Orbit Determination Practice Based on GNSS Weak Signals and Analysis of Cislunar Space Applications

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1. Features and On-Orbit Applications of HEO Spaceborne GNSS

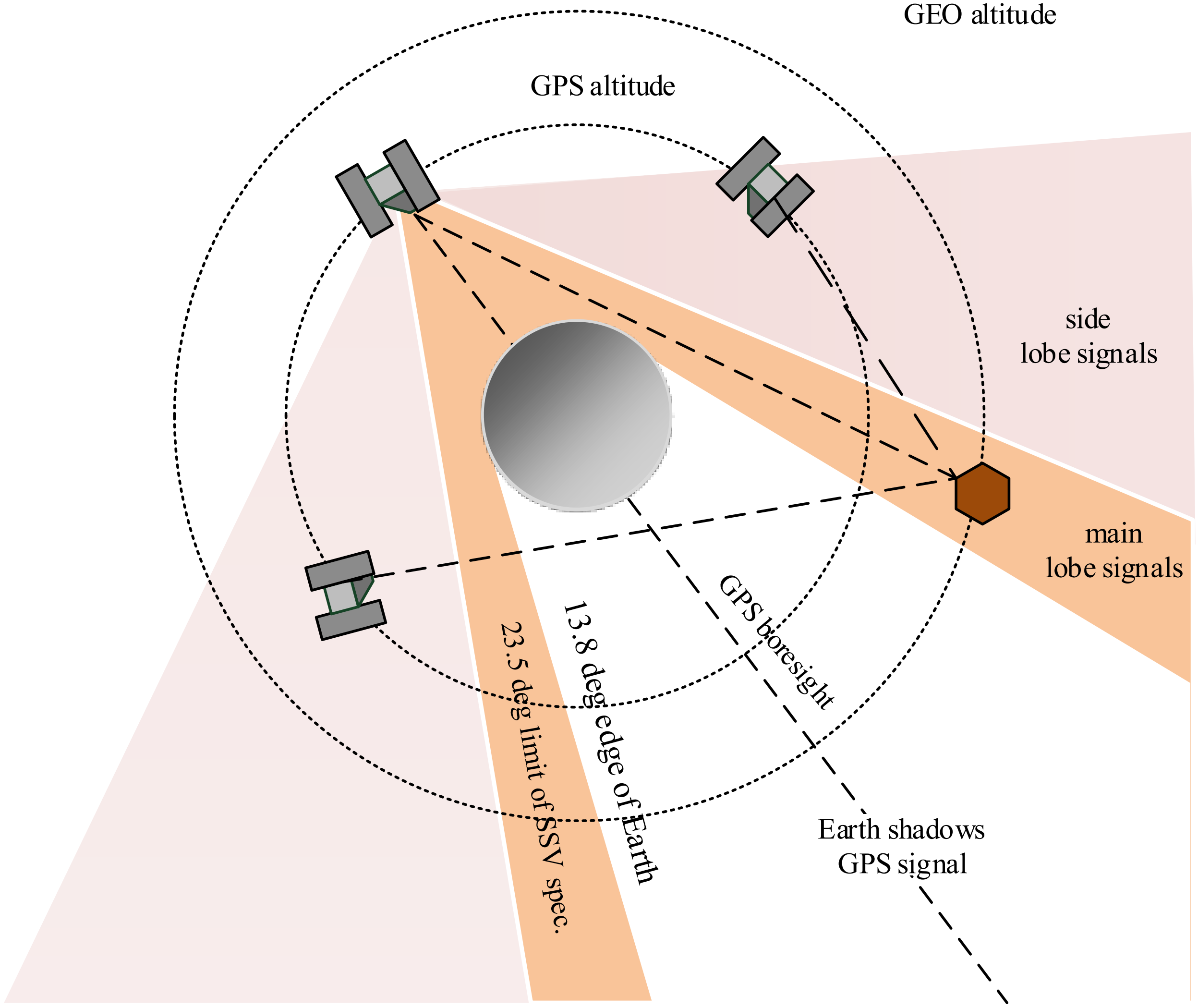
☐ Features of HEO Spaceborne GNSS

- **weak signal :** path loss (~10dB) + side lobe leads to weak signal, and highly sensitive signal processing will amplify noise

- **poor geometric distribution:** main lobe of GNSS antenna is ~23.5°, most obscured by the earth. HEO needs to receive side lobe signal, ~15dB lower than the main lobe, resulting in fewer satellites

- **large ranging error:** GNSS signals pass the ionosphere and troposphere, resulting a significant impact

- **strong ground interference:** HEO antenna points to the earth with high gain, ground interference signal being received together



1. Features and On-Orbit Applications of HEO Spaceborne GNSS

☐ HEO GNSS Code/Carrier Noise

Received Signal Power

$$P_{rx,k}^{i} = EIRP^{i}(\beta_k^i) - 20\log_{10}\left(\frac{4\pi f\left|r_k^i - r_k\right|}{c}\right)$$

Carrier to Noise Ratio

$$(C_{N0})_k^i = P_{rx,k}^i + G_{rx}(\theta_k^i) - 10\log_{10}(\Gamma_{sys}) - L_{sys} - k_{dB}$$

Code Noise

$$(\sigma_{\rho,k}^i)^2 = (\sigma_{DLL,k}^i)^2 + \sigma_{GNSS,orb}^2 + \sigma_{GNSS,clk}^2$$

$$(\sigma_{DLL,k}^i)^2 = (cT_c)^2 \frac{B_{n,c}}{2(C_{N0})_k^i} D\left[D(1+\frac{2}{(2-D)T(C_{N0})_k^i})\right]$$

Carrier Noise

$$(\sigma_{\varphi,k}^i)^2 = (\frac{\lambda_L}{2\pi})^2\left[\frac{B_n}{(C_{N0})_k^i}(1+\frac{1}{2T(C_{N0})_k^i})\right] + (cT\sigma_A)^2$$

c	Light speed	299792458m/s
T_c	Code chip width	977.5ns(GPS1.023MHz) 488.8ns(BDS2.046MHz)
$B_{n,c}$	Code loop filter noise bandwidth	**0.5Hz**
B_{front}	Front-end bandwidth	**20.46 MHz**
$\sigma_{GNSS,orb}^2$	GNSS orbit error	0.6m
$\sigma_{GNSS,clk}^2$	GNSS clock error	0.5m
λ_L	Carrier wave length	0.1904m(GPS) 0.1922m(BDS)
B_n	Carrier loop filter noise bandwidth	24Hz
T	Integration time	**0.02s**
σ_A	Allan deviation oscillator phase noise	5.0E-11s/s
$P_{rx,k}^i$	**Received signal power**	**-173.3dBW**
$G_{rx}(\cdot)$	Receiving antenna gain	**8dBi**
β_k^i	Received off-boresight angle	8.7°
Γ_{sys}	System temperature	246K
L_{sys}	Additional system loss	0.5dB
$EIRP^i(\cdot)$	Effective isotropic radiated power	20dBW
θ_k^i	Transmitting off-boresight angle	20°
$\left\|r_k^i - r_k\right\|$	Receiver and GNSS distance	400000000m
f	Carrier frequency	1575.42MHz
$(C_{N0})_k^i$	**Carrier to noise ratio**	**41.8dBHz**
$\sigma_{\rho,k}^i$	**Code noise/m**	**GPS 1.59/ BDS 1.21**
$\sigma_{\varphi,k}^i$	**Carrier noise/mm**	**GPS 1.24/ BDS 1.26**

1. Features and On-Orbit Applications of HEO Spaceborne GNSS

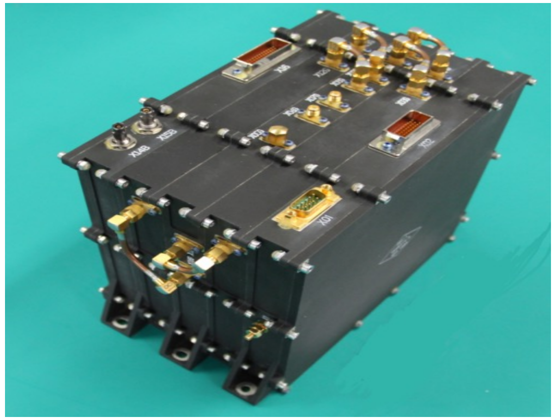
❑ First Gen: -173dBW

- CE-5T1, 2014, first real-time OD of HEO, 200000km GPS signal reception, 5000~50000km OD 30m (3D)
- TJS-2, 2017, has been in orbit for 8 years, code precision 3.5m(STD), carrier 2.6cm(STD)

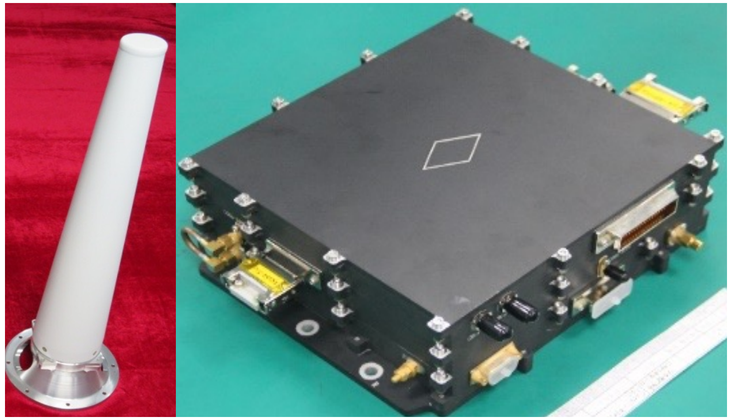
❑ Second Gen: -180dBW, GPS L1+BDS B1I, SoC

- TJS-5, 2020, code precision 2.2m, carrier precision 1.2cm, real-time OD 15.8m, GPS+BDS POD 1.7m(3D)
- LT4A, 2023, IGSO, code 1.5m, carrier 0.3cm, real-time OD 40.0m, GPS+BDS POD 4.2m(3D)

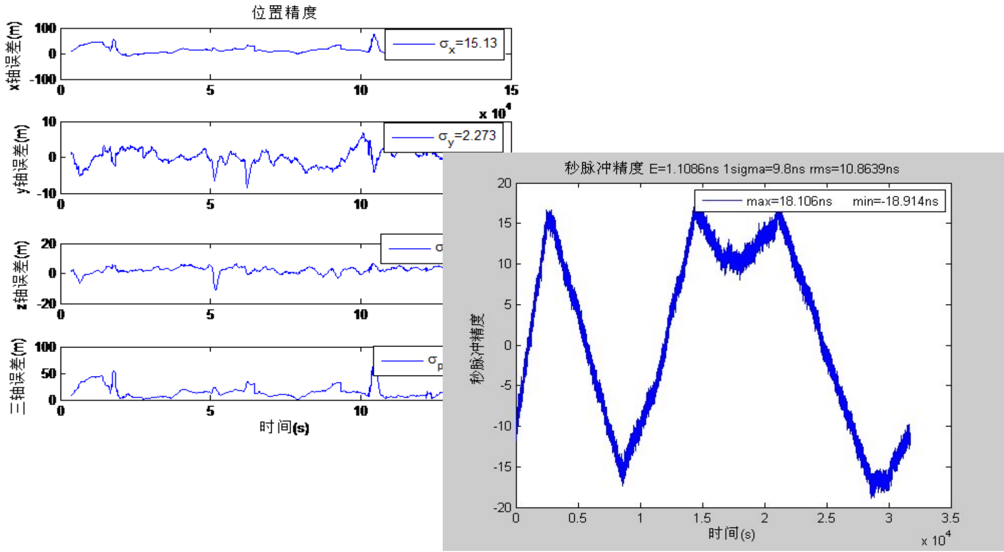
❑ Third Gen: -184dBW, BDS3, SoC, for Cislunar space



First Gen weak signal receiver



Second Gen weak signal receiver



Real time OD and timing of TJS-5 (15m & 20ns)

By 2025.9，35 HEO satellites carried SSTC’s GNSS receiver

1. Features and On-Orbit Applications of HEO Spaceborne GNSS

Task	Country	Time	GNSS receiver	HEO GNSS validation
TEAMSAT/YES	Europe	1997-10	Trimble TANS-II	GTO, GPS signal reception at 26000 km
Falcon Gold	United States	1997-11	NAVSYS TID-GIT	GTO, GPS signal reception at 1500~33000 km
Equator-S	United States	1997-12	Motorola Viceroy	GTO, GPS signals reception at 34 000 km
AO-40	United States	2000-11	Trimble TANS Vectors	HEO, GPS signals reception up to 58 000 km
GIOVE-A	Europe	2005-12	SGR-GEO	MEO, GPS signals reception at 23 000 km
SBIRS GEO 1	United States	2011-03	Dual-band GPS receiver	GEO, real-time OD, use L1/L2 data to analyze ionospheric delay
MMS	United States	2015-03	GSFC Navigator	HEO, GPS signals reception at 180 000 km
CE-5T1	China	2014-10	GNSS compatible machine	Moon-earth transfer orbit, GPS and GLONASS signals reception at 5 000~50 000 km
TJS-2	China	2017-01	GNSS compatible machine	GEO, GPS/GLONASS/BDS signal reception
GOES-R	United States	2016-11	General Dynamics Viceroy-4	GEO, 11 GPS satellites are tracked, DOP is 5~15, position accuracy 30 m
SmallGEO	Europe	2017-01	Astrium Mosaic	GEO, Small GEO platform, GPS signal reception and navigation
TJS-5	China	2020-01	GNSS SoC products	GEO, GPS/BDS-2/BDS-3 signals received simultaneously for the first time, POD 1m
LT4A	China	2023-08	GNSS SoC products	IGSO, equipped with GNSS/Ka/SLR payload, GNSS OD and Ka OD radial consistence 2m
Blue Ghost 1	United States	2025-01	LuGRE	For the first time, GPS and Galileo L1/L5 signals reception at 430 000 km

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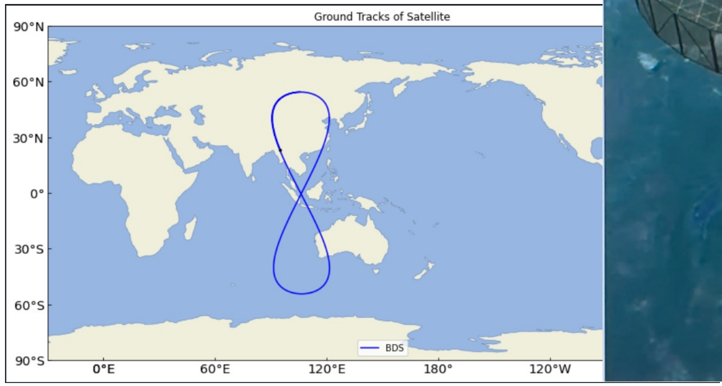
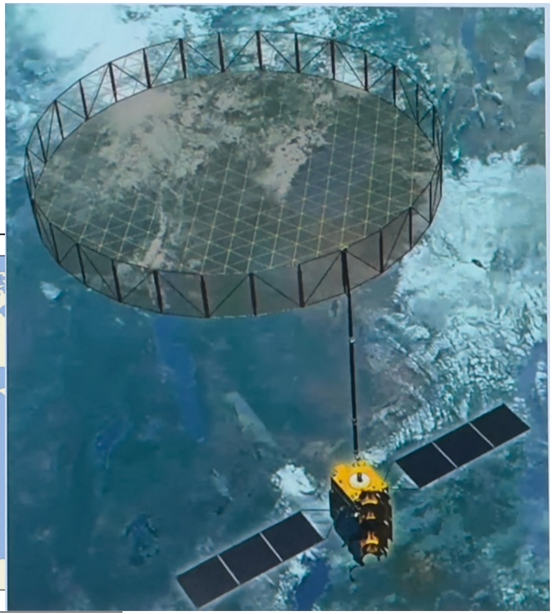
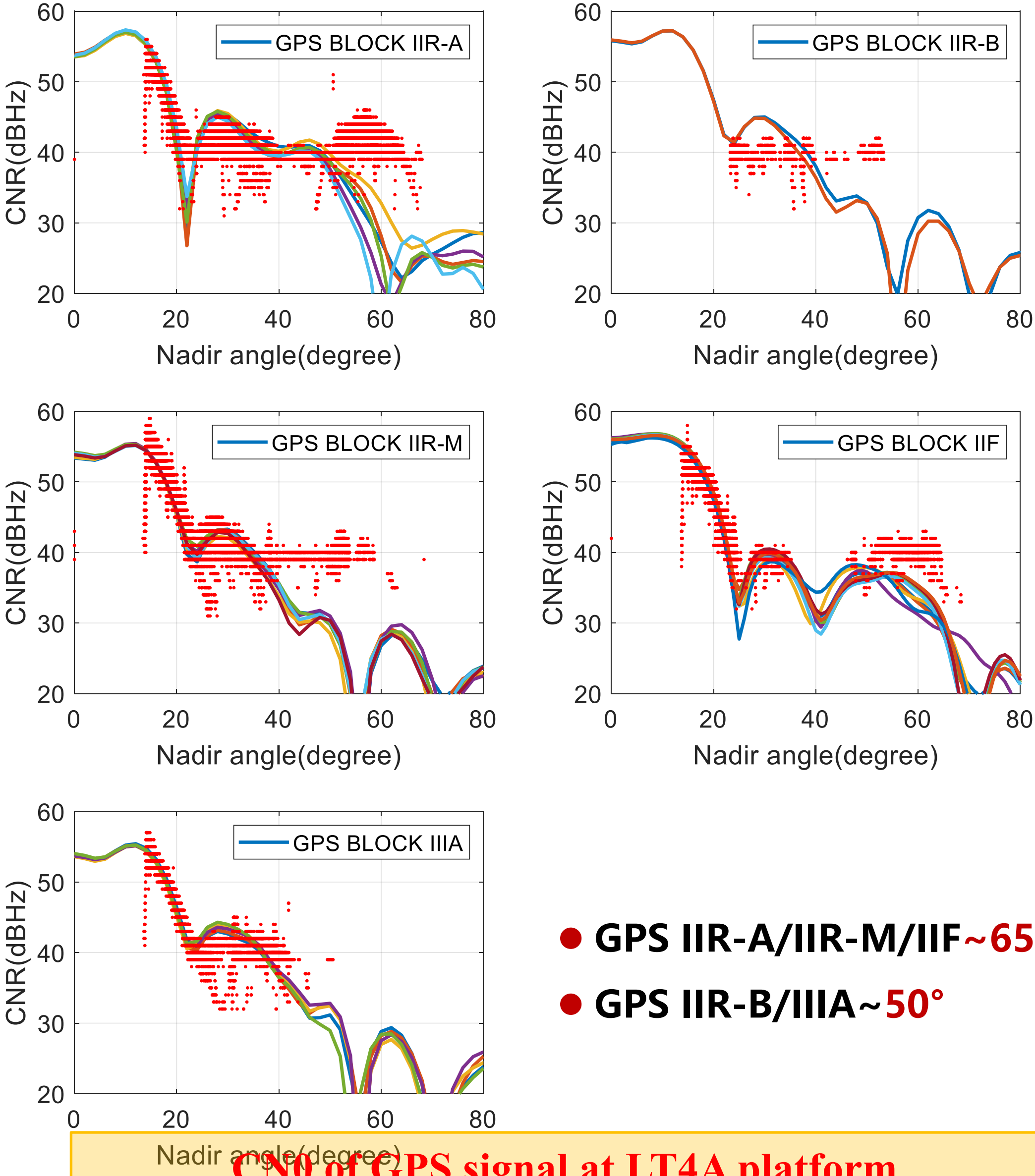
2. Data Quality and Orbit Determination of HEO Spaceborne GNSS

LT4A satellite

- Launch: August 13, 2023
- Orbit: IGSO, inclination of 16°
- POD payload:
  - GNSS receiver (dual SoC, GPS/L1+BDS/B1I)
  - Ground based Ka (4 stations)
  - Accelerometer
  - SLR
- Ground calibration:
  - Surfaces optical properties



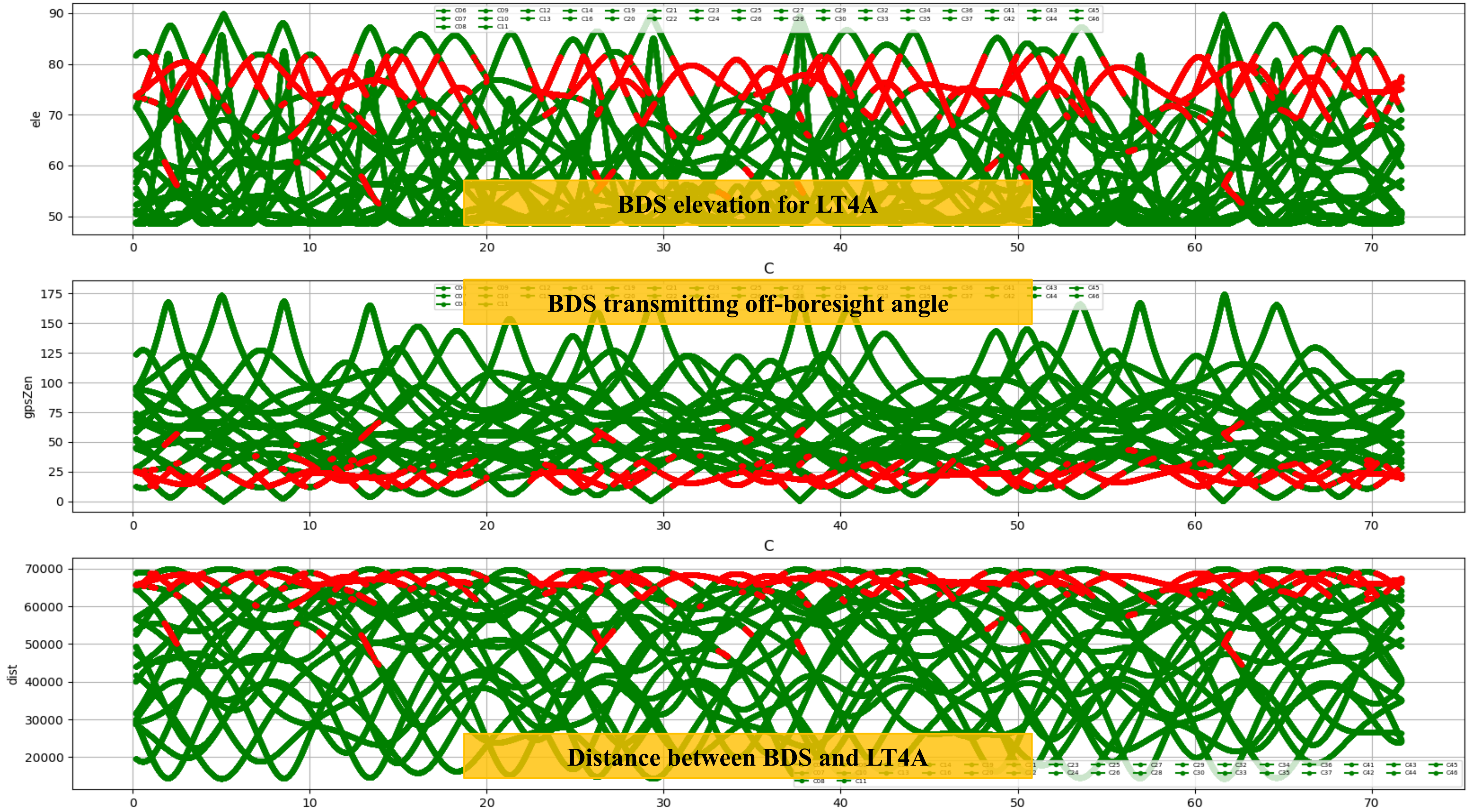




- GPS IIR-A/IIR-M/IIF~65°
- GPS IIR-B/IIIA~50°

CN0 of GPS signal at LT4A platform

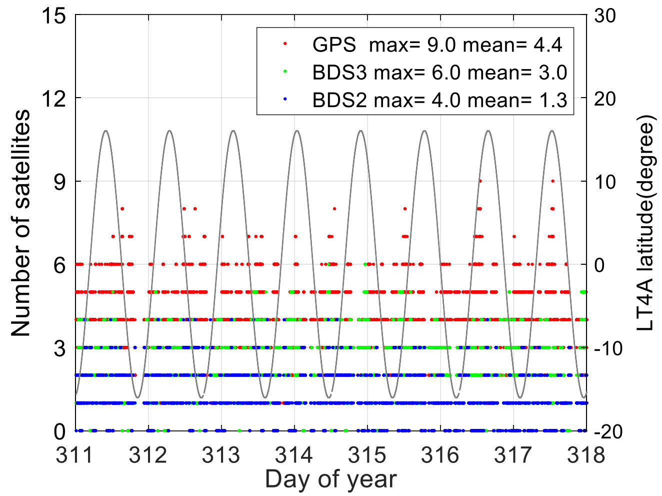
2. Data Quality and Orbit Determination of HEO Spaceborne GNSS - Geometry

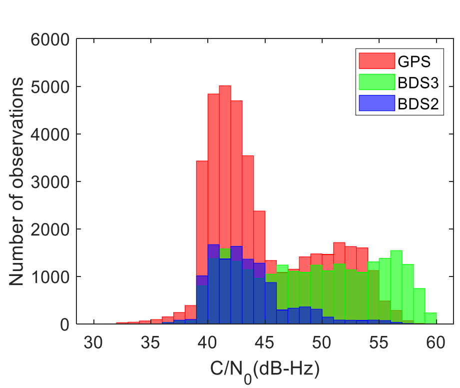


2. Data Quality and Orbit Determination of HEO Spaceborne GNSS – Visible Satellite

□ LT4A tracking satellites

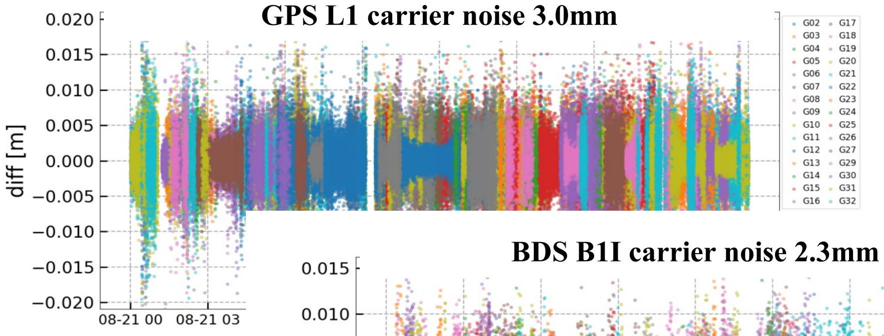
- GPS 4.4，BDS 4.3，G+C PDOP 23.8

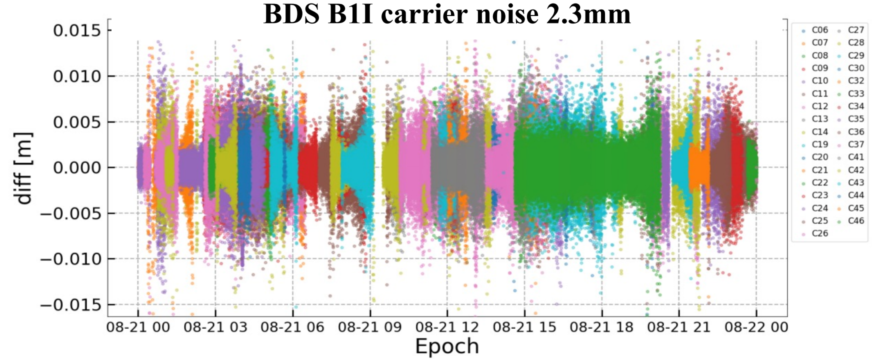




□ LT4A observation noise

- GPS L1 code 1.47m/carrier 3.0mm, BDS B1I 2.51m/2.3mm





□ Epoch difference: eliminate refraction/clock/orbit error, only noise

$$\Delta\varepsilon = [(L_{r,1}^{s,(i)} - L_{r,1}^{s,(i+1)}) - (L_{r,1}^{s,(i+1)} - L_{r,1}^{s,(i+2)})] - [(L_{r,1}^{s,(i+1)} - L_{r,1}^{s,(i+2)}) - (L_{r,1}^{s,(i+2)} - L_{r,1}^{s,(i+3)})] = L_{r,1}^{s,(i)} - 3L_{r,1}^{s,(i+1)} + 3L_{r,1}^{s,(i+2)} - L_{r,1}^{s,(i+3)}$$

$$\Delta\delta = [(P_{r,1}^{s,(i)} - P_{r,1}^{s,(i+1)}) - (P_{r,1}^{s,(i+1)} - P_{r,1}^{s,(i+2)})] - [(P_{r,1}^{s,(i+1)} - P_{r,1}^{s,(i+2)}) - (P_{r,1}^{s,(i+2)} - P_{r,1}^{s,(i+3)})] = P_{r,1}^{s,(i)} - 3P_{r,1}^{s,(i+1)} + 3P_{r,1}^{s,(i+2)} - P_{r,1}^{s,(i+3)}$$

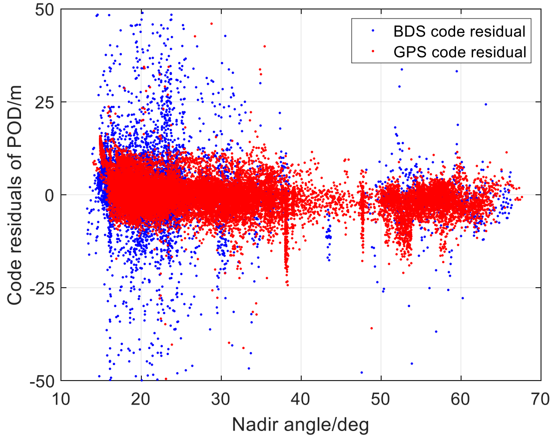
$$\sigma_{\Delta}^2 = [1^2 + (-3)^2 + 3^2 + 1^2]\sigma_0^2 = 20\sigma_0^2$$

2. Data Quality and Orbit Determination of HEO Spaceborne GNSS –POD Strategy

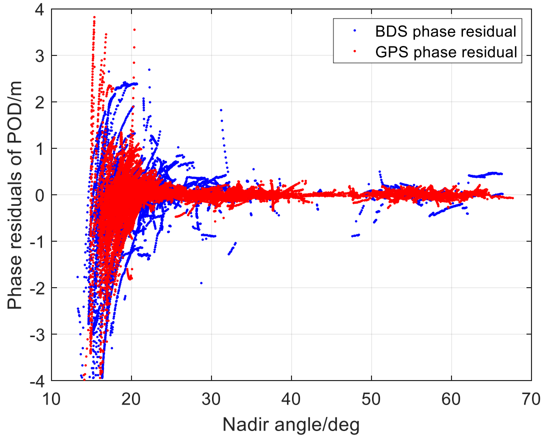
- **Data close to the Earth surface (4000km) affected by ionosphere and plasma, large errors**
- **Nadir angle weighting method**

$$P(\varphi)=\begin{cases} P_0,\varphi \geq \psi \\ P_0 \cdot \sin^2(\frac{\varphi}{\psi}),0 \leq \varphi < \psi \end{cases}$$

nadir angle<21°
downweighting



LT4A code residuals VS nadir angle



LT4A carrier residuals VS nadir angle

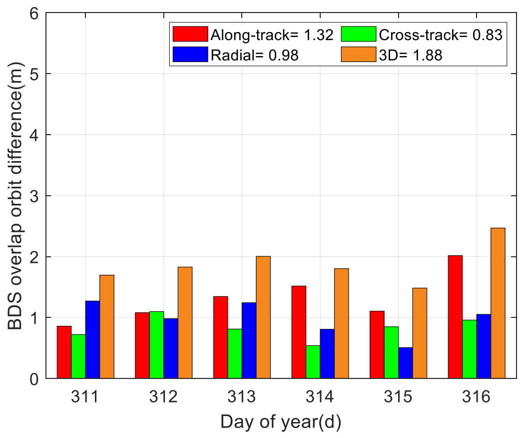
Item	Parameter
Observation model	single frequency, non-differential, non-combined
Interval	**30s**
POD arc	48h
GNSS	BDS/GPS
Observation weight	**code 10m; carrier 3cm**
Elevation mask	0°
Gravity	EIGEN_06C, 12×12
Solid tide	IERS 2010
Ocean tide	FES2012, 30×30
Relativity	IERS 2010
Atmospheric drag	N/A
Solar pressure	**9-parameter ECOM model**
Third body	solar system large objects, DE405 Ephemeris
Estimated parameter	position/velocity, clock, 9 para solar pressure

2. Data Quality and Orbit Determination of HEO Spaceborne GNSS –POD Accuracy

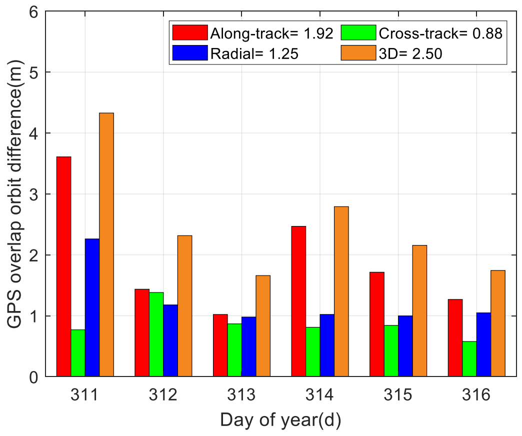
□ LT4A GNSS based POD precision, overlapped(3D)

- BDS-only 1.88m
- GPS-only 2.50m
- BDS+GPS 1.45m

POD mode	Along/m	Cross/m	Radial/m	3D/m
BDS-only	1.32	0.83	0.98	1.88
GPS-only	1.92	0.88	1.25	2.50
GPS+BDS	1.11	0.51	0.77	1.45



LT4A BDS-only POD overlapped differences

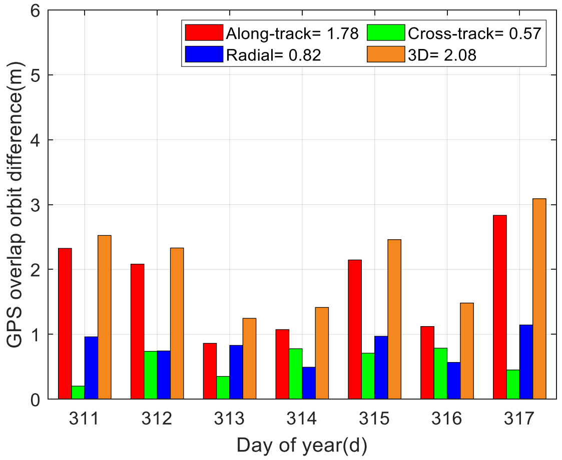


LT4A GPS-only POD overlapped differences

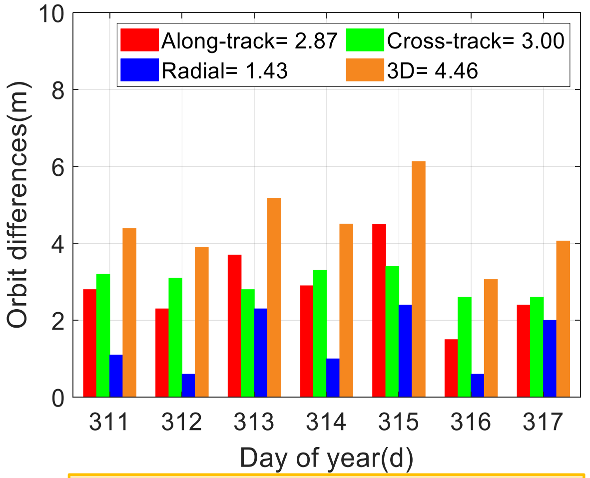
□ LT4A POD consistency with different data(3D)

- Using SoC1 VS SoC2 data, 2.08m
- Using GNSS VS Ka data, 4.46m

POD mode	Along/m	Cross/m	Radial/m	3D/m
SoC1 overlapped	1.11	0.51	0.77	1.45
SoC2 overlapped	1.59	0.46	0.89	1.92
SoC1 VS SoC2	1.78	0.57	0.82	2.08
SoC1 VS Ka	2.87	3.00	1.43	4.46



SoC1/SoC2 based orbit consistency

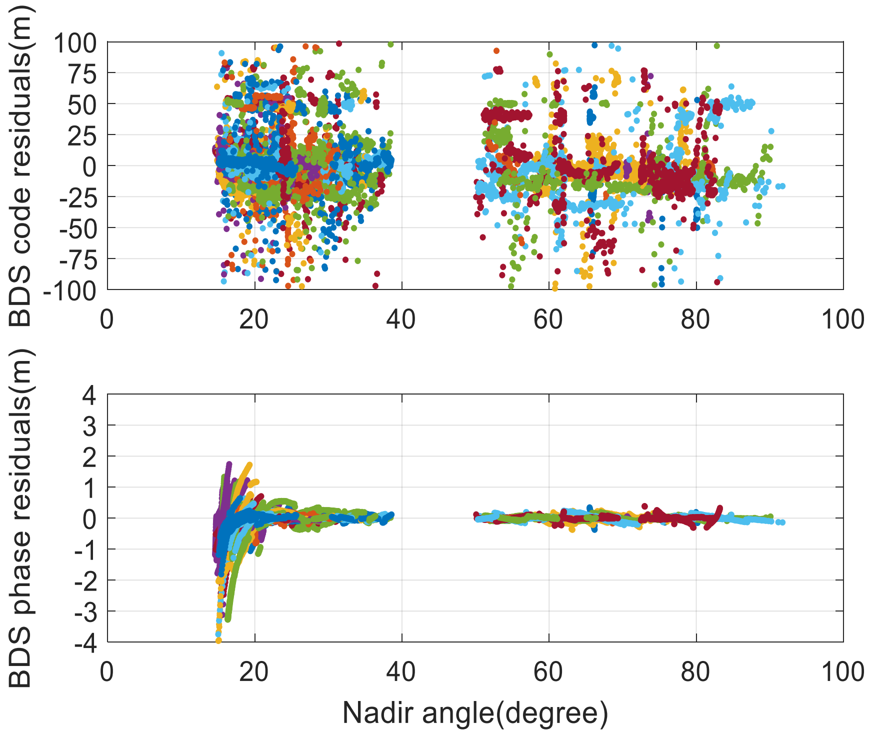


GNSS/Ka based orbit consistency

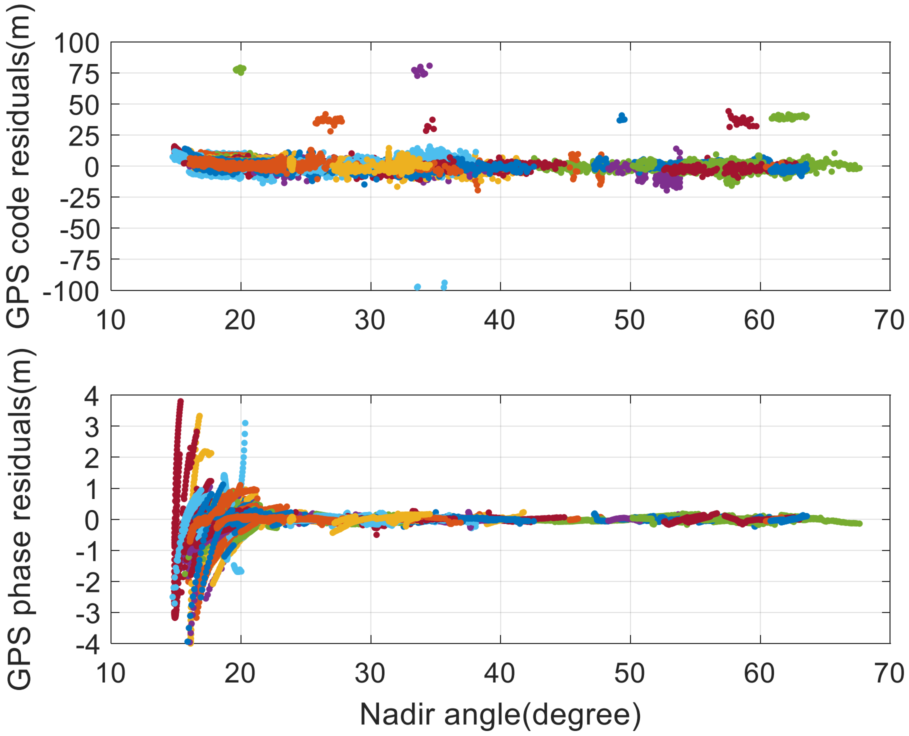
2. Data Quality and Orbit Determination of HEO Spaceborne GNSS –POD residuals

☐ LT4A POD residuals

- **BDS code residuals 24.0m, carrier residuals 8.5cm**
- **GPS code residuals 6.9m, carrier residuals 6.3cm**
- **Carrier are affected more significantly**



BDS code and carrier residuals



GPS code and carrier residuals

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3. GNSS Characteristics and Simulation Validation in Cislunar Space

Lunar space GNSS code/carrier noise

Received Signal Power

$$P_{rx,k}^{i} = EIRP^{i}(\beta_k^i) - 20\log_{10}\left(\frac{4\pi f\left|r_k^i - r_k\right|}{c}\right)$$

Carrier to Noise Ratio

$$(C_{N0})_k^i = P_{rx,k}^i + G_{rx}(\theta_k^i) - 10\log_{10}(\Gamma_{sys}) - L_{sys} - k_{dB}$$

Code Noise

$$(\sigma_{\rho,k}^i)^2 = (\sigma_{DLL,k}^i)^2 + \sigma_{GNSS,orb}^2 + \sigma_{GNSS,clk}^2$$

$$(\sigma_{DLL,k}^i)^2 = (cT_c)^2 \frac{B_{n,c}}{2(C_{N0})_k^i} D\left[D(1+\frac{2}{(2-D)T(C_{N0})_k^i})\right]$$

Carrier Noise

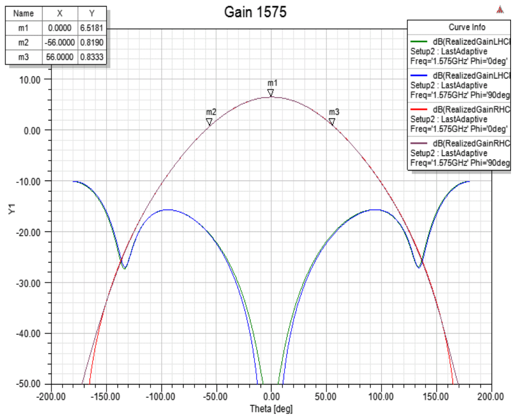
$$(\sigma_{\varphi,k}^i)^2 = (\frac{\lambda_L}{2\pi})^2\left[\frac{B_n}{(C_{N0})_k^i}(1+\frac{1}{2T(C_{N0})_k^i})\right] + (cT\sigma_A)^2$$

c	Light speed	299792458m/s
T_c	Code chip width	977.5ns(GPS1.023MHz) 488.8ns(BDS2.046MHz)
$B_{n,c}$	**Code loop filter noise bandwidth**	**0.4Hz**
B_{front}	**Front-end bandwidth**	**20.46 MHz**
$\sigma_{GNSS,orb}^2$	GNSS orbit error	0.6m
$\sigma_{GNSS,clk}^2$	GNSS clock error	0.5m
λ_L	Carrier wave length	0.1904m 0.1922m
B_n	**Carrier loop filter noise bandwidth**	**12Hz**
T	**Integration time**	**0.02s**
σ_A	Allan deviation oscillator phase noise	5.0E-11s/s
$P_{rx,k}^i$	**Received signal power**	**-188.4dBW**
$G_{rx}(\cdot)$	**Receiving antenna gain**	**15dBi**
β_k^i	Received off-boresight angle	2°
Γ_{sys}	System temperature	246K
L_{sys}	Additional system loss	0.5dB
$EIRP^i(\cdot)$	Effective isotropic radiated power	20dBW
θ_k^i	Transmitting off-boresight angle	20°
$\left\|r_k^i - r_k\right\|$	Receiver and GNSS distance	400000000m
f	Carrier frequency	1575.42MHz
$(C_{N0})_k^i$	**Carrier to noise ratio**	**30.7dBHz**
$\sigma_{\rho,k}^i$	**Code noise/m**	**GPS 4.57/ BDS 2.46**
$\sigma_{\varphi,k}^i$	**Carrier noise/mm**	**GPS 3.11/ BDS 3.14**

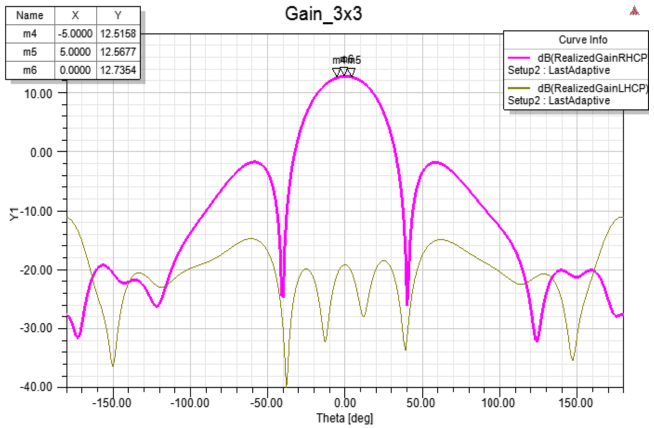
3. GNSS Characteristics and Simulation Validation in Cislunar Space

GNSS receiving antenna for Lunar space

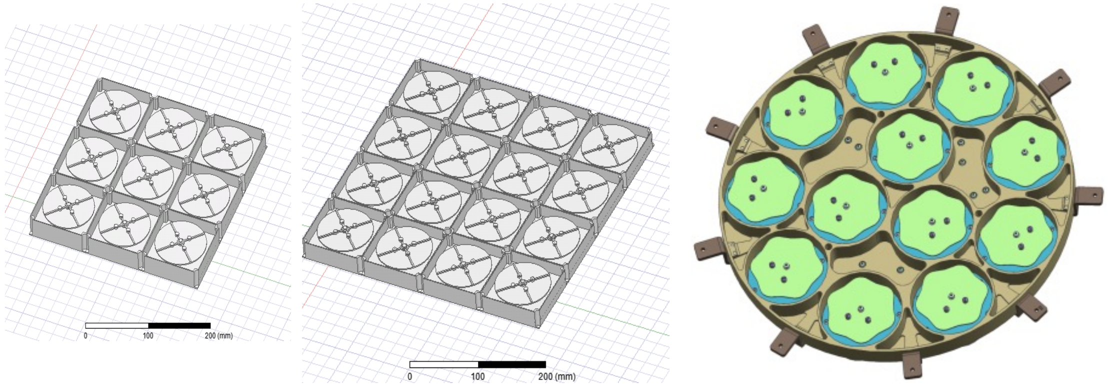
- For cislunar, lunar orbit, lunar surface cases
- Support GPS L1, BDS B1I, BDS B1C
- 3×3 array, size 291mm×291mm, 2.4kg
- 4×4 array, size 388mm×388mm, 3.5kg
- Planar array antenna, size Φ1100mm, 8.5kg(Mg-Al)



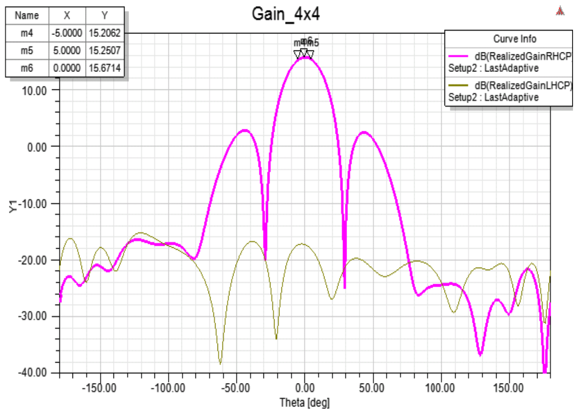
Gain of array element



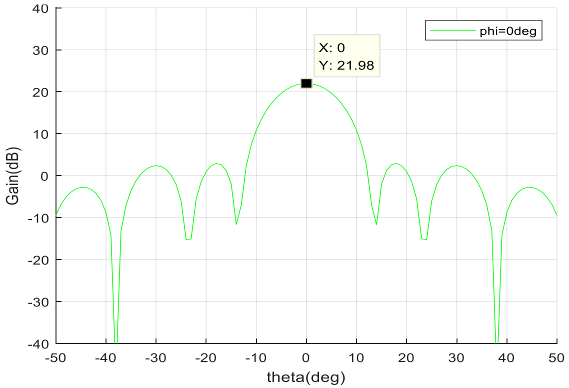
Max 12.7dB for 3×3 array



High gain antenna form



Max 15.7dB for 4×4 array



Max 21.9dB for planar array

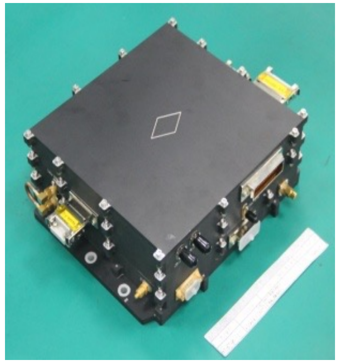
3. GNSS Characteristics and Simulation Validation in Cislunar Space

Lunar Space GNSS Receiver

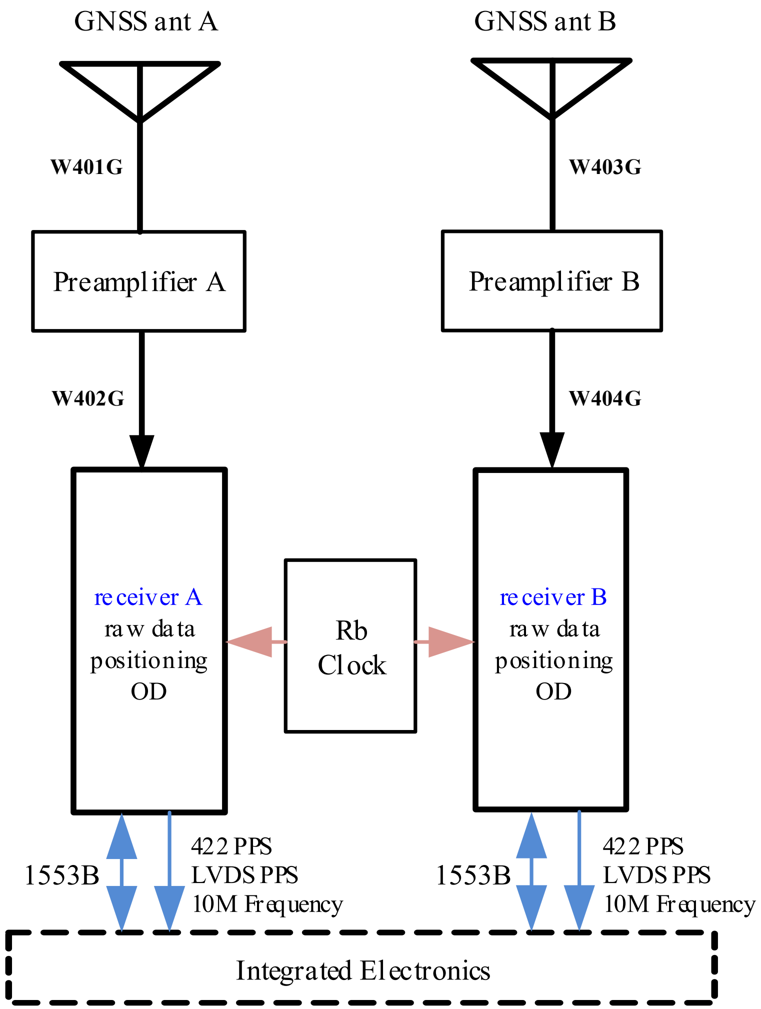
- 3rd-Gen SoC
- GNSS Signal: BDS B1I, BDS B1C, GPS L1
- Sensitivity: -184dBW
- Code noise: 10m
- Provide raw data and navigation service for lunar space
- High-stability rubidium clock/clock disciplining

3rd-Gen BDS-3 Aerospace-Grade Chip (SoC3.0)

- Process: 40nm
- Acquisition : -184dBw
- Frequency Bands: GREC, full frequency, BDS RDSS
- Main Functions: RNSS, RDSS, interference resistance
- Grade: Aerospace



SoC3.0



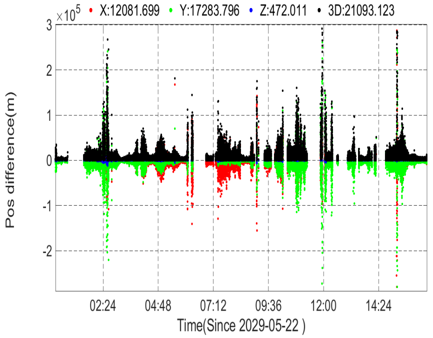
3. GNSS Characteristics and Simulation Validation in Cislunar Space

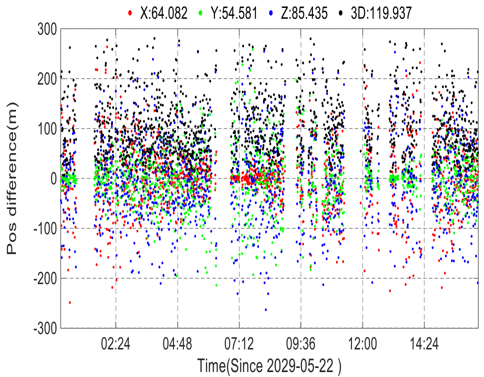
☐ Positioning accuracy of DRO orbit

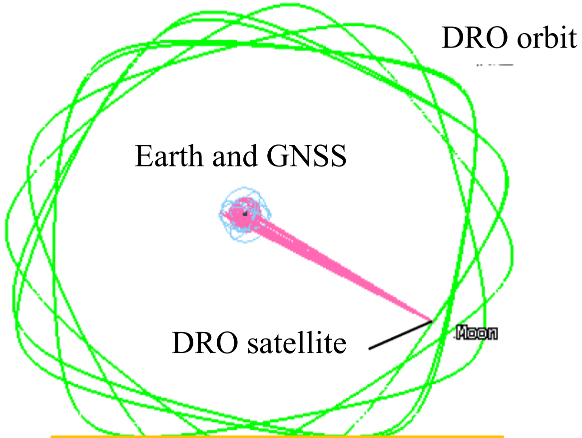
- DRO orbit, high stability, good lunar coverage
- DRO orbit altitude 350000 km ~ 372000 km

GNSS simulation strategy

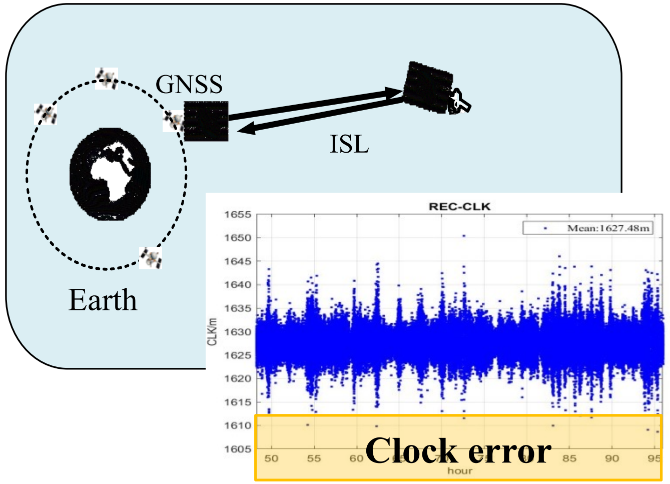
Item	Description
observation	BDS B1I pseudorange
interval	1s
clock error	GNSS clock error: 0 Receiver clock error: actual, solved
GNSS orbit error	theoretical orbit, error: 0
propagation error	Earth rotation, relativity
Code noise	receives signal from simulator code noise set at 10m



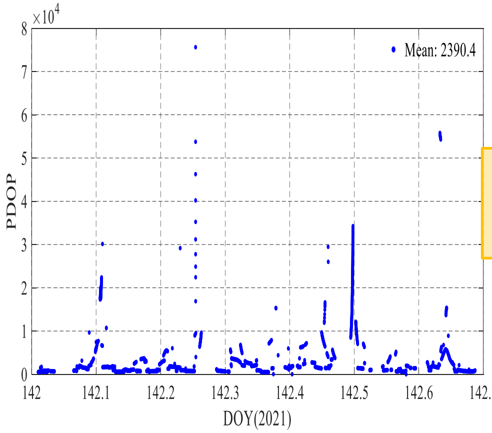




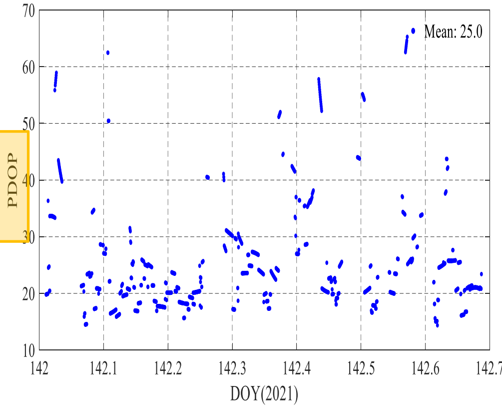
GNSS and DRO orbit



Clock error



Decoupled clock



Strategy 1: solve clock error
PDOP: 2390
Positioning error 21093m

→

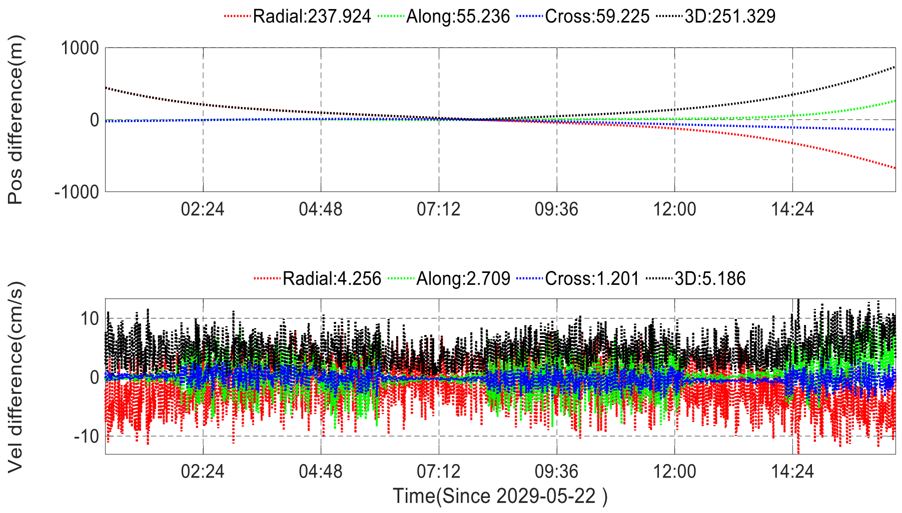
Strategy 2: decoupled clock
PDOP: 25.0
Positioning error 120m

3. GNSS Characteristics and Simulation Validation in Cislunar Space

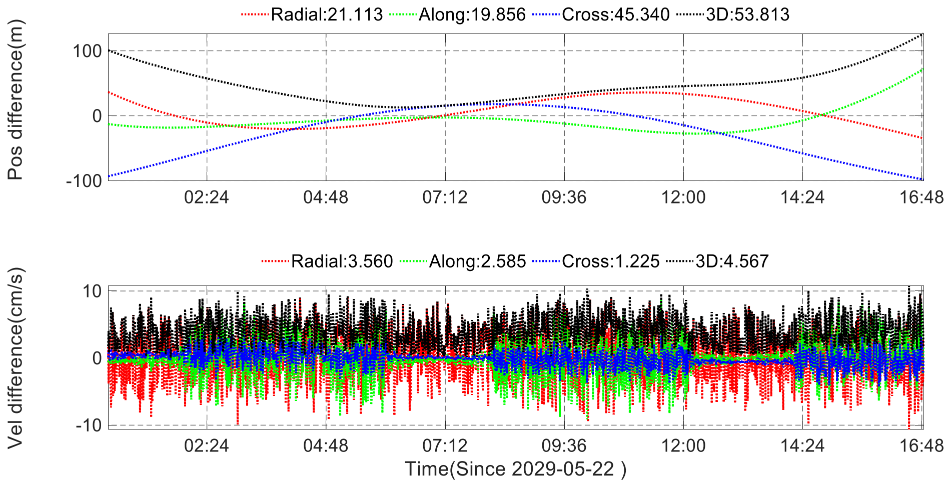
□ POD accuracy of DRO orbit

- Strategy 1: 3D POD error 251.3 m
- Strategy 2: 3DPOD error 53.8 m
- POD accuracy improved 78.6% using decoupling clock method

Item	Description
observation	BDS B1I pseudorange
interval	1s
estimation method	Batch LSQ
force model	2 body, N body, tide, solar pressure, relativity, non-spherical perturbations
estimated parameters	Strategy 1: Solar pressure coefficient, position, velocity, empirical force, clock Strategy 2: Solar pressure coefficient, position, velocity, empirical force



Strategy 1: POD error 251.3m



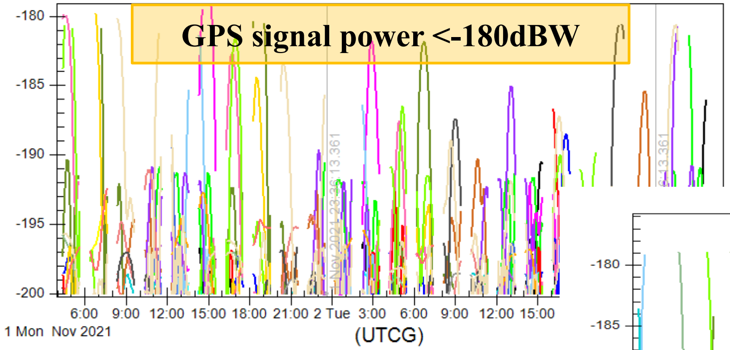
Strategy 2: POD error 53.8m

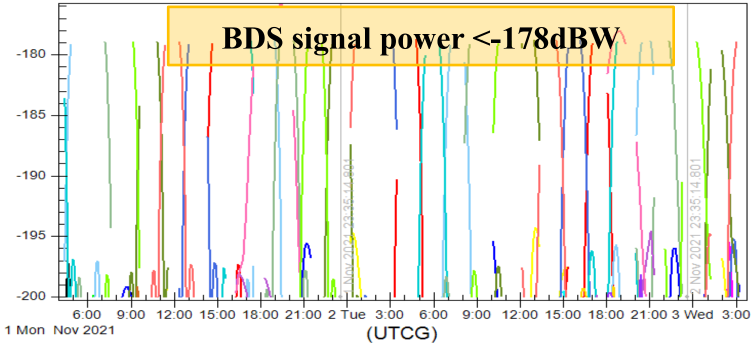
3. GNSS Characteristics and Simulation Validation in Cislunar Space

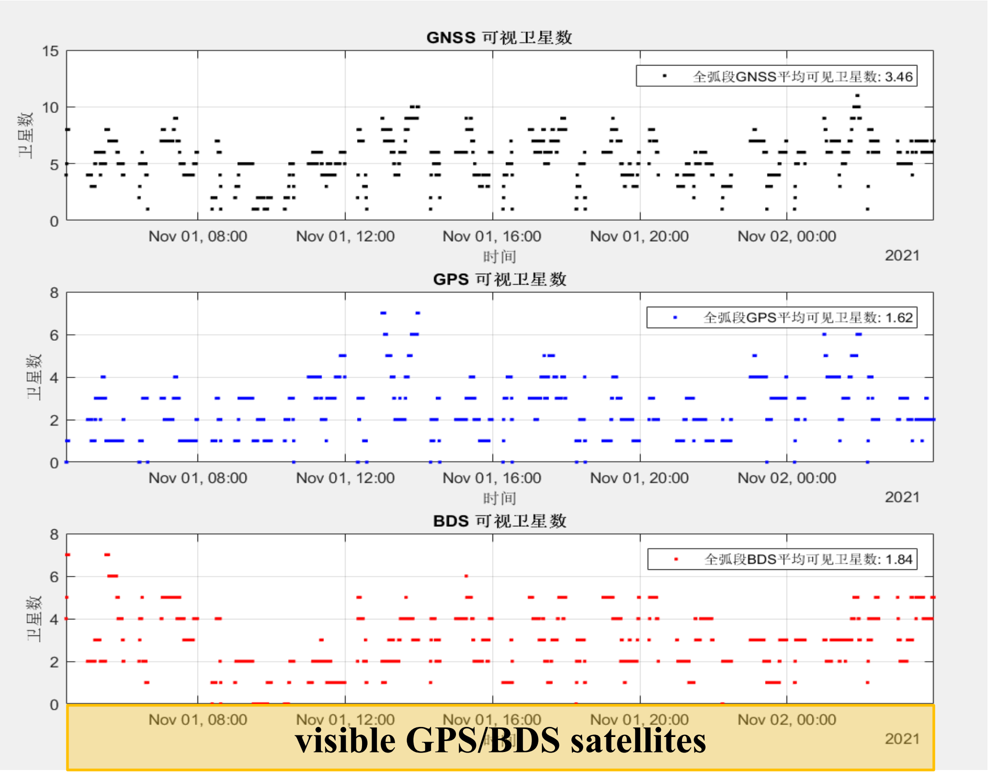
◻ POD accuracy of 100km lunar orbit

observation simulation strategy

item	description
observation	BDS B1I/GPS L1 pseudorange
interval	1s
clock error	GNSS clock error: 0 receiver clock error: a0, a1, a2
GNSS orbit error	theoretical orbit, error: 0
propagation error	Earth rotation, relativity
Code noise	30m Gaussian white noise







- GNSS visible time 62.73%, average 3.46
- GPS visible time 61.95%, average 1.62
- BDS visible time 60.40%, average 1.84

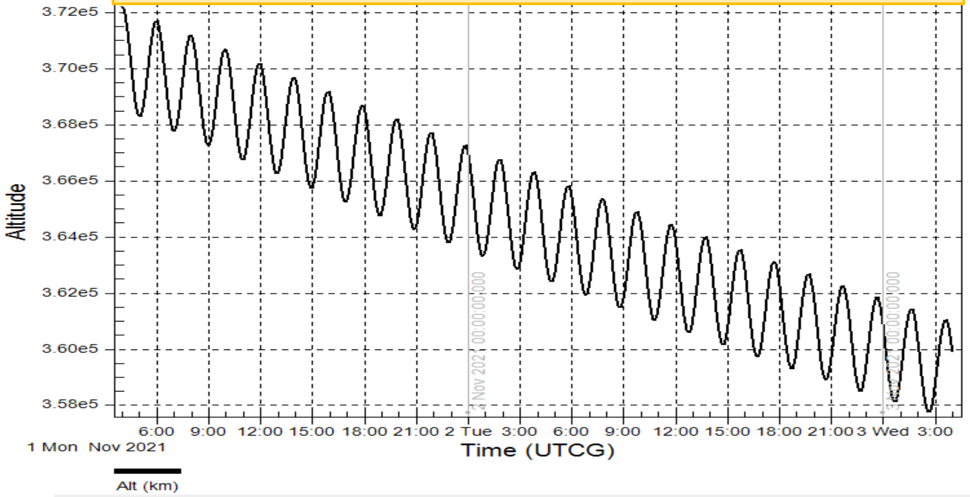
3. GNSS Characteristics and Simulation Validation in Cislunar Space

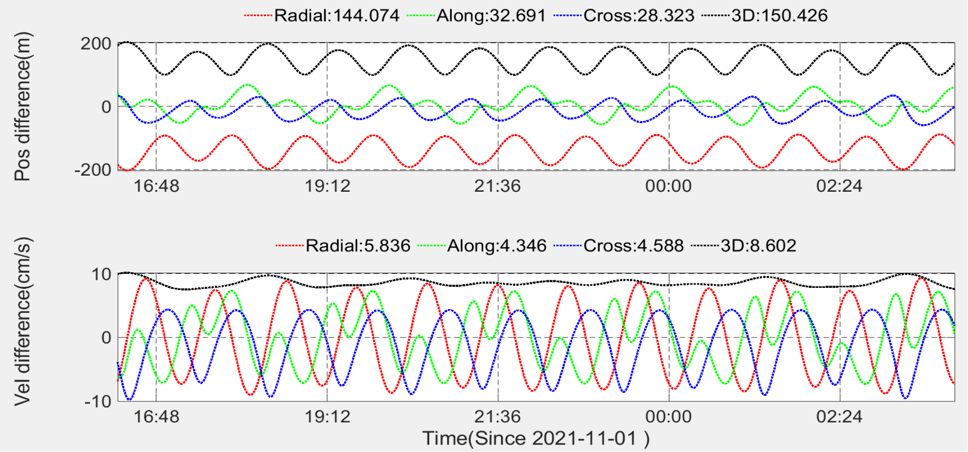
POD accuracy of 100km lunar orbit

POD strategy

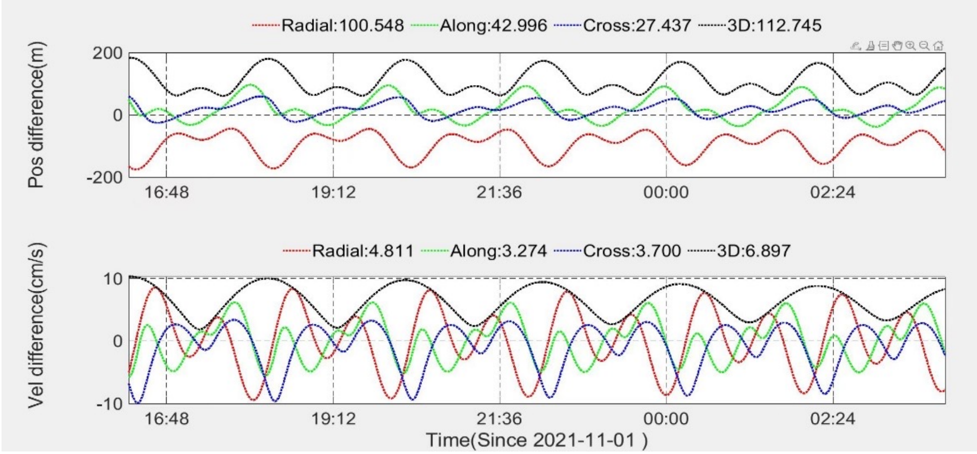
Item	Description
observation	BDS B1I/GPS L1 pseudorange
interval	30s
estimation method	Batch LSQ
force model	2 body, N body, tide, solar pressure relativity, non-spherical perturbations 10% model error is added
parameters	solar pressure coefficient, position, velocity, empirical force parameters
evaluation method	compare with theoretical orbit

distance between orbit and Earth





BDS only POD accuracy 150.4m



GPS+BDS POD accuracy 112.7 m

Conclusion

Earth-based GNSS can support the establishment and maintenance of lunar PNT

- Determination of spatio-temporal datum for lunar navigation constellation
- Provide PNT services for users in cislunar space, near-moon space and on lunar surface

China has conducted multiple GNSS weak signal-based space applications, with technical capability fully verified

- GEO/IGSO/HEO, 35 SSTC satellites in orbit cumulatively
- GNSS signal reception achieved at 200,000 km in cislunar transfer orbit; orbit determination achieved at 5,000~50,000 km
- CAS DRO Constellation: 1.17 million km inter-satellite/ground-satellite microwave measurement and communication realized

Calculations based on GNSS satellite antenna pattern and link budget

- HEO scenario, 8 dB receiving antenna: C/N0 41.8 dBHz, code accuracy (GPS L1 C/A 1.59 m, BDS B1I 1.21 m), carrier at mm level
- Cislunar and near-moon space, 15 dB receiving antenna : C/N0 30.7 dBHz, code accuracy (GPS L1 C/A 4.57 m, BDS B1I 2.46 m), carrier at mm level

BDS inter-satellite links can be used to decouple receiver clock error and improve orbit determination accuracy

Thank you!