# GNSS Radio Occultation on FY-3: Current status and future perspective

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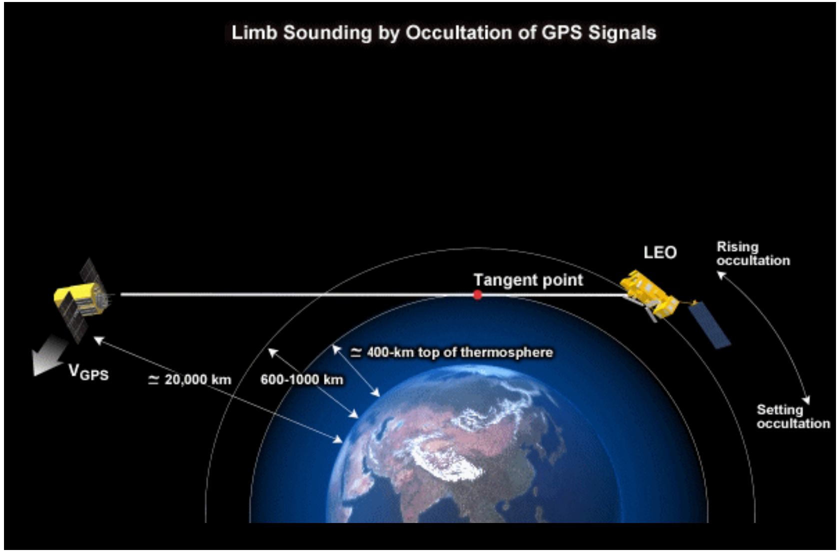
CONTENT

01

# GNSS RO Introduction

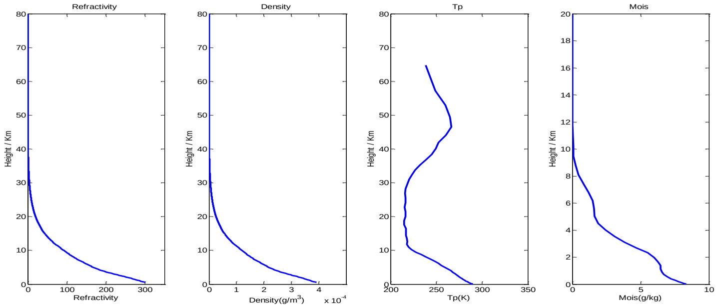
# 01 GNSS RO Introduction

Transmitting from GNSS system, rays will **bend or delay** passing through the atmosphere before reaching the GNSS receiver. The GNSS receiver records the delay in terms of **time and phase.**




**Advantages:**

- high vertical resolution
- high accuracy
- all-weather sounding
- free of calibration
- long-term constant
- global coverage




Occultation date is 2 Otc.2013, and the time is 03:22(UTC).Occultation located at 136.43E,49.18N， which received signal from GPS14 by GNOS/FY3C.

# RO Algorithms

- **Step1. Time and Phase to Excess Phase**

  $\Delta S(t) = \varphi(t) - \varphi_0\ (t)$, *$\varphi_0$ is the vacuum phase path for the GPS-LEO straight line.*

- **Step2. Excess Phase to Bending Angle**

  $d = d^{(0)} - \frac{1}{c}\frac{d\Delta s}{dt}$ *doppler drift;*

  $\frac{c - v_L \cdot u_L}{c - v_G \cdot u_G} - 1 = d;$

  $r_L \times u_L - r_G \times u_G = 0;$ the angle between $u_L$ and $u_G$ is bending angle $\alpha$.

  $u_L \cdot u_L = 1; u_G \cdot u_G = 1$

  ***Geometric optics above 25km;wave optics below 25km***

- **Step3. Bending angle to refractivity**

  3.1 ionospheric correction

  $\alpha(a) = \frac{f_1{}^2\ \alpha_1(a) - f_2{}^2\ \alpha_2(a)}{f_1{}^2 - f_2{}^2},$

  *$f_1$ and $f_2$ are two L-band frequencies transmitted by Each GPS satellite*

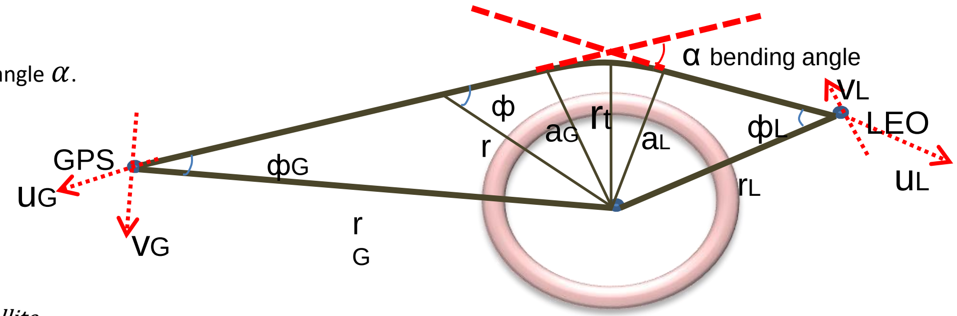
  3.2 Abel inversion

  $n(r) = \exp[\frac{1}{\pi}\int_x^{\infty} \frac{\alpha}{\sqrt{\alpha^2 - x^2}} da\ ]$

  $N = (n-1) \times 10^6$

- **Step4. Refractivity to Temperature, Pressure, Humidity**

  $N = 77.6 \times \frac{P_d}{T} + \frac{3.73 \times 10^5 \times e}{T^2} + \frac{77.6 \times e}{T}$



02

# FengYun Meteorological Satellites

# 02 FengYun Meteorological Satellites

## Chinese FengYun Meteorological Satellites

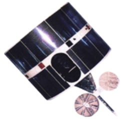
**LEO System**

**First Generation**
FY-1 A, B, C, D

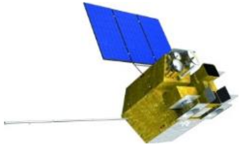
**Second Generation**
FY-3 A, B, C, D, E

FY-3F, G, H planned until 2030

**GEO System**



**First Generation**
FY-2 A, B, C, D, E, F, G, H



**Second Generation**
FY-4 A, B

FY-4C, D planned until 2035

# 風雲 FENGYUN SATELLITE PROGRAM

## FENGYUN-1

First-generation polar-orbiting meteorological satellites

**FY-1A**
LD:07.Sep.1988
EOL:16 Oct 1988

**FY-1B**
LD:03.Sep.1990
EOL:05 Aug 1991

**FY-1C**
LD:10.May.1999
EOL:26 Apr 2004

**FY-1D**
LD:15.May.2002
EOL:01 Apr 2012

## FENGYUN-2

First-generation geostationary meteorological satellites

**FY-2A**
LD:10.Jun.1997
EOL:08 Apr 1998

**FY-2B**
LD:25.Jun.2000
EOL:Sep 2004

**FY-2C**
LD:19.Oct.2004
EOL:23 Nov 2009

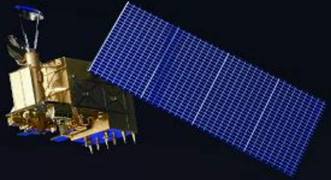
**FY-2D**
LD:08.Dec.2006
EOL:Jul 2015

**FY-2E**
LD:13.Dec.2008
EOL:31 Dec 2018

**FY-2F**
LD:13.Jan.2012
EOL:≥2021

**FY-2G**
LD:13.Dec.2014
EOL:≥2021

**FY-2H**
LD:05.Jun.2018
EOL:≥2022



## FENGYUN-3

Second-generation polar-orbiting meteorological satellites

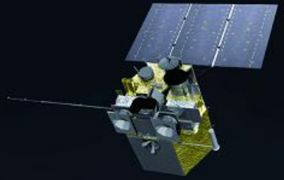
**FY-3A**
LD:27.May.2008
EOL:05 Jan 2015

**FY-3B**
LD:05.Nov.2010
EOL:≥2021

**FY-3C**
LD:23.Sep.2013
EOL:≥2021

**FY-3D**
LD:15.Nov.2017
EOL:≥2022

**FY-3E**
LD:05.Jul.2021
EOL:≥2026



## FENGYUN-4

Second-generation geostationary meteorological satellites

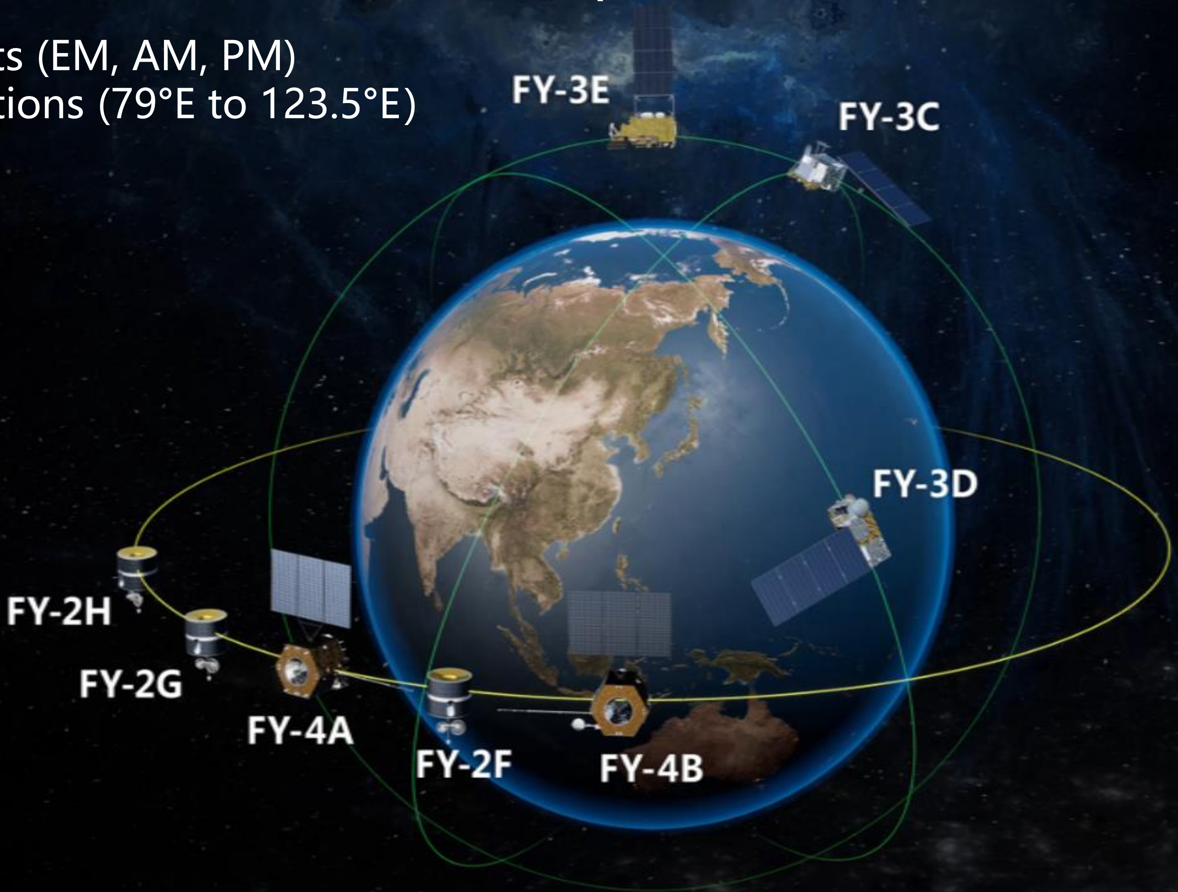
**FY-4A**
LD:11.Dec.2016
EOL:≥2021

**FY-4B**
LD:03.Jun.2021
EOL:≥2028

LD : Launch time
EOL : End of life

# On-Orit in Operation （8 satellites）

LEO : 3 orbits (EM, AM, PM)
GEO: 5 positions (79°E to 123.5°E)




P. Zhang, et al., 2019, Advances in Atmospheric Sciences

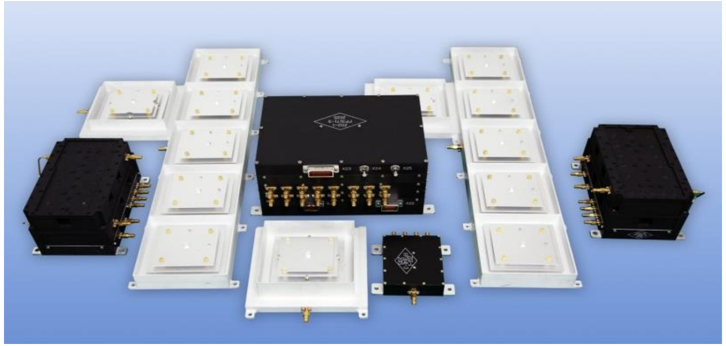
# Multi-GNSS RO receiver on FY-3

**GNOS----*Global Navigation Satellite System Occultation Sounder, The first RO sounder of FY-3 series***

**GNOS** ： FY3C, 2013, BDS/GPS RO
**GNOS** ： FY3D, 2017, BDS/GPS RO
**GNOS-**Ⅱ ： FY3E, 2021, BDS/GPS RO + Reflectomery

**FY-3C/D GNOS**

**FY-3E GNOS-II**



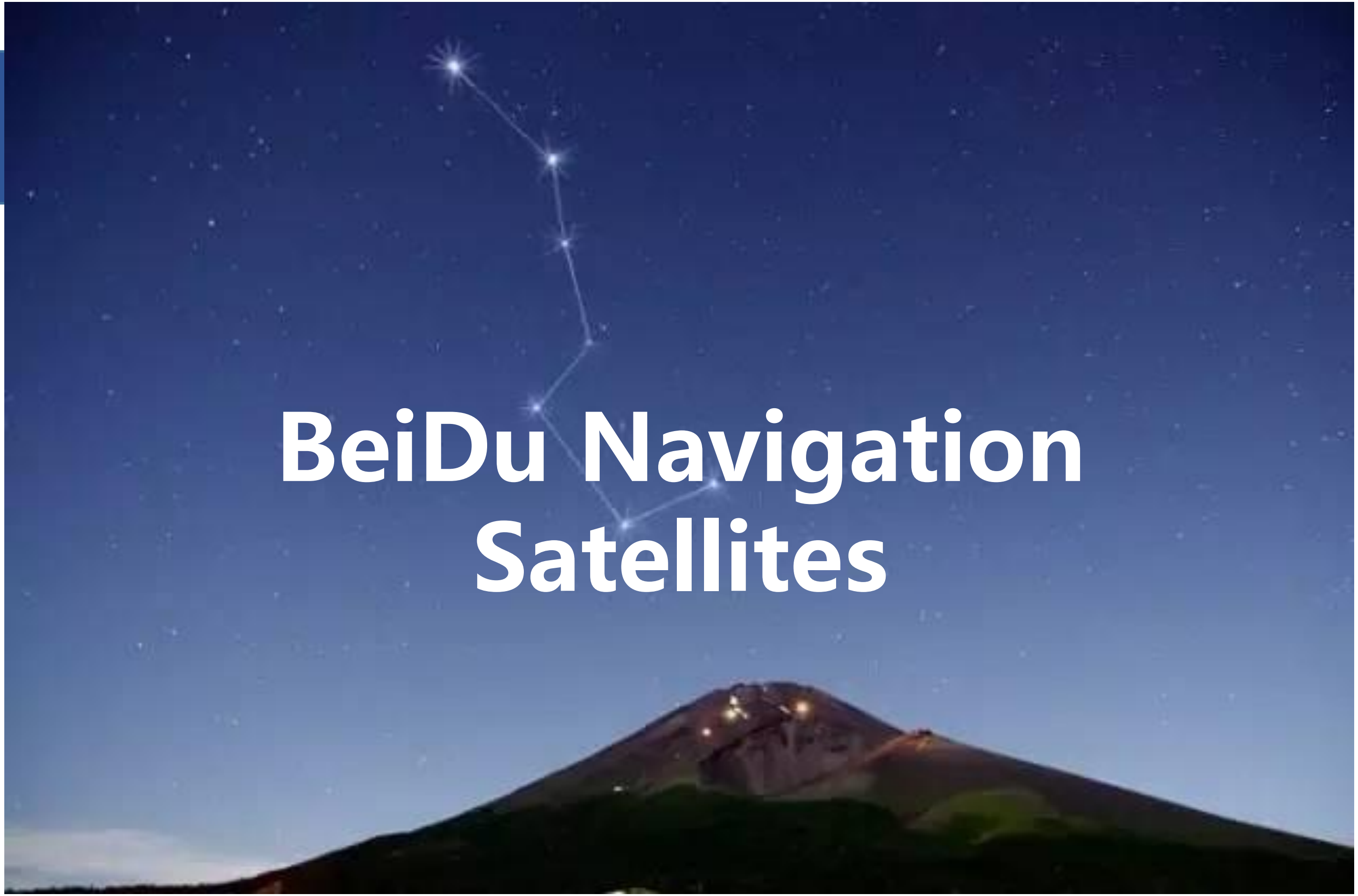
# GNOS instrumental parameters of FY-3 series



| Parameters | FY-3C | FY-3D | FY-3E |
|---|---|---|---|
| Instrument mass | 7.5kg | The same as FY3C | The same as FY3C |
| GNSS Constellation | BDS B1、B2(f1=1561.098 MHz; f2=1207.14 MHz)<br>GPS L1、L2(f1=1575.42 MHz; f2=1227.60 MHz) | The same as FY3C | BDS B1I,B2I<br>GPS L1, L2(L5,optional)<br>Galileo E1, E5b (E5a,optional) |
| Code type | BDS B1I、B2I<br>GPS L1C/A、L2C、L2P | + Open loop tracking for B1 | The same as FY3D |
| Channels | Positioning: BDS 4 GPS 8<br>Occultation : BDS 4 GPS 6 | Positioning: BDS 8 GPS 9<br>Occultation : BDS 6 GPS 6 | 30 for Positioning (3 systems)<br>24 for Occultation (3 systems) |
| Sampling rate | Positioning & Ionosphere occultation: 1Hz<br>Atmosphere occultation: CL 50Hz ; OL 100Hz | The same as FY3C | The same as FY3D |
| Clock stability | $1\times10^{-12}$（1secAllan） | The same as FY3C | The same as FY3C |
| Antenna specification | Atmosphere occultation antenna：<br>Gain: >10dBi<br>Antenna field of view: (El ±7.5° Az ±35° )<br>Positioning & Ionosphere occultation antenna：<br>Gain: -1dBi<br>Antenna field of view: ±60° | 8.5dBi@45° azimuth<br>Peak gain increased | The same as FY3D |
| Pseudorange precision | ≤30cm | The same as FY3C | The same as FY3C |
| Carrier phase precision | ≤2mm | The same as FY3C | The same as FY3C |
| Range | -145~-100dBm | The same as FY3C | The same as FY3C |
| NEK | 250K | The same as FY3C | The same as FY3C |
| GNSS-R | \ | \ | Share power and data down link with RO<br>~13dBi |

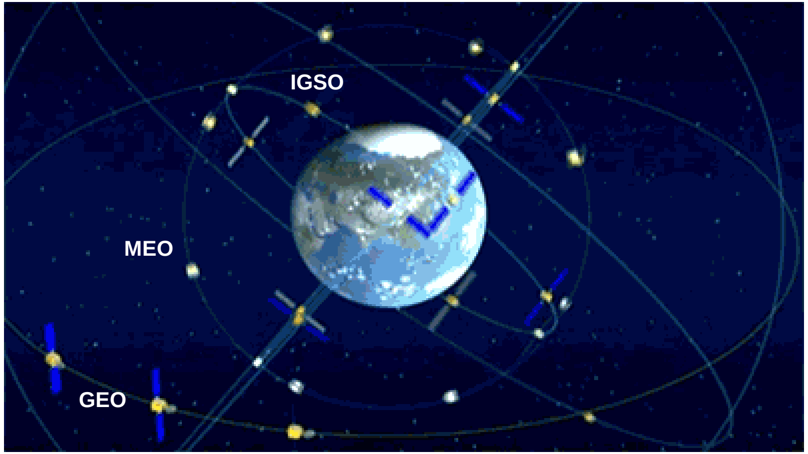
03

# BeiDu Navigation Satellites

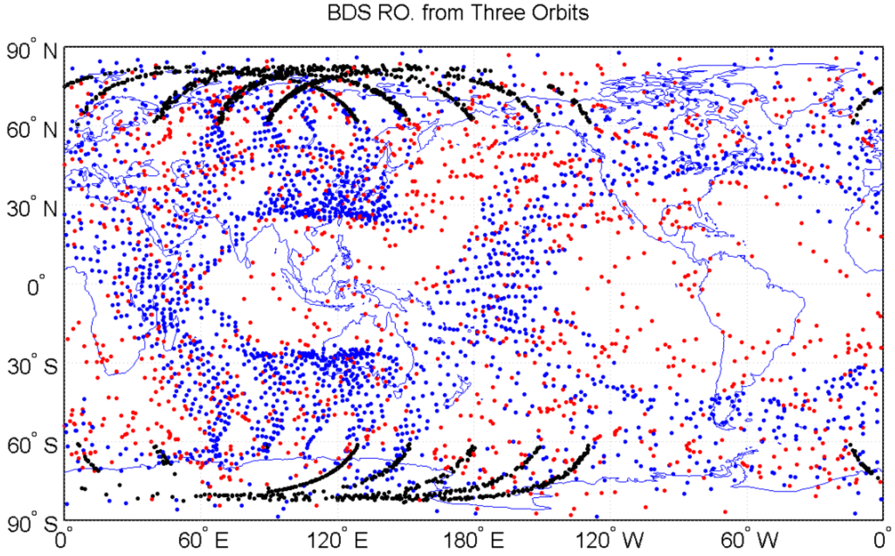


# 03 BeiDu Navigation Satellites

Beidou system has launched 55 satellites.
At present, 48 satellites in orbits




Distribution of FY-3C BDS RO (1months)




## Three orbits:

**MEO** medium Earth orbit, 21 528 km (29 satellites)
**IGSO** inclined geosynchronous stationary Earth orbit,35 786 km (12 satellites)
**GEO** geosynchronous orbit, 35 786 km (7 satellites)

- MEO RO
- IGSO RO
- GEO RO

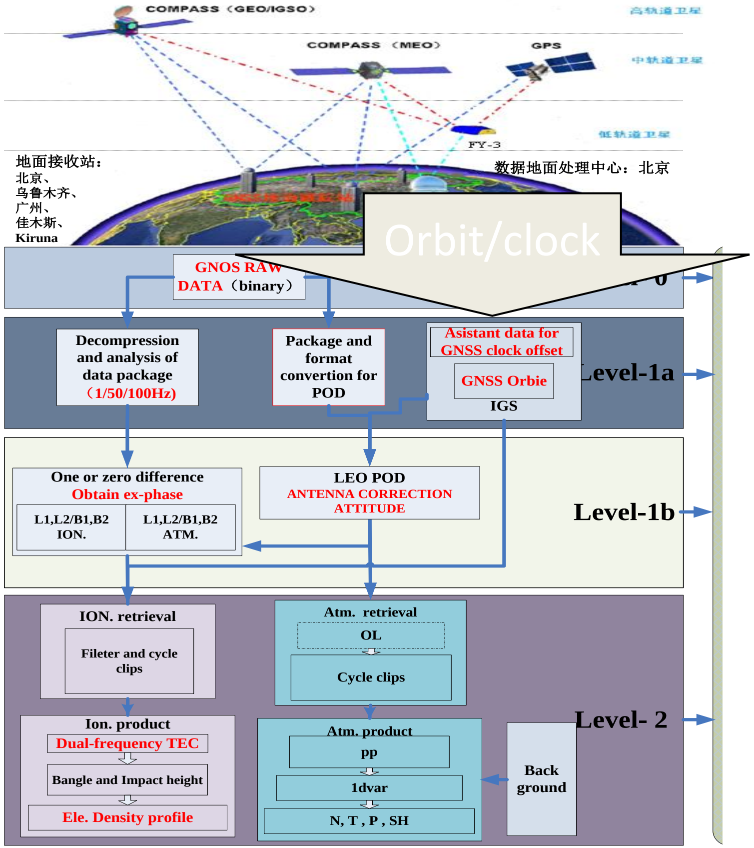
**Refer to www.beidou.gov.cn**

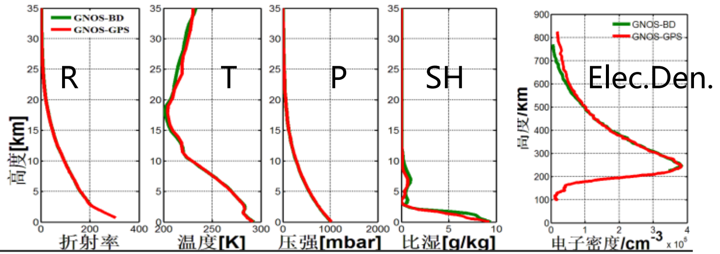
04

# FY-3 GNOS Results

# 04 FY-3 RO Results and Validation

## GNOS radio occultation data processing flow




Raw observe package

Excess phase (Ion. & Atm)

POD

Bending angle & Impact height

Refractivity

T,H,P(Atm.)

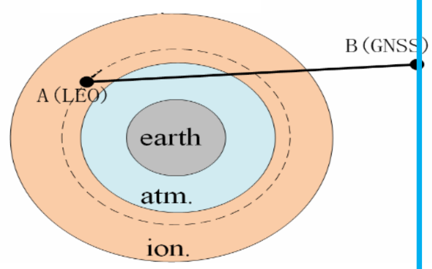
Electron density, TEC, S4(Ion.)

# GNOS excess phase calculated in Zero-diff. for BDS-2

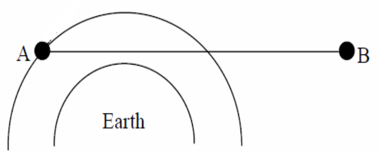
**Zero-diff.**

**Ultra-stable oscillator Non-adjust -clock modle**

**BDS-2**




Zero-diff.




Carrier phase (Occultation path A-B ):

geometric range | LEO clock offset | GPS clock offset | rel: relativity | Ambiguity | Ion. and Atm. Ex. phase

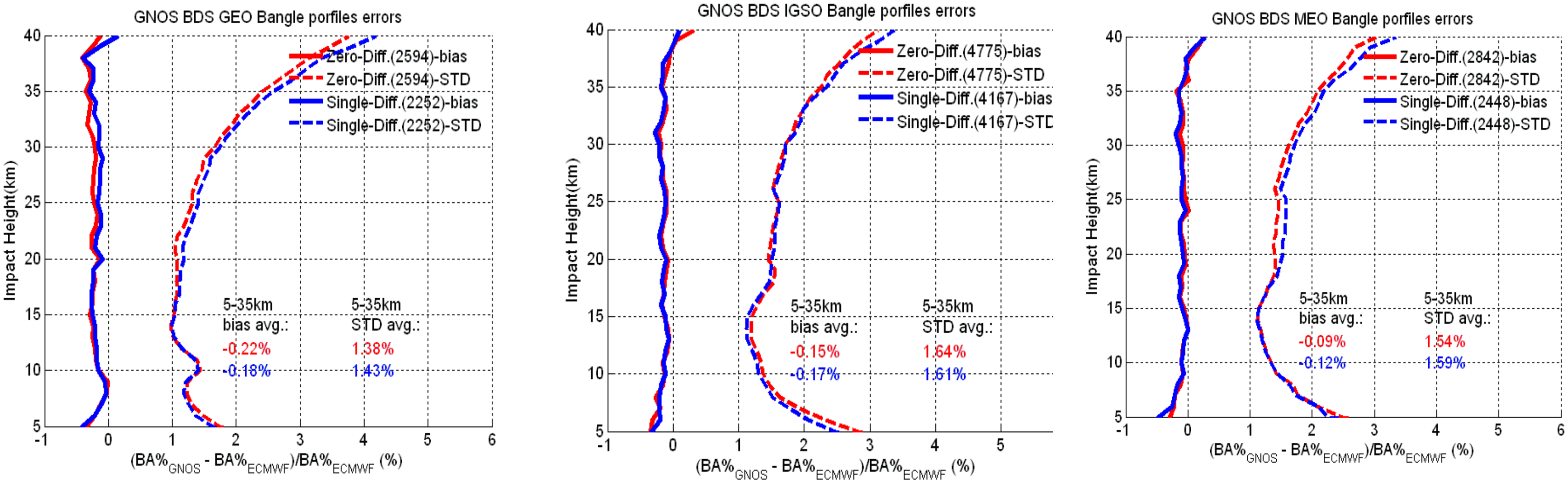
$$L^b_{a,i}(t_r) = \rho^b_a(t_r) + c\left(\delta t_a(t_r) - \delta t_{a,rel}(t_r)\right) - c\left(\delta t^b(t_r - \tau^b_a) - \delta t^b_{rel}(t_r - \tau^b_a)\right) + \delta\rho^b_{a,rel}(t_r) + \Delta\phi^b_{a,i}(t_r) + \delta\rho^b_{a,ion,i}(t_r) + \delta\rho^b_{a,trop,i}(t_r)$$

Excess phase

All the variables are calculated and removed, including LEO receiver clock

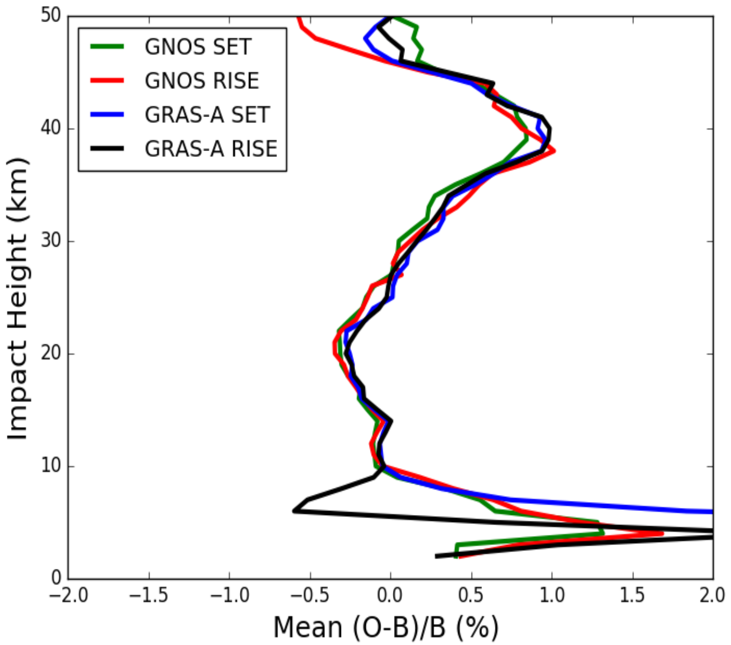
$$\delta\rho^b_{a,ion,i}(t_r) + \delta\rho^b_{a,trop,i}(t_r) = L^b_{a,i}(t_r) - \left(\rho^b_a(t_r) + c\left(\delta t_a(t_r) - \delta t_{a,rel}(t_r)\right) - c\left(\delta t^b(t_r - \tau^b_a) - \delta t^b_{rel}(t_r - \tau^b_a)\right) + \delta\rho^b_{a,rel}(t_r) + \Delta\phi^b_{a,i}(t_r)\right)$$

# Statistics of different orbits of BDS RO

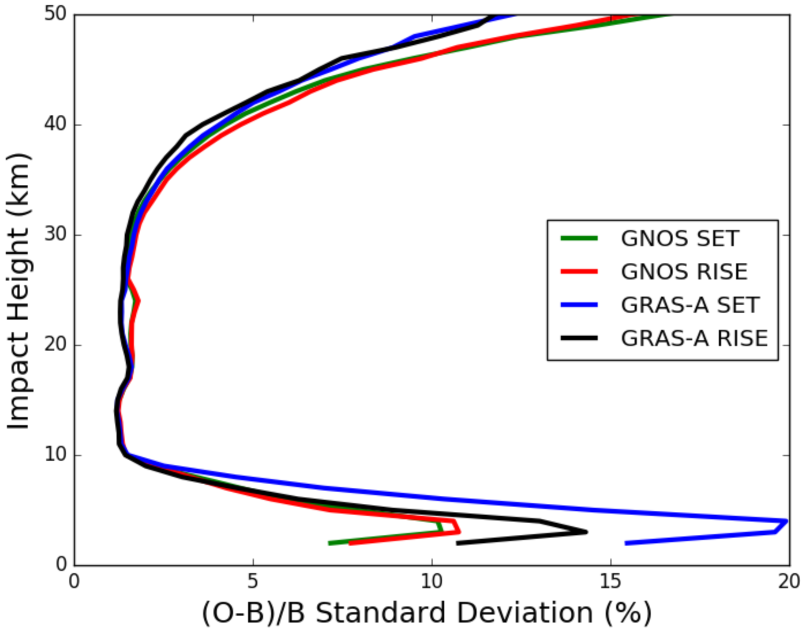



W. Bai, et al., 2018, Atmospheric Measurement Techniques

# Compared with MetOp



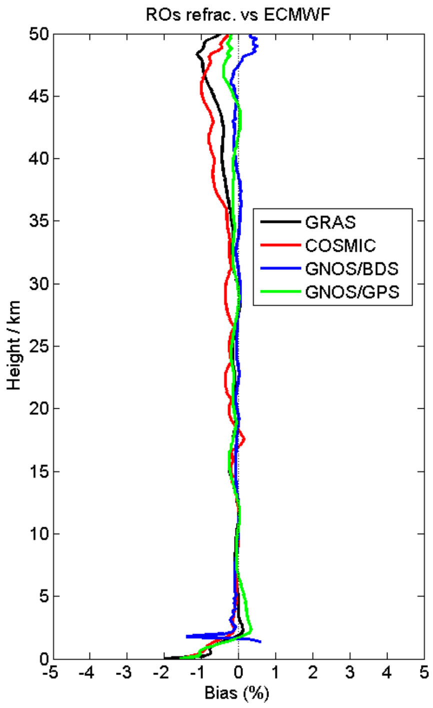

GNOS and GRAS are very consistent with eachother above 10 km

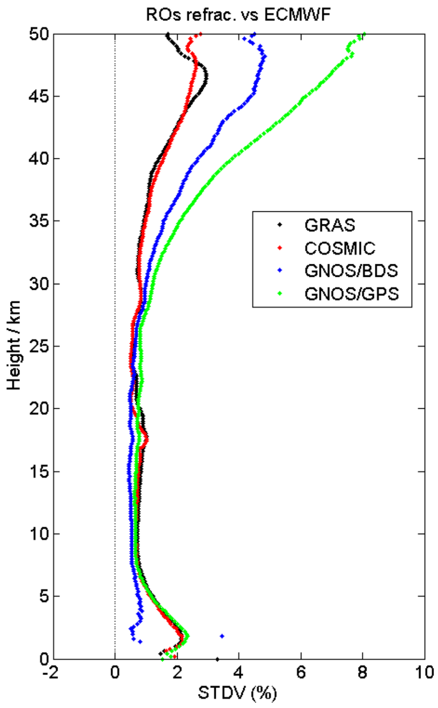



GNOS standard deviations are comparable to GRAS in the 10–40 km interval. The difference in the 20 to 25 km interval is related to the transition from wave optics to geometric optics for the GNOS.

M. Liao, et al., 2018, Atmospheric Measurement Techniques

# Statistics of FY-3C BDS/GPS RO

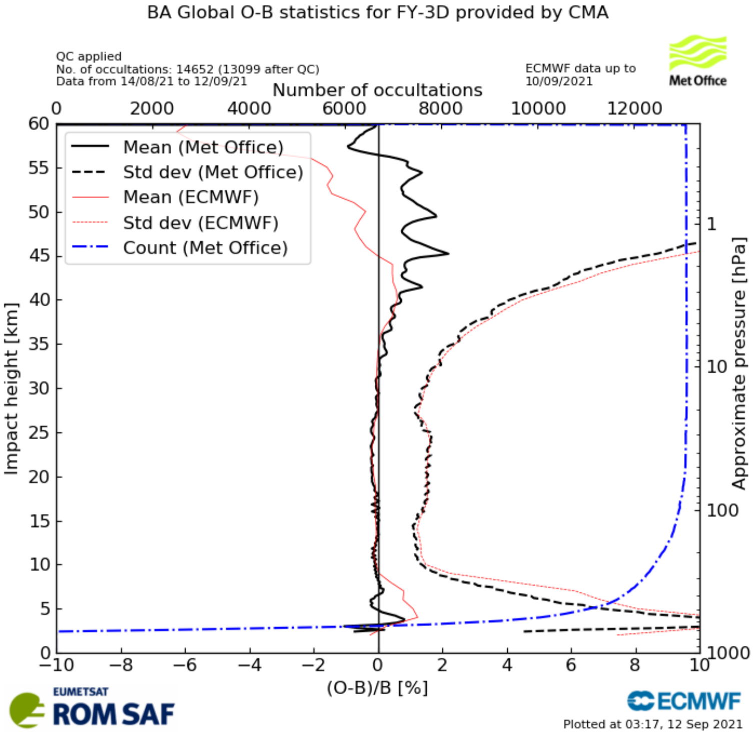


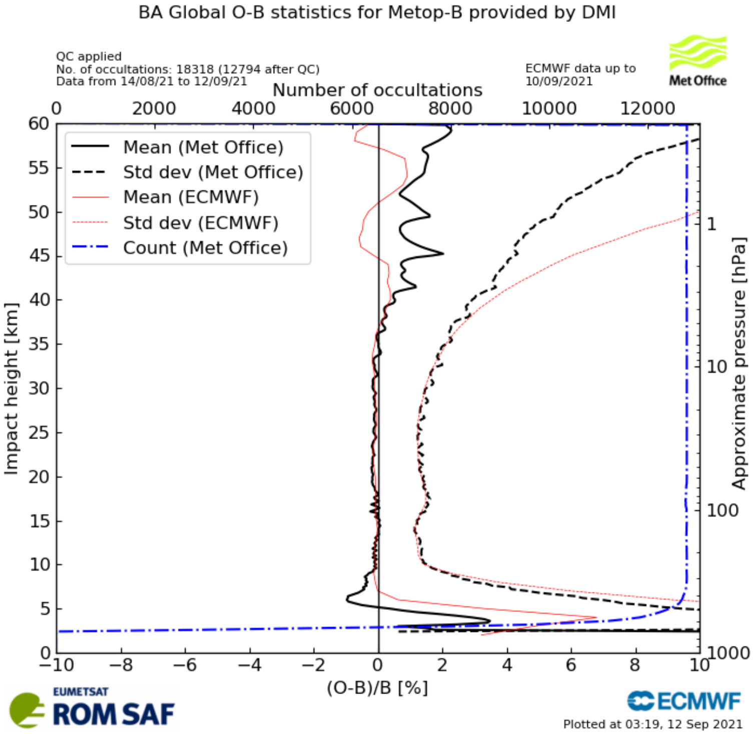




At 0-30km GNOS BDS/GPS RO is similar to MetOp/GRAS and COSMIC.

The bias of BDS and GPS RO is in good agreement

# Operational monitoring at ROM SAF




**The plots are from ROM SAF website: https://www.romsaf.org/monitoring/index.php**

05

# Applications in NWP

# 05 Applications in Numerical Weather Prediction

## Including CMA , ECMWF, UK Met Office, DWD, JMA, KMA NWP centers

WMO OMM
World Meteorological Organization
Organisation météorologique mondiale
Organización Meteorológica Mundial
Всемирная метеорологическая организация
المنظمة العالمية للأرصاد الجوية
世界气象组织

Secrétariat
7 bis, avenue de la Paix – Case postale 2300
CH 1211 Genève 2 – Suisse
Tél.: +41 (0) 22 730 81 11
Fax: +41 (0) 22 730 81 81
wmo@wmo.int – public.wmo.int

Our ref.: 13348/2021/I/SSU/NSMC

Mr Zhuang Guotai
Permanent Representative of China with WMO
China Meteorological Administration
46 Zhongguancun Nandajie
Beijing 100081
China

4 June 2021

Subject: Letter of Support for CMA Radio-occultation missions

Dear Mr Zhuang,

I wish to inform you that the World Meteorological Organization's (WMO) position on the future space-based observing system is defined in the WMO Integrated Global Observing System (WIGOS) Vision 2040. A key element of the Vision 2040 are radio-occultation observations provided by various satellite agencies. The importance of these observations as one of the most important measurements was recently reconfirmed at the 7th WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction (NWP).

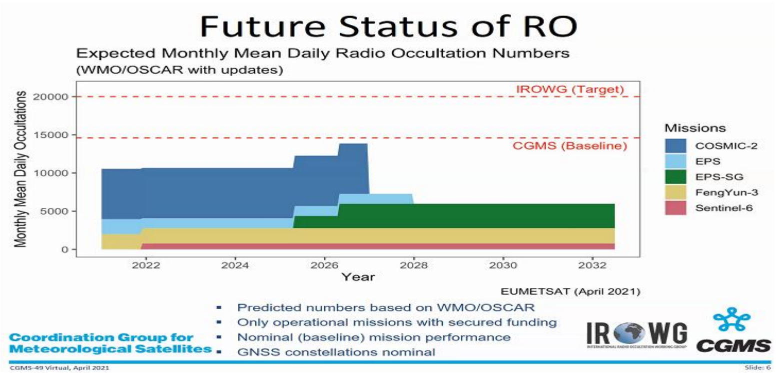
Following the guidance of WMO technical regulations, NSMC/CMA distributes the FY-3 radio occultation data via the WMO Global Telecommunication System since 2017. Several global NWP centres such as the European Centre for Medium-range Weather Forecasts, the UK Met Office, the German Weather Service (DWD, Deutsche Wetterdienst), the Japan Meteorological Agency, the Korea Meteorological Administration, have accessed, evaluated and some also assimilated operationally FY-3 GNOS data. It is important also to note that the Coordination Group for Meteorological Satellites (CGMS) has included the provision of radio-occultation data in its baseline which represents the CGMS contribution towards the WIGOS Vision 2040. At the recent CGMS-49 meeting in May 2021, the decline in available radio-occultation data in the coming years was noted with concern, jeopardizing the CGMS agencies ability to meet CGMS baseline. The importance and value of FY-3 GNOS data is therefore emphasized and particularly important when the number of other agency provided radio occultation observations is declining.

On this occasion, I would like to express my sincere appreciation for the contribution by CMA/NSMC of FY-3 radio occultation data to the WMO community. I look forward to increased data sharing of FY-3 GNOS data for the benefit of global NWP and other related communities.

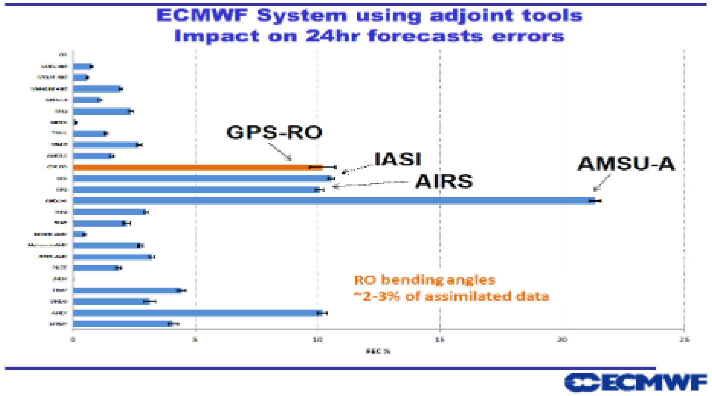
Yours sincerely,

Dr Wenjian Zhang
for the Secretary-General

cc: Dr Jinsong Wang, Director-General, National Satellite Meteorological Center




**RO data from FY3/FY5 would be increasing and plays more important role in NWP**



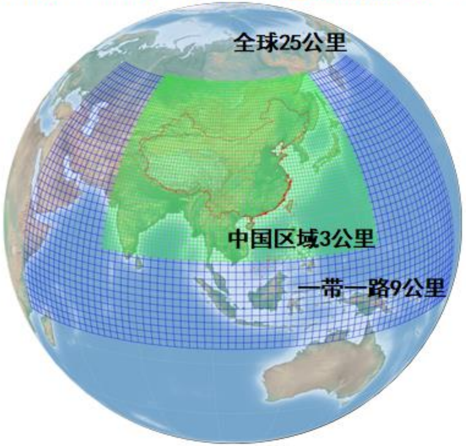

GPS RO ranks No.4

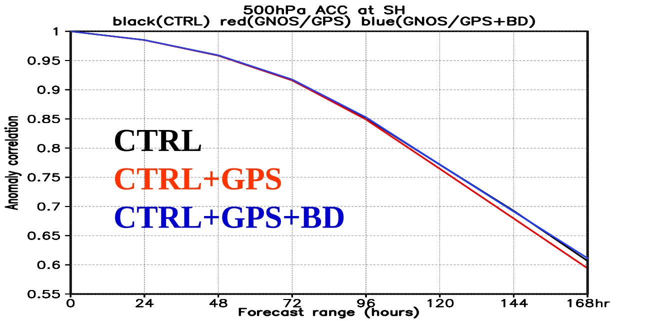
# CMA Results – Preliminary Forecast Impact Experiment



## Impact on GRAPES Forecast Accuracy

GRAPES 数值模式系统
(Global/Regional Assimilation PrEdiction System)




ACC scores (the higher the better) for forecast days.

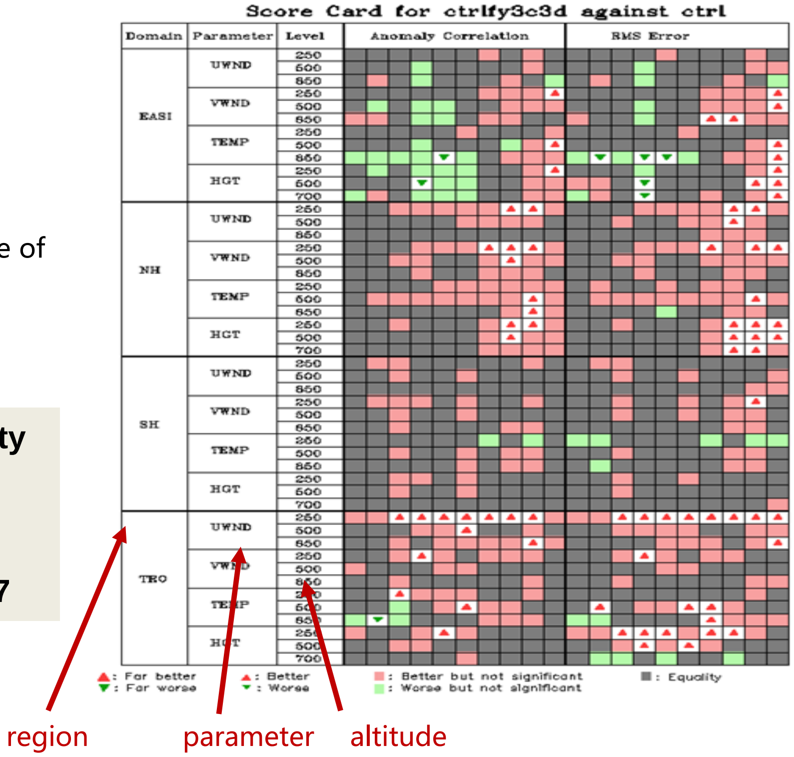
red: positive

gray: neutral

green: negative

triangle: magnitude of impact for p/n

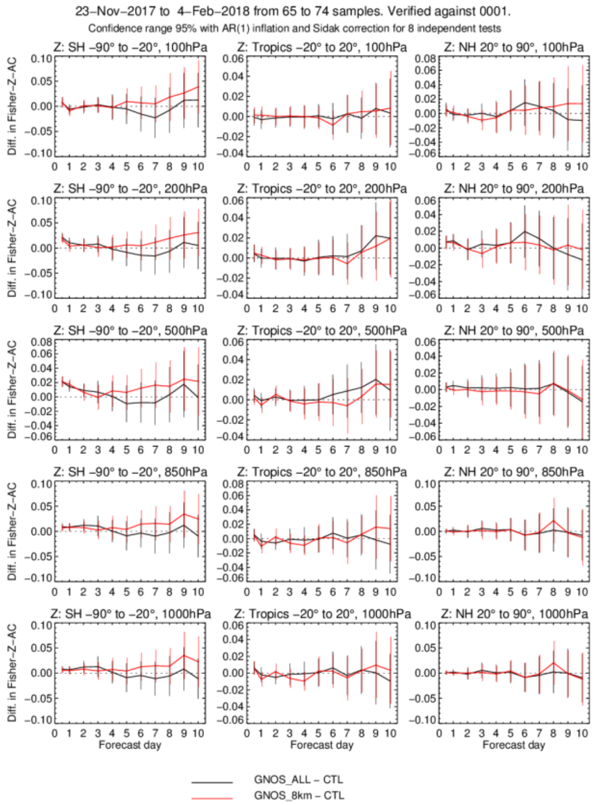
**GNOS Refractivity profiles are assimilated into GRAPES started from June 1,2017**




**GNOS data has a neutral and positive impact on GRAPES analysis and forecast skill.**

# ECMWF results

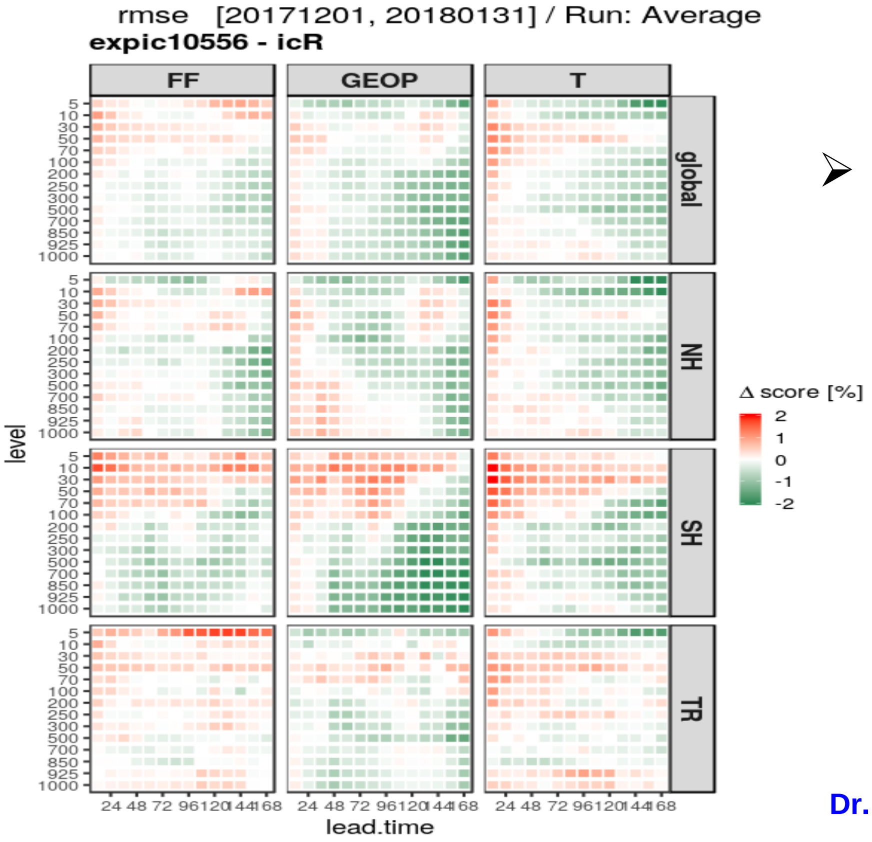
- Assimilated into ECMWF NWP systems since March 6,2018;




The geopotential height scores **show a small positive impact** in the southern hemisphere at day-1, but more generally the results are **broadly neutral** when compared with a no GNOS control experiment.

**Dr. Sean Healy from ECMWF provided the results**

# DWD results




- Assimilated into DWD NWP systems since April 25,2018;

**Green is better**, and green dominates!

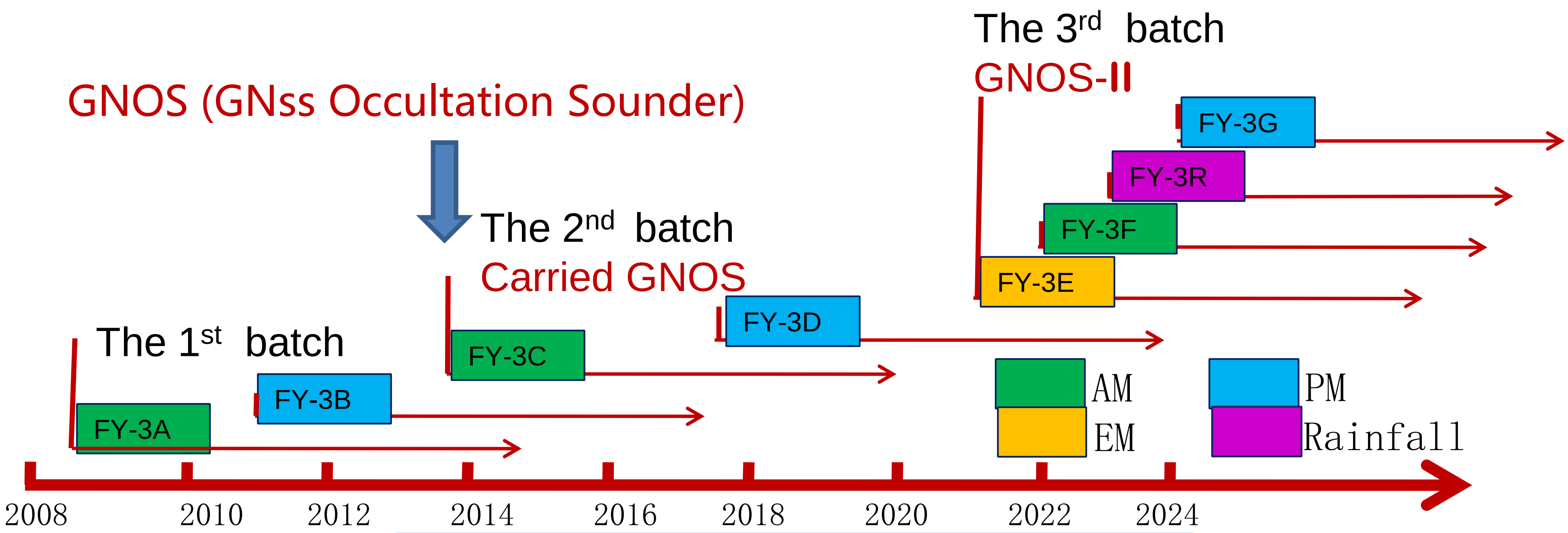
**Dr. Harald Anlauf from DWD provided the results**

06

# Future Perspective

# 06 Future Perspective

## Payloads Configuration for FY-3E/F/G and Rainfall Mission




Operational and future missions of FY-3 series satellites

# Payloads Configuration for FY-3E/F/G and Rainfall Mission

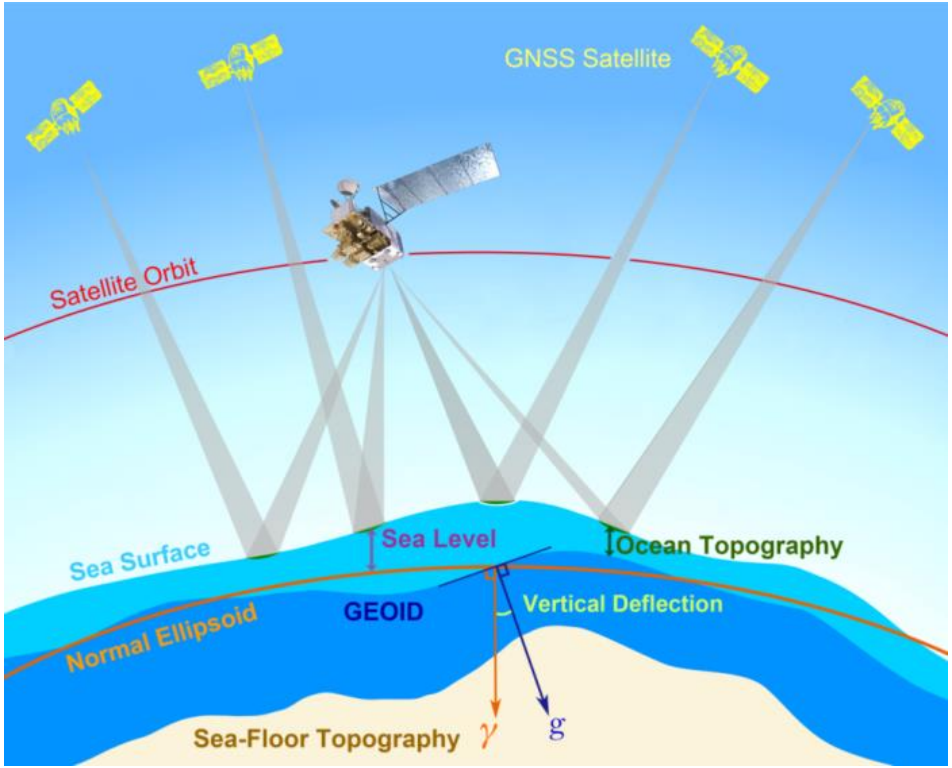
| **N0.** | **Sensor Siute** | **Satellite / Sensor** | **FY-3E （05） EM Satellite** | **FY-3F（06 ） AM Satellite** | **FY-3G（07） PM Satellite** | **FY-3R（08） Rainfall Satellite** |
|---|---|---|---|---|---|---|
| | | Scheduled Launch Date | 2018 | 2019 | 2021 | 2020 |
| 1 | Optical Imagers | MERSI | √（III-Low Light） | √（III） | √（III） | √（III-Simplified） |
| 2 | Passive Microwave Sensors | MWTS | √ | √ | √ | √ |
| | | MWHS | √ | √ | √ | √ |
| | | MWRI | | √ | √ | √ |
| **3** | **Occultation Sounder** | **GNOS-II** | **√** | **√** | **√** | **√** |
| 4 | Active Microwave Sensors | WindRAD | √ | √ | | |
| | | Rainfall RAD | | | | √ |
| 5 | Hyperspectral Sounding Sensors | HIRAS | √ | √ | √ | |
| | | GAS (Greenhouse Gases Absorption Spectrometer) | | | √ | |
| | | OMS (Ozone Mapping Spectrometer) | | √ | | |
| 6 | Radiance Observation Sensor Suite | ERM | | √ | | |
| | | SIM | √ | √ | | |
| | | SSIM (Solar Spectral Irradiation Monitor) | √ | | | |
| 7 | Space Weather Sensor Suite | SEM | | √ | √ | |
| | | Wide Angle Aurora Imager | | √ | √ | |
| | | Ionosphere photometer | √(Multi-angle) | √ | √ | |
| | | Solar X-EUV Imager | √ | | | |

# GNSS-Reflectometry (GNSS-II): Use the reflection of GNSS signals for Earth remote sensing

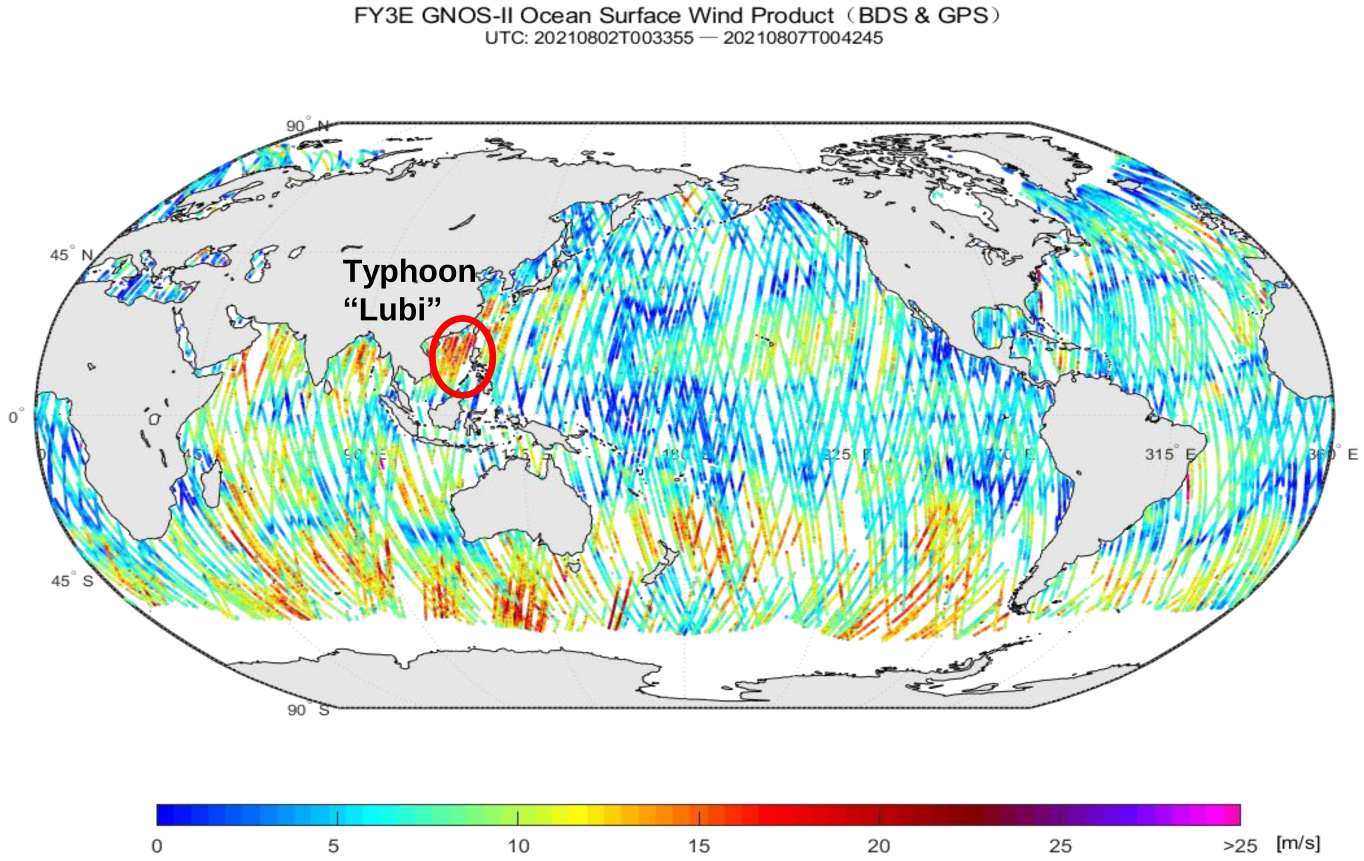
FY-3E GNOS-II implemented the reflectometry

Integrate one antenna for reflective signals on GNOS-II

- Share power, positioning antenna and data down link with RO
- ~13dBi
- Only for monitoring sea surface wind
- For experiments, not operation



# GNOS-II Ocean Surface Wind Product



# Conclusion

- RO sounding has been implemented by FY-3C **since 2013**. In the follow-up, continuous observation will be carried out to support operational use.
- The reflectometry is added **on FY-3E**, which expands the observation ability of ocean surface wind and soil moisture, making GNOS-II a multi-functional sensor.
- GNOS BDS/GPS RO has **equivalent quality** to other missions. The number of BDS RO would be tripled starting from FY-3E.
- Since 2018, GNOS GPS RO data has been assimilated by a few of NWP centers including CMA, ECMWF, Met office, DWD and etc. Positive or neutral impact is proved.
- CMA would continue to promote the data sharing and application of RO measurements to the international communities

# Thank you

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