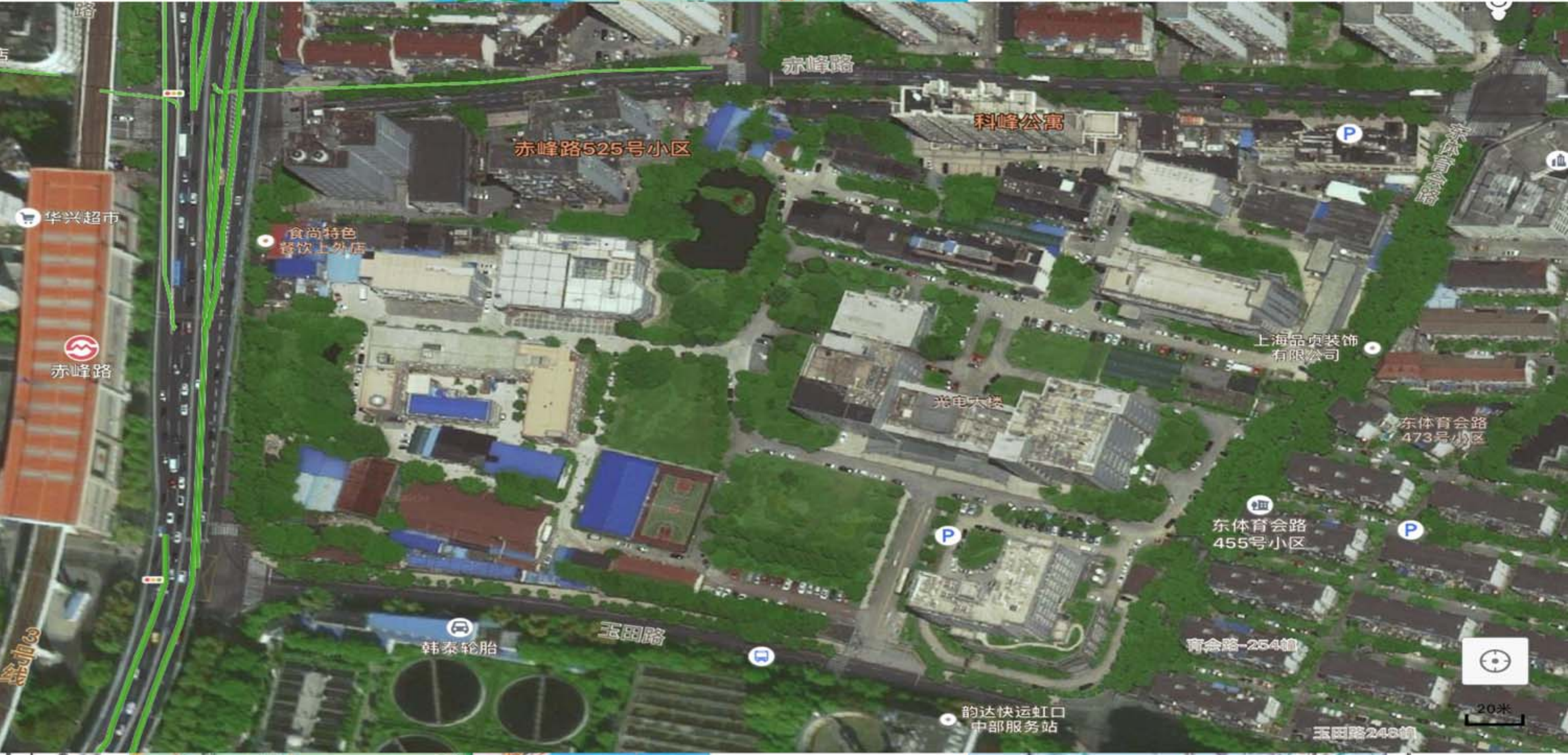
Impact

- GIIRS, the first hyperspectral IR payload in the world working in geostationary orbit
- Opening an era of real-time detection of atmospheric characteristics
- GIIRS onFY-4B, better specification, new applications


红外与毫米波学报


红外与毫米波学报


40
[1982-2022]
Journal of Infrared and Millimeter Waves
红外与毫米波学报



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赤峰路
上海品贞装饰
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473号小区
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455号小区
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玉田路
韩泰轮胎
韵达快运虹口
中部服务站
20米

Thanks for your attention

The authors would like to thank Yaohai Dong, Yili Shen,Qiang Chen from SAST, Zhiqing Zhang, Qiang Guo,Xuan Feng from NSMC.