The FengYun-3 radio occultation sounder GNOS: a review of the missions and results

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Overview of the FY-3 series Satellites

Operational and future missions of FY-3 series satellites

GNOS (GNss Occultation Sounder)

The 1st batch
FY-3A, FY-3B, FY-3C

The 2nd batch
Carried GNOS
FY-3C, FY-3D

The 3rd batch
Will carry GNOS II
FY-3E, FY-3F, FY-3G

FY-3D

AM
PM
EM
Rainfall

Overview of the GNOS instruments

FY-3C GNOS has been launched on Sep. 23rd, 2013, which can receive both GPS and BDS signals.

FY-3D GNOS has been launched on Nov. 11th, 2017, it is testing in-orbit.

The following FY-3 satellites will carry GNOS II as a key payload…

FY-3E GNOS II plan to be launched in 2020, and its will integrate the GNSS RO and GNSS R techniques in one payload.
Overview of the GNOS instruments

**FY-3C GNOS parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument mass</td>
<td>7.5kg</td>
</tr>
<tr>
<td>Constellation</td>
<td>GPS L1、L2 Beidou B1、B2</td>
</tr>
<tr>
<td>Channel number</td>
<td>Positioning: 8 Occultation: GPS 6 Beidou 4</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>Positioning &amp; Ionosphere occultation: 1Hz</td>
</tr>
<tr>
<td></td>
<td>Atmosphere occultation: CL 50Hz OL 100Hz</td>
</tr>
<tr>
<td>Clock stability</td>
<td>1×10^{-12} (1secAllan)</td>
</tr>
<tr>
<td>Antenna specification</td>
<td>Atmosphere occultation antenna: Gain: &gt;10dB</td>
</tr>
<tr>
<td></td>
<td>Antenna field of view: El ±7.5° Az ±35°</td>
</tr>
<tr>
<td></td>
<td>Positioning &amp; Ionosphere occultation antenna:Gain: -1dB</td>
</tr>
<tr>
<td></td>
<td>Antenna field of view: ±60°</td>
</tr>
<tr>
<td>Pseudorange precision</td>
<td>≤30cm</td>
</tr>
<tr>
<td>Carrier phase precision</td>
<td>≤2mm</td>
</tr>
</tbody>
</table>

**Improvements of FY-3D GNOS**

<table>
<thead>
<tr>
<th>Main parameters</th>
<th>FY-3C GNOS</th>
<th>FY-3D GNOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of occultation channels</td>
<td>GPS: 6 BDS: 4</td>
<td>GPS: 8 BDS: 6</td>
</tr>
<tr>
<td>Occultation antenna beamwidth (BW)</td>
<td>±35°</td>
<td>±40°</td>
</tr>
</tbody>
</table>

GPS/GNOS RO:
~ 500 events/day/LEO (blue)
BDS/GNOS RO:
~ 200 events/day/LEO (red)
FY-3C/-3D GNOS mission

Product validation (Precise Orbit Determination)

Signal from the up-looking antenna are used for POD of the FY-3C satellite.

Table 1: POD Precision Statistics of Position

<table>
<thead>
<tr>
<th></th>
<th>Radial RMS (cm)</th>
<th>Along RMS (cm)</th>
<th>Cross RMS (cm)</th>
<th>3D RMS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>0.919</td>
<td>1.460</td>
<td>2.232</td>
<td>2.868</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>0.925</td>
<td>1.460</td>
<td>2.330</td>
<td>2.911</td>
</tr>
</tbody>
</table>

Table 2: POD Precision Statistics of Velocity

<table>
<thead>
<tr>
<th></th>
<th>Radial RMS (mm/s)</th>
<th>Along RMS (mm/s)</th>
<th>Cross RMS (mm/s)</th>
<th>3D RMS (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN</td>
<td>0.018</td>
<td>0.014</td>
<td>0.009</td>
<td>0.025</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>0.018</td>
<td>0.014</td>
<td>0.009</td>
<td>0.024</td>
</tr>
</tbody>
</table>

GPS POD:
3D RMS position error is 2.868 cm
3D RMS velocity error is 0.025 mm/s

BDS POD:
3D RMS position error is 30 cm
Error Sources:
Regional coverage, BDS channel number, POD algorithm...

POD error using BDS (5 days)
Product validation (Atmospheric products)

<table>
<thead>
<tr>
<th>5-25km</th>
<th>Ref (%)</th>
<th>Bias</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNOS-GPS vs ECMWF</td>
<td>-0.09</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>GNOS-BDS vs ECMWF</td>
<td>-0.04</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>COSMIC vs ECMWF</td>
<td>-0.12</td>
<td>0.71</td>
<td></td>
</tr>
</tbody>
</table>

within 200km, ±1 h(time)


Mi Lao (CMA), a detailed talk will be on Tuesday from Mi Lao

FY3D preliminary results of in-orbit testing are consistent with those of FY3C
Product Application (Atmosphere NWP)

- From June 2017, NSMC has published the products of GNOS via GTS.
- On March 6th 2018, ECMWF started to use GNOS GPS bending angle data in assimilation processing.

EUMESAT real-time quality monitoring of FY-3C GNOS product

ECMWF real-time quality monitoring of FY-3C GNOS product

GNOS/F-3C data has a neutral and positive impacts on GRAPES and ECMWF forecast skill.

Courtesy: EUMESAT, ECWMF and ROM-SAF

Yan Liu (CMA), a talk about NWP is on Tuesday
Product Application (Atmosphere Climate)

- Red dot for Global Climate Observing System Reference Upper-Air Network (GRUAN) station (2014.1~2017.12)
- Blue dot for IGRA station (2016.1~2017.12)

Product Application  (Atmosphere Climate)

Tropopause Para.

- Red dot for Global Climate Observing System Reference Upper-Air Network (GRUAN) station (2014.1~2017.12)
- Blue dot for IGRA station (2016.1~2017.12)

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Collocate pairs</th>
<th>TPH Bias</th>
<th>TPT Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAR</td>
<td>71.4N, 155.6W</td>
<td>36</td>
<td>0.27 km</td>
<td>–1.43 K</td>
</tr>
<tr>
<td>GRA</td>
<td>39.0N, 27.4W</td>
<td>15</td>
<td>0.05 km</td>
<td>–0.22 K</td>
</tr>
<tr>
<td>LIN</td>
<td>52.2N, 15.2E</td>
<td>151</td>
<td>0.07 km</td>
<td>–0.32 K</td>
</tr>
<tr>
<td>NYA</td>
<td>78.9N, 13.8E</td>
<td>84</td>
<td>0.21 km</td>
<td>–0.85 K</td>
</tr>
<tr>
<td>SGP</td>
<td>36.4N, 96.2W</td>
<td>48</td>
<td>0.40 km</td>
<td>–1.70 K</td>
</tr>
<tr>
<td>SOD</td>
<td>67.2N, 26.7E</td>
<td>49</td>
<td>0.20 km</td>
<td>–0.20 K</td>
</tr>
<tr>
<td>USM</td>
<td>37.9N, 75.5W</td>
<td>46</td>
<td>0.15 km</td>
<td>0.08 K</td>
</tr>
<tr>
<td>FMM</td>
<td>9.5N, 138.1E</td>
<td>27</td>
<td>0.05 km</td>
<td>–0.13 K</td>
</tr>
<tr>
<td>RMM</td>
<td>7.1N, 171.4E</td>
<td>18</td>
<td>0.02 km</td>
<td>0.25 K</td>
</tr>
</tbody>
</table>

Product Application (Atmosphere Climate)

Tropopause Para.

- Annual cycle TPH and TPT for different latitude bands derived from collocated 2014-2017 FY3C and COSMIC data.
- Collocated criteria: <3 h and <300 km.
- Results from two RO missions show consistency. The TPH difference is concentrated at Antarctica during Jul to Nov, where FY3C show positive bias compared with COSMIC. This bias may be because the TPH over Antarctica raises during summer and autumn.

For the TPT, the major bias occurs over tropics and 30S-60S during Jan. to Apr.

In spring (MAM), the global tropopause parameters presented a good symmetry between Southern and Northern hemispheres.
The tropical tropopause widened toward the north pole and the southern boundary of tropical tropopause narrowed. In South Asia, the extremely high tropopause caused by deep convective activity was found, also leads to the considerable variability. The phenomena confirm with Rieckh, T. et. al. 2014 and Li W. et al. 2017.
Product Application (Atmosphere Climate)

Tropopause Para.

Sept.~Nov.

During summer and autumn (SON), **TPH** above Antarctica rises obviously, about 2 km higher than it in spring, while **TPH** above the Arctic increased less than 1 km, agrees with Tomikawa et al 2009.

**TPT** above Antarctica reached its minima in the annual cycle while **TPT** above the Arctic reached its maxima, which was caused by the differences in dynamical heating of the stratosphere [Zängl, et. al. 2001].

Liu Z.Y. Bai W.H. et al. 2019,
In winter (DJF), strong zonal asymmetry can be seen in the Northern hemisphere. TPH above the tropics increased to its maxima, and the corresponding TPT decreased to around 196 K. Two regions with extremely low TPH occurred at Eastern Canada and Eastern Russia, which are similar with Rieckh, T. et al. 2014 and Li, W. et al. 2017.

Liu, Z.Y. Bai, W.H. et al. 2019
**Product validation (Ionosphere products)**

<table>
<thead>
<tr>
<th>Elec. Density peak</th>
<th>Bias</th>
<th>Std</th>
<th>correlation</th>
<th>Sample No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NmF2(GPS)</td>
<td>6.62%</td>
<td>18.39%</td>
<td>0.96</td>
<td>548</td>
</tr>
<tr>
<td>NmF2(BDS)</td>
<td>8.31%</td>
<td>17.24%</td>
<td>0.96</td>
<td>354</td>
</tr>
</tbody>
</table>

Product validation (Ionosphere)

Validation of S4max in F2 layer derived from FY-3C GNOS.

Matching principles:
- Occultation data quality control (eliminate incomplete and negative EDPs)
- Temporal matching principle (observed within ±1 hour in time)
- Spatial matching principle (observed within ±2° in space)
- Direction consistency (azimuth angle difference less than 15°)

Selection conditions enable S4max data observed by FY3C/GNOS and COSMIC to match into data pairs and comparable.

Bai Weihua, et al. Validation results of maximum S4 index in F layer derived from GNOS on FY3C satellite[J]. GPS SOLUTION,2019,23(1):UNSP 19
Validation Results

The differences of the F2 layer max. S4 pairs of FY3C and COSMIC (all day)

Numerical differences of S4max data pairs in whole day from January 10, 2014 to January 9, 2015

Statistical errors distribution of numerical differences of S4max data pairs in whole day from January 10, 2014 to January 9, 2015

<table>
<thead>
<tr>
<th></th>
<th>Bias</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole day</td>
<td>0.004</td>
<td>0.063</td>
</tr>
<tr>
<td>nighttime</td>
<td>0.007</td>
<td>0.080</td>
</tr>
<tr>
<td>daytime</td>
<td>0.001</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Bai Weihua, et al. Validation results of maximum S4 index in F layer derived from GNOS on FY3C satellite[J]. GPS SOLUTION, 2019, 23(1): UNSP 19

FY-3C/-3D GNOS mission

Product validation (Ionosphere)

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Courtesy: CDAAC, COSMIC
FY-3C/-3D GNOS mission

Product Application (Space Weather)
Magnetic Storm Event study

Mar. 2015 Mag. index (data from ISGI)
Magnetic Storm Event study

NmF2 from Level 2 electron density profile

Magnetic Storm Event study

GNOS can obtain about 220 events in nighttime.

- The number distribution of GNOS S4 profiles v.s. LT during 12-23 March.
- 75% of S4 profiles locate in the morning and in the evening.

FY-3C/-3D GNOS mission

Product Application (Space Weather)

Magnetic Storm Event study

Distribution of max S4 in F layer in night

S4max mainly locate between -25° and 25° Dip Latitude.

Scintillation enhancement in India and around 160 E sectors during MP, decrease at all longitudes during initial recovery phase of storm.


**Magnetic Storm Event study**

**Distribution of maxS4 (>0.3) in night**

- **S4max** mainly locate between -25° and 25° Dip Latitude.
- Scintillation enhancement in India and around 160 E sectors during MP, decrease at all longitudes during initial recovery phase of storm.

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S4max mainly locate between -25° and 25° Dip Latitude.

Scintillation enhancement in India and around 160 E sectors during MP, decrease at all longitudes during initial recovery phase of storm.
FY-3C/-3D GNOS mission

Product Application (Climate Monitoring)

Level 3 Product and Climate Monitoring

Three-dimensional slice of electron density data (FY3C GNOS 2014.12.01-12.31)

Three-dimensional distribution of electron density data (FY3C GNOS 2014.12.01-12.31)

FY3D GNOS 2018年10月 电离层电子密度数据切片（白天）

FY3D GNOS 2018年10月 电离层电子密度数据切片（夜晚）
In ME-month, FY3C/GNOS and COSMIC both show Equatorial Ionospheric Anomaly (EIA) (Berkner et al., 1936) and peak longitude structures (Potula et al., 2011), and the peak structures of COSMIC NmF2 are more noticeable than that of FY3C/GNOS.

The discrepancies increase at nighttime, NmF2 of FY3C/GNOS are higher than those of COSMIC in mid-high latitudes but lower in low latitudes.

Bai W.H., Tan G.Y., Sun Y.Q., et al., Comparison and validation of the ionospheric climatological morphology of FY3C/GNOS with COSMIC. Remote Sensing, 2019(under review)
**Product Application (Ionospheric Climatology)**

**NmF2**

**JS-month**

(±45 days to June solstice)

Daytime NmF2 measured by FY3C/GNOS and COSMIC in winter are higher than those in summer, this behavior of the ionosphere is the winter anomaly (Duncan 1969).

The NmF2 nighttime enhancement can be seen in mid-latitude (around 60° dip) longitude section in northern summer ionosphere, where the magnetic equator shifts farthest toward the geographic pole, this is the general WSA (Weddell Sea Anomaly), which is consistent with work of Lin et al (2009).

Bai W.H., Tan G.Y., Sun Y.Q., et al., Comparison and validation of the ionospheric climatological morphology of FY3C/GNOS with COSMIC. Remote Sensing, 2019 (under review)
**Product Application (Ionospheric Climatology)**

**NmF2**

**SE-month**

(±45 days to Sept. equinox)

The season pattern of NmF2 in SE-month are largely close to ME-month, but in lower magnitude.

At daytime, NmF2 observed by FY3C/GNOS and COSMIC during ME-month have a more continuous EIA than that in SE-month, at nighttime, NmF2 during ME-month have more evident peak structures, the stronger NmF2 in ME-month than in SE-month is known as equinoctial asymmetry (Balan et al., 2000).

Bai W.H., Tan G.Y., Sun Y.Q., et al., Comparison and validation of the ionospheric climatological morphology of FY3C/GNOS with COSMIC. Remote Sensing, 2019 (under review)
**Product Application (Ionospheric Climatology)**

**NmF2**

**DS-month**
(±45 days to Dec. solstice)

In DS-month, winter anomaly is also presented, which means that the daytime NmF2 measured by FY3C/GNOS and COSMIC in winter (north hemisphere) are higher than those in summer (south hemisphere).

FY3C/GNOS and COSMIC both show general WSA (NmF2 nighttime enhancement in about -60° dip) and special WSA (NmF2 nighttime enhancement in Weddell sea area) (Penndorf, 1965), Horvath (2003, 2006) also observed the TEC enhancement in southeast Pacific Ocean during 22LT to 24 LT.

Bai W.H., Tan G.Y., Sun Y.Q., et al., Comparison and validation of the ionospheric climatological morphology of FY3C/GNOS with COSMIC. Remote Sensing, 2019 (under review)
FY-3C/-3D GNOS mission

Product Application (Ionospheric Climatology)

- Equatorial ionosphere Anomaly (EIA)
- Semiannual anomaly
- Winter anomaly
- Weddell Sea anomaly (WSA)
- Equinoctial asymmetry

Climatology Consistency
GNOS II is the upgraded version of FY3 C satellite and D satellite’s GNOS I, and possesses both GNSS occultation and reflection functions, and can be used to monitor the ionosphere, atmosphere and Earth surface. It will be firstly launched into space by FY3 E satellite in 2020 as scheduled. After FY3 E satellite, FY3 F/G/R satellite will carry GNOS II into space as scheduled.

Primary GNSS-R product:
Ocean surface wind speed.

Main characters:
✓ Provide both BDS-R and GPS-R products
✓ Cooperate with a microwave scatterometer fitted on the same satellite.

Orbit:
✓ Altitude: 833km
✓ Inclination: 98.8°

Reflection antenna (Off-pointing to the back: 20°)
### Payload introduction

GNOS II is the **upgraded version** of FY-3C/-3D GNOS, and Possesses both GNSS occultation and reflection remote sensing functions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>The length of sampling time</td>
<td>10 s (could be reset)</td>
</tr>
<tr>
<td>Operation limit</td>
<td>&lt;50 km 12 hot points (could be reset)</td>
</tr>
</tbody>
</table>

**Block Diagram of GNOS-II for FY-3E**

- POD antenna A
- POD antenna B
- RF
- Signal Processing Unit
- GNSS-R Antenna
- Reflectometry of GNOS-II:
  - On-board DDM
  - Raw sampling data

**GNOS II’s Non-uniform DDM Model**

- Raw sampling Model
GNOS II and following missions

Data processing system

Ground Data Processing Systems for GNOS II

TDS-1 data testing
Wind speed: ~ 2m/s
**Airborne testing experiment**

**Time:** 18-25 October, 2018  
**Place:** Bohai Sea, China  
**Flight altitude:** 3000 m  
**Flight times:** 4

<table>
<thead>
<tr>
<th>Flight Number</th>
<th>Time</th>
<th>Sea surface wind speed ranges (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Am, 18, Oct, 2018</td>
<td>5.6 ~ 9.3</td>
</tr>
<tr>
<td>2</td>
<td>Am, 18, Oct, 2018</td>
<td>1.9 ~ 5.8</td>
</tr>
<tr>
<td>3</td>
<td>Am, 25, Oct, 2018</td>
<td>6.4 ~ 9.9</td>
</tr>
<tr>
<td>4</td>
<td>Pm, 25, Oct, 2018</td>
<td>7.1 ~ 9.8</td>
</tr>
</tbody>
</table>

Compared with ship-borne meteorological station, Wind speeds’ RMS is 0.6 m/s (2m/s ~ 10m/s)
FY-3C GNOS products have been using in weather, climate and space weather fields successfully.

FY-3D GNOS is at the end of in-orbit testing. The validation results are as well as FY-3C.

FY-3E with GNOS II is planned to launch in 2020.

Following FY-3 satellites will carry GNOS II as a key payload...

Look forwards your cooperation...
THANKS ALL

Email: bjbwh@163.com
Product Application (Ionospheric Climatology)

The global ionospheric climatological characteristics of NmF2 predicted by IRI-2016 are highly consistent with that of NmF2 probed by FY3C&COSMIC like:

- EIA
- Annual anomaly
- Semiannual anomaly
- WSA

Though exceptions do exist in IRI-2016 like:

- Absence of the equinoctial asymmetry and the longitude structures of NmF2 in nighttime sector of ME-month.
- Large overestimation of NmF2 in SE-month and DS-month.
- Wider and larger WSA in southern summer ionosphere.
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