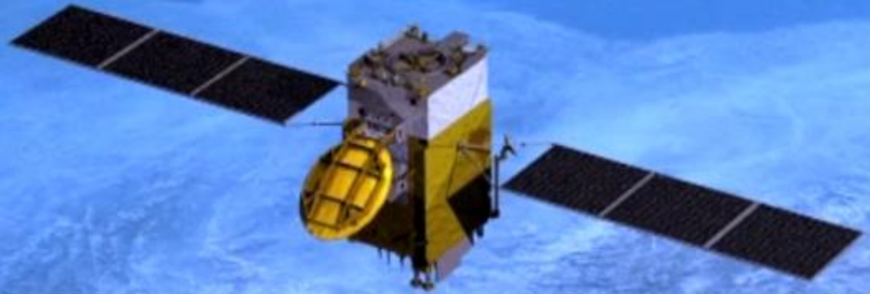
17th Meeting of the International Committee on Global Navigation Satellite Systems

BDS Space Service Volume (SSV) Performance and Applications



Xinuo CHANG, Jinjun ZHENG

China Academy of Space Technology

Madrid, Spain

October 17, 2023

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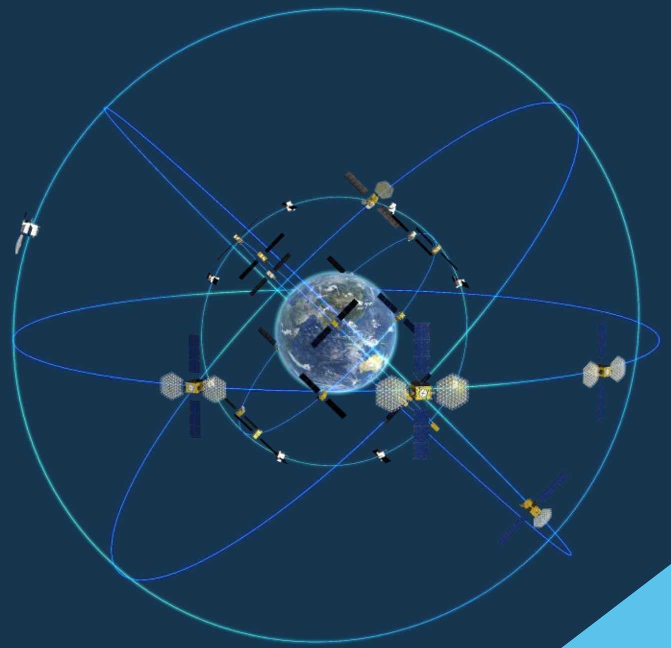


01

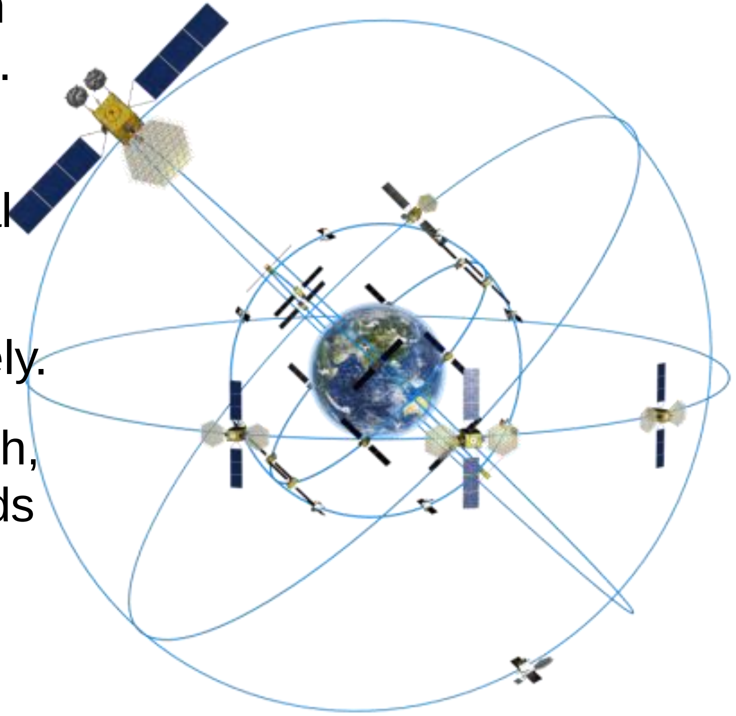
BDS Constellation Support to Interoperable GNSS SSV

BDS Constellation Support to Interoperable GNSS SSV

BDS Constellation

- consists of satellites located in the Geostationary Earth Orbit (GEO), Inclined Geo-Synchronous Orbit (IGSO) and Medium Earth Orbit (MEO).

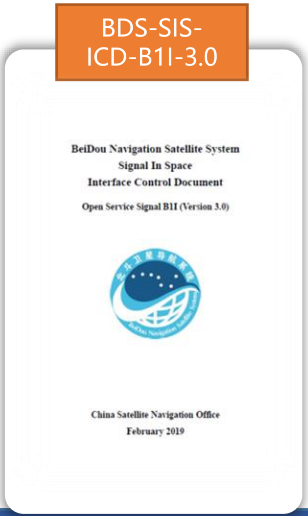
- 24 MEO satellites operate in orbit at an altitude of 21,528 km and an inclination of 55°, and are distributed in a Walker 24/3/1 constellation.
- 3 IGSO satellites, with an orbital altitude of 35786 km and the orbital inclination of 55°, are distributed in 3 orbital planes. The geographical longitudes of the ascending nodes locate at 118°E.
- 3 GEO satellites are located at 80°E, 110.5°E, and 140°E respectively.
- GEO-4 , the 1st backup satellite of BDS-3, was launched on May 17th, 2023 and located at160°E. It is serving as on-orbit backup. It expands the communication capacity of regional SMS and enhances performance of SBAS and PPP service .

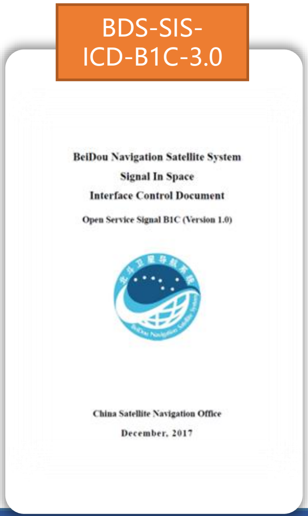


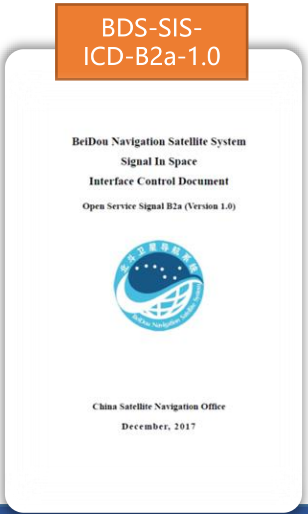
BDS Constellation Support to Interoperable GNSS SSV

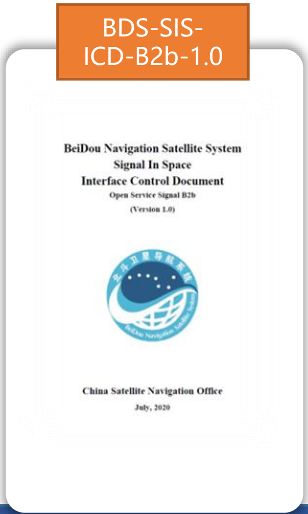
Signal in Space

- BDS transmits Positioning, Navigation and Timing (RNSS) signals in 3 frequency bands: B1 (1575.42MHz), B2 (1191.795MHz), B3 (1268.52MHz).
- 5 types of Open Service (OS) signals are broadcasted
  - B1I and B3I are broadcasted by all BDS satellites in orbit
  - B1C, B2a, B2b are new OS signals broadcasted by BDS-3 IGSO and MEO Satellites









The detailed signal characteristics are specified in BDS SIS-ICDs (http://en.beidou.gov.cn/SYSTEMS/ICD)

BDS Constellation Support to Interoperable GNSS SSV

Interoperability with Other GNSSs

Signal Structure

- User level Interoperability could be realized between BDS B1C and GPS L1C / Galileo E1OS, BDS B2a and GPS L5 /Galileo E5a signals.

Time System

- The BDT traces back to the Coordinated Universal Time.
- BDT-UTC time offsets parameters and BDT-GNSS time offsets parameters are broadcasted in the navigation messages.

Coordinate System

- The BDS coordinate system is consistent with the International Earth Reference Frame (ITRF).

Table 7-20 Definitions of the BDT-UTC time offset parameters

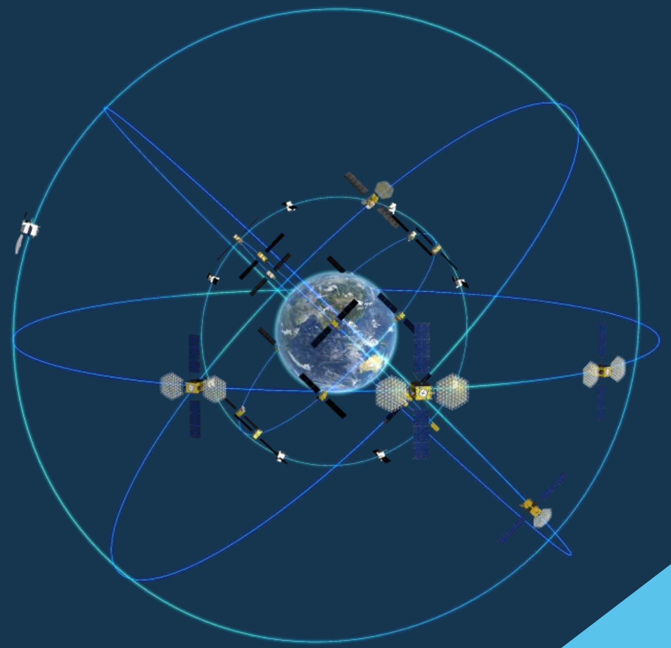
No.	Parameter	Definition	No. of bits	Scale factor	Effective range**	Unit
1	A_{0UTC}	Bias coefficient of BDT time scale relative to UTC time scale	16*	2^{-35}	--	s
2	A_{1UTC}	Drift coefficient of BDT time scale relative to UTC time scale	13*	2^{-51}	--	s/s
3	A_{2UTC}	Drift rate coefficient of BDT time scale relative to UTC time scale	7*	2^{-68}	--	s/s^2
4	Δt_{LS}	Current or past leap second count	8*	1	--	s
5	t_{ot}	Reference time of week	16	2^4	0~604784	s
6	WN_{ot}	Reference week number	13	1	--	week
7	WN_{LSF}	Leap second reference week number	13	1	--	week
8	DN	Leap second reference day number	3	1	0~6	day
9	Δt_{LSF}	Current or future leap second count	8*	1	--	s

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB.
** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

Table 7-21 Definitions of the BGTO parameters

No.	Parameter	Definition	No. of bits	Scale factor	Effective range**	Unit
1	GNSS ID	GNSS type identification	3	--	--	dimensionless
2	WN_{0BGTO}	Reference week number	13	1	--	week
3	t_{0BGTO}	Reference time of week	16	2^4	0~604784	s
4	A_{0BGTO}	Bias coefficient of BDT time scale relative to GNSS time scale	16*	2^{-35}	--	s
5	A_{1BGTO}	Drift coefficient of BDT time scale relative to GNSS time scale	13*	2^{-51}	--	s/s
6	A_{2BGTO}	Drift rate coefficient of BDT time scale relative to GNSS time scale	7*	2^{-68}	--	s/s^2

* Parameters so indicated are two's complement, with the sign bit (+ or -)occupying the MSB.
** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.



02 BDS Satellite Antenna Models

BDS Satellite Antenna Models

Needs for GNSS Satellite Antenna Data

- According to recommendations of ICG-11(2016) and ICG-14(2019), it was recommended that GNSS Service Providers consider releasing the antenna gain pattern or equivalent representative modelling to support space mission analysis and GNSS equipment development.

Additional Data for Space Service Volume (ICG-11, 2016)

…

In order to fully support in-depth mission-specific navigation studies, WG-B invites the providers to consider for the future, to provide the following additional data if available:

•GNSS transmit antenna gain patterns for each frequency, measured by antenna panel elevation angle at multiple azimuth cuts, at least to the extent provided in each constellation's SSV template.

…

Release of GNSS Transmit Antenna Patterns including Side Lobes (ICG-14, 2019)

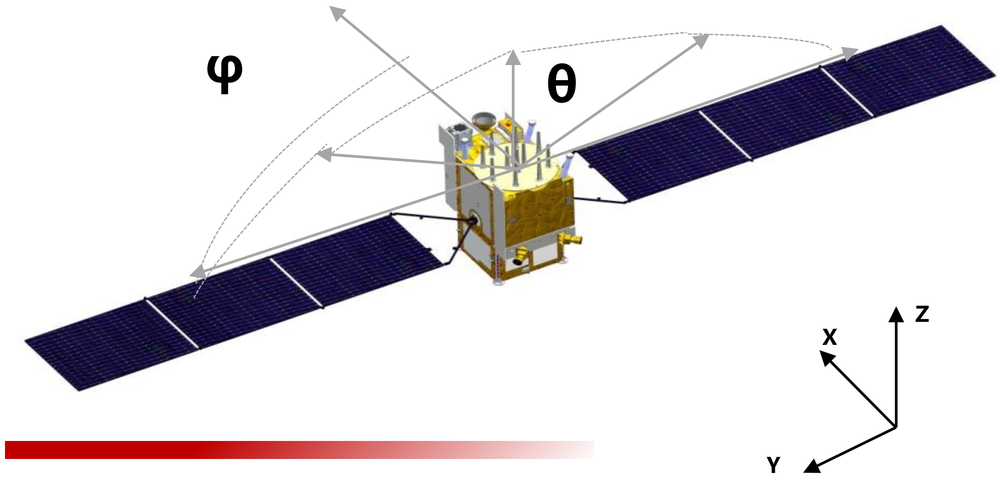
…

WG-B recommends that GNSS Service Providers consider releasing the antenna gain patterns or equivalent representative modelling information (including both main lobe and side lobes for each frequency, for open services) for each of the transmit antennas of the GNSS satellites in the respective satellite constellations in order to enable and/or improve the use of GNSS in the SSV. In addition, for future satellite developments, WG-B recommends that GNSS Service Providers consider conducting antenna gain measurements, testing and/or characterization, including both main lobe and side lobes for each open service signal.

BDS Satellite Antenna Models

Pre-flight Satellite Transmit Antenna Test Data

- BDS satellites antenna panels were tested in ground near-field range, covering 3 frequency bands: B1 1575.42MHz, B2 1191.795MHz, B3 1268.52MHz.
- High resolution antenna gain data including side-lobes were processed and under review.

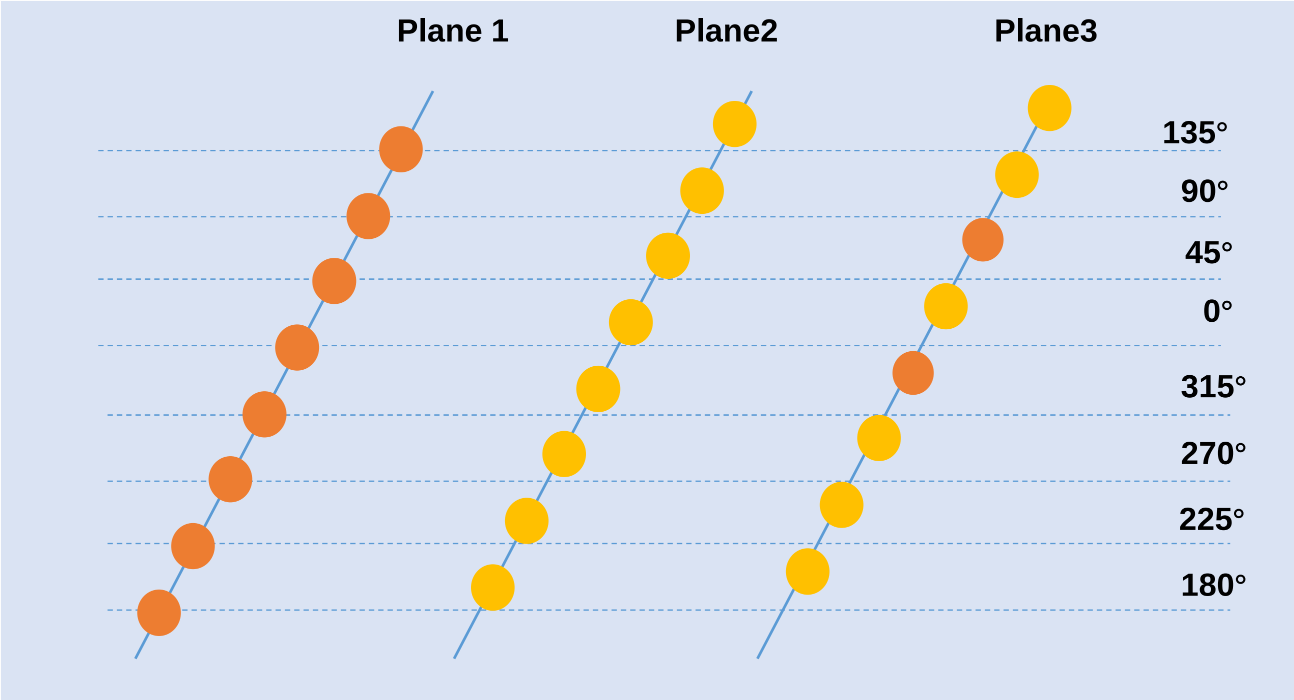


<u>Measurement Coordinates</u>
Off-boresight angle θ
= angle between z-axis and the vector to the point from +Y to –Y axis(-90 °to 90°)
Azimuth angle φ
= angle from the x-axis around the z-axis from +X through +Y to –X axis (0°to 180°)

BDS Satellite Antenna Models

BDS Satellite Antenna Types and Configurations

- 3 Types of antenna panel are used on different types of BDS satellites.
- The orbital phase configuration of MEO satellites are shown on the right.



Type 1	14 MEO Satellites	
Type 2	10 MEO Satellites	
Type 3	IGSO & GEO Satellites	All

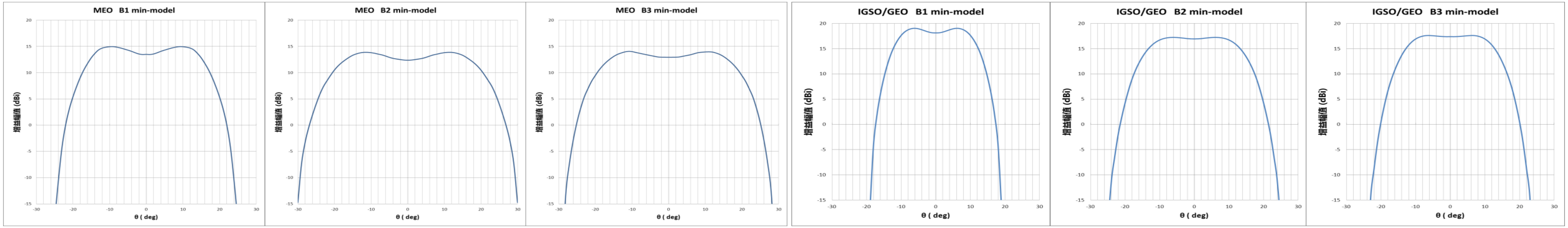
BDS Satellite Antenna Models

Antenna Gain Min-Model

- The antenna gain min value of all azimuth angle sections can reflect the relatively stable characteristics in the range of main lobe.
- Based on the minimum envelope of all antenna ground test data, the main-lobe model can be constructed as follows.

Frequency	Peak	0dBi	-5dBi	-10dBi
MEO B1	9°~10°	22°	23°	24°
MEO B2	11°~12°	27°	28°	29.5°
MEO B3	10°~12°	25°	26°	27.5°
IGSO/GEO B1	6°	17°	18°	18.5°
IGSO/GEO B2	7°	21.5°	22.5°	23.5°
IGSO/GEO B3	6°	20.5°	21.5°	22°

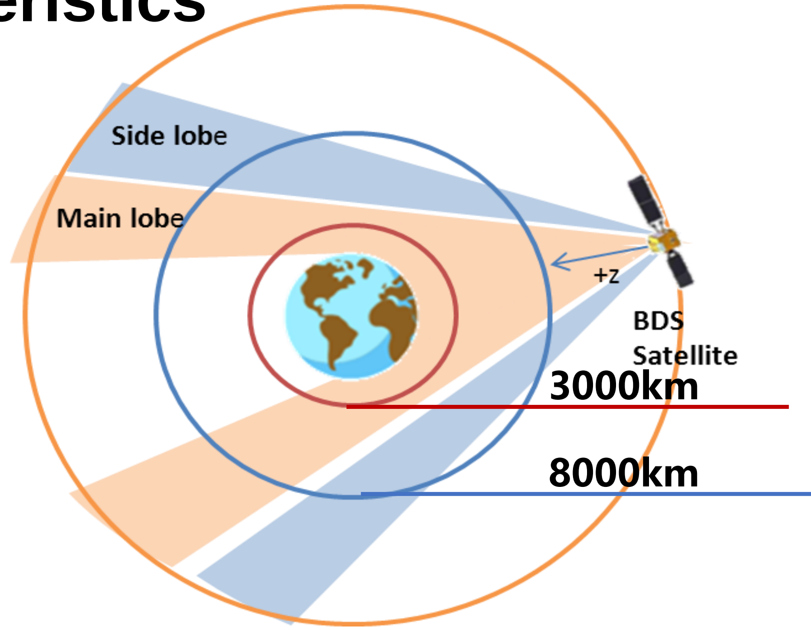
Antenna gain and off-boresight angle relationships of different satellite and frequencies



BDS Satellite Antenna Models

Antenna Gain Min-Model and related service characteristics

- BDS satellites are operating at the altitude of 21528km(MEO) and 35786km(GEO, IGSO) , and the corresponding off-boresight angle of EOE, 1000km, 3000km and 4000km are shown in the table below.
- space users under 4000km altitude are inside the coverage volume of antenna main lobe, mission analysis for users in this area can directly apply antenna gain min-model.

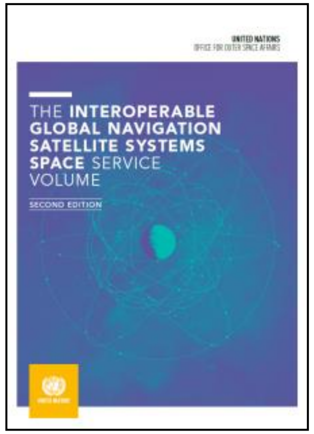


Satellite Orbit Type	Edge of Earth	1000km	3000km	4000km
MEO	13.2°	15.3°	19.6°	21.8°
GEO/IGSO	8.7°	10.1°	12.9°	14.2°

BDS Satellite Antenna Models

Comparison between Min-Model and SSV Booklet Template

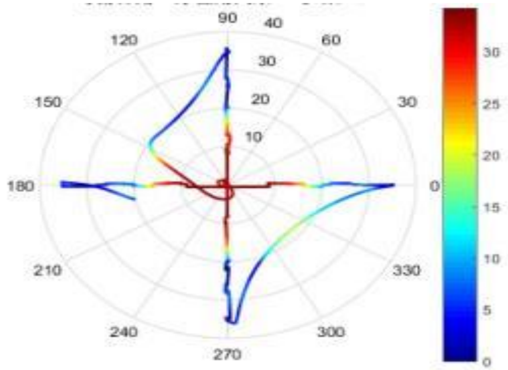
Frequency	SSV Booklet	Min-model 0dBi	Min-model -5dBi	Min-model -10dBi
MEO B1	25°	22°	23°	24°
MEO B2	28°	27°	28°	29.5°
MEO B3	28°	25°	26°	27.5°
IGSO/GEO B1	19°	17°	18°	18.5°
IGSO/GEO B2	22°	21.5°	22.5°	23.5°
IGSO/GEO B3	22°	20.5°	21.5°	22°



- Min-Models of B2 signal meet he reference off-boresight angle from SSV booklet, indicating antenna gain minimum envelop of of all BDS satellites meet the value.
- Min-Models of B1 and B3 shows difference from the booklet, indicating that by applying high resolution data some azimuth section of antenna pattern affect the minimum envelop.
- Min-Model can well represent antenna main lobe characteristics.

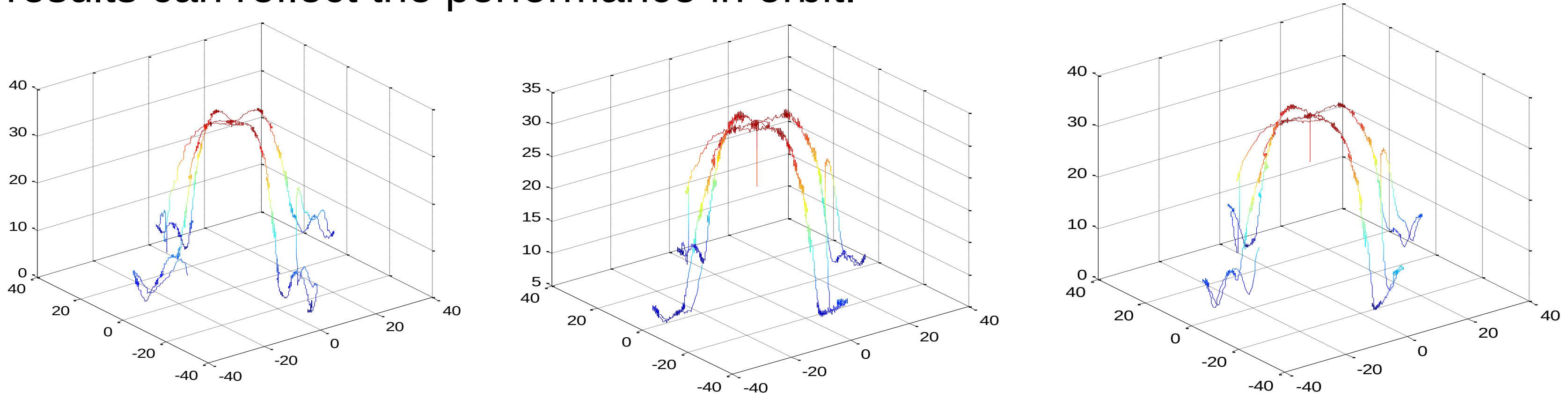
In-orbit Antenna Pattern Test

- In-orbit test was implemented on BDS IGSO test satellite to
  - characterize of satellite transmit antenna, especially the gain pattern on the margin of main lobe and 1st side lobe
  - to study the feasibility of satellite maneuver for antenna pattern measurement
  - analyze the difference between ground and in-orbit test results
- In orbit test results shows
  - good consistency with ground near-field test in B1/B2/B3 main lobe and similar feature at side lobe area.
  - The pre-flight antenna test results can reflect the performance in orbit.

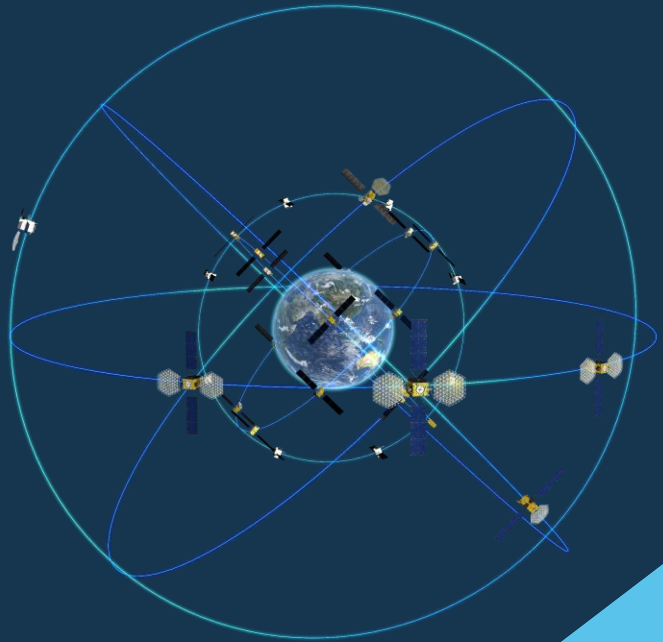


the maneuver trace of the satellite

Haoping Ground Station (40m)



the reconstructed 3-D antenna pattern of B1B2B3 (XOZ plane & YOZ plane)

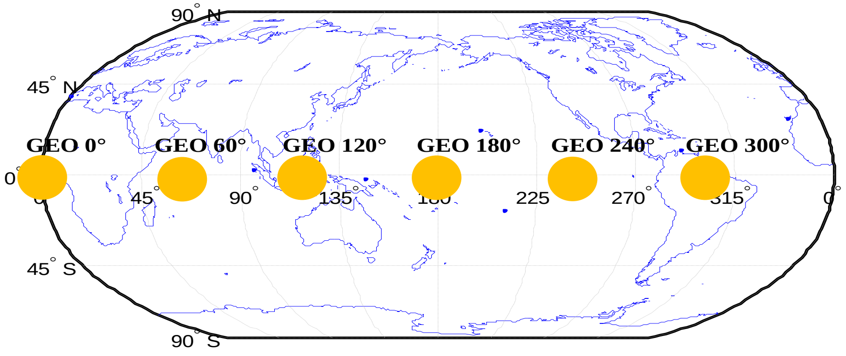


03

GEO Mission Performance Analysis

- with pre-flight antenna test data including side-lobes

GEO Mission Performance Analysis



Simulation with BDS pre-flight antenna test data including side-lobes

- 6 GEO mission were selected with longitude interval of 60°.
- A nadir pointing antenna with 7dBi gain(±30°)
- Receiver sensitivity threshold at -173/ -178/-183/-188dBW

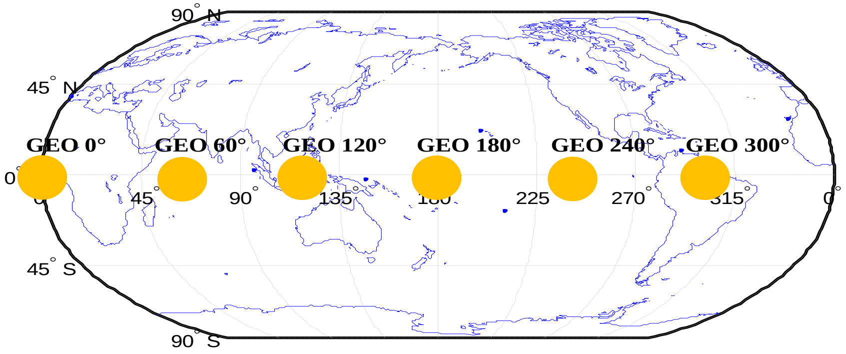
GEO User Visibility of 1 satellite and Maximum Outage Duration

Receiver threshold		-173dBW						-178dBW					
GEO USER		0°	60°	120°	180°	240°	300°	0°	60°	120°	180°	240°	300°
B1I	Visibility/%	96.3	94.4	95.0	95.4	100	100	100	99.9	99.9	100	100	100
	MOD/min	37	34	33	28	0	0	0	6	5	0	0	0
B1C	Visibility/%	95.3	94.2	94.8	95.3	95.0	95.9	100	99.9	99.9	99.9	99.8	99.8
	MOD/min	37	34	33	28	40	29	0	6	5	1	10	8
B2a	Visibility/%	100	100	100	100	100	100	100	100	100	100	100	100
	MOD/min	0	0	0	0	0	0	0	0	0	0	0	0
B2b	Visibility/%	100	100	100	100	100	100	100	100	100	100	100	100
	MOD/min	0	0	0	0	0	0	0	0	0	0	0	0
B3I	Visibility/%	100	100	99.9	99.9	100	100	100	100	100	100	100	100
	MOD/min	0	0	2	6	0	0	0	0	0	0	0	0

- 1 signal at B2 can be continuously received with receiver threshold -173dBW. All signal can reach 99.9% visibility with receiver threshold -178dBW.
- GEO Users located around longitude 240°~300° have better signal availability which is benefit from BDS IGSO and GEO satellite.
- Single signal visibility simulation result is92%~100% base on SSV booklet template (minimum received power and reference 0ff-boresight angle) and 99.9%~100%based on test gain data both with around -178dBW receiver threshold.

GEO Mission Performance Analysis

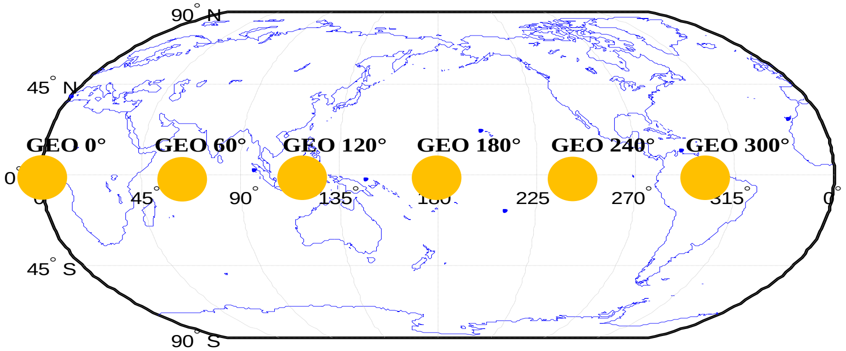
GEO User Visibility of 4 satellite and Maximum Outage Duration													
Receiver threshold		-173dBW						-178dBW					
GEO USER		0°	60°	120°	180	240	300°	0°	60°	120°	180	240	300°
B1I	Visibility/%	28.7	20.4	20.1	19.5	52.2	60.7	94.2	83.6	84.6	84.3	98.0	97.8
	MOD/min	211	437	267	399	156	121	51	95	64	81	25	28
B1C	Visibility/%	23.4	19.3	19.4	18.6	21.9	42.3	90.6	82.5	83.7	83.5	92.2	89.5
	MOD/min	212	437	267	399	219	179	51	95	64	81	50	66
B2a	Visibility/%	75.8	72.5	71.8	70.8	76.5	75.8	99.9	96.9	96.7	96.9	99.5	99.9
	MOD/min	93	92	89	112	110	76	4	36	23	65	10	8
B2b	Visibility/%	63.2	64.4	64.1	62.4	66.2	93.2	99.5	92.8	91.5	92.8	98.6	99.4
	MOD/min	114	116	108	118	111	85	14	61	44	90	29	26
B3I	Visibility/%	61.1	33.0	31.5	29.7	62.8	99.6	98.9	72.8	74.2	75.1	99.0	100
	MOD/min	114	214	200	203	115	10	20	135	98	103	17	0
Receiver threshold		-183dBW						-188 dBW					
GEO USER		0°	60°	120°	180	240	300°	0°	60°	120°	180	240	300°
B1I	Visibility/%	100	100	99.9	99.9	100	100	100	100	100	100	100	100
	MOD/min	0	0	3	2	0	0	0	0	0	0	0	0
B1C	Visibility/%	100	100	99.9	99.9	99.9	99.9	100	100	100	100	100	100
	MOD/min	0	0	4	3	1	2	0	0	0	0	0	0
B2a	Visibility/%	100	100	100	100	100	100	100	100	100	100	100	100
	MOD/min	0	0	0	0	0	0	0	0	0	0	0	0
B2b	Visibility/%	100	100	100	100	100	100	100	100	100	100	100	100
	MOD/min	0	0	0	0	0	0	0	0	0	0	0	0
B3I	Visibility/%	100	98.5	99.0	99.9	100	100	100	100	100	100	100	100
	MOD/min	0	20	18	13	0	0	0	0	0	0	0	0



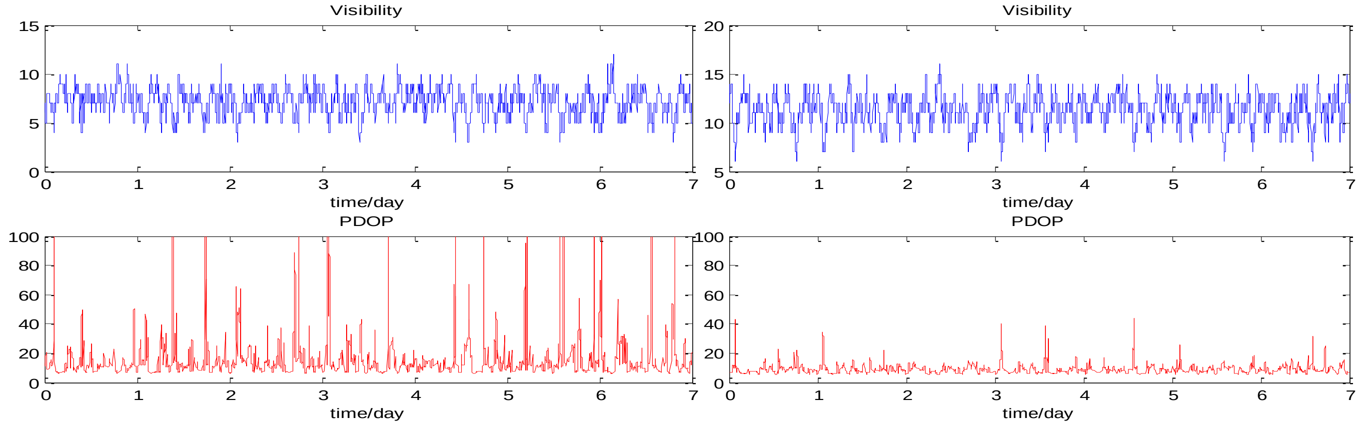
- 4 signals at B3 can be continuously received with receiver threshold -178dBW at 300° longitude region. 4 signals visibility is better than 98% with receiver threshold -183dBW .
- 4 signal visibility simulation result is 1.7%~57% based on SSV booklet template (minimum received power and reference 0ff-boresight angle) and 82.5%~100% based on test gain data both with around -178dBW receiver threshold.

GEO Mission Performance Analysis

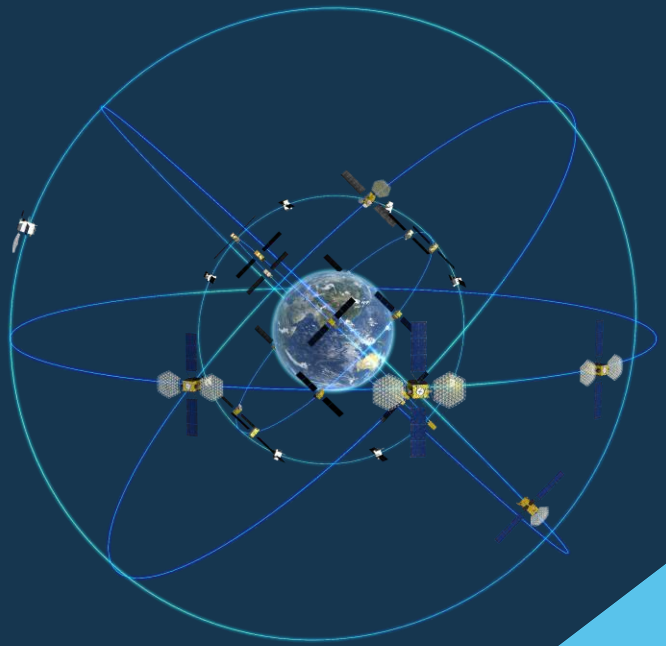
GEO USER PDOP													
Receiver threshold		-184dBW						-188 dBW					
GEO USER		0°	60°	120°	180	240	300°	0°	60°	120°	180	240	300°
B1I	PDOP mean	6.3	12.7	11.4	9.8	5.7	7.9	5.2	4.9	8.5	6.4	4.7	6.8
	PDOP 95%	8.8	18.5	18.5	17.4	7.1	11.5	6.4	9.6	12.3	12.1	5.6	9.8
B1C	PDOP mean	7.0	11.9	11.6	10.3	7.2	9.3	5.8	7.5	8.5	7.3	6.2	7.8
	PDOP 95%	10.8	18.8	18.7	17.8	11.3	14.4	7.8	12.2	12.3	12.3	9.1	11.9
B2a	PDOP mean	5.7	5.1	9.1	4.5	6.1	8.1	5.2	3.7	7.4	3.5	5.6	6.8
	PDOP 95%	7.1	9.3	13.7	6.1	7.8	11.7	6.2	4.9	9.6	4.7	6.6	8.8
B2b	PDOP mean	5.9	6.1	10.1	5.0	6.4	8.8	5.3	4.0	7.7	3.7	5.7	7.0
	PDOP 95%	7.5	12.2	18.2	7.9	8.3	13.5	6.3	5.3	10.4	4.9	6.9	9.3
B3I	PDOP mean	6.0	/	/	6.3	5.5	8.8	5.3	5.6	8.7	4.5	4.8	6.9
	PDOP 95%	7.8	27.4	31.7	10.2	7.3	13.2	6.3	10.4	12.3	6.2	5.8	9.1



- GEO users mean PDOP is better than 15 with receiver threshold -183dBW, better than 10 with receiver threshold -188dBW
- With the same receiver threshold, GEO user located at longitude 300° region expect better PNT performance than GEO user located at longitude 120° region .



Visibility and PDOP of GEO mission at 120°(left) and 300° (right)



BDS/GNSS Space Applications

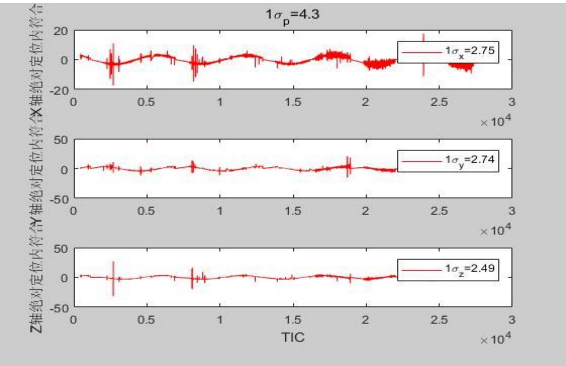
- typical space mission profiles

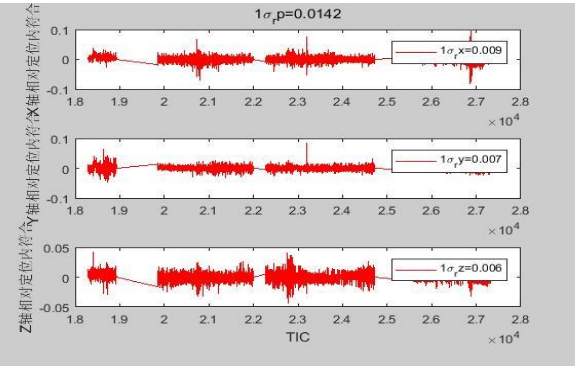
04

BDS/GNSS Space Applications

China Space Station Mission
Launch Date: : 2021-4-29 (core module)
Mission Description: Manned space station with core module and following 7 missions
Mission Orbit: LEO
GNSS Mission Need:
support the assembly, construction and on-orbit operation of the space station by providing real time PVT information and relative measurement of the core module (target terminal) and the visiting spacecraft during rendezvous and docking.
GNSS Signals Used: BDS B1 , GPS L1
On-Orbit Results:
10 days of in-orbit testing shows:
(1) positioning accuracy better than 5m
(2) relative measurement positioning accuracy better than 1.5cm

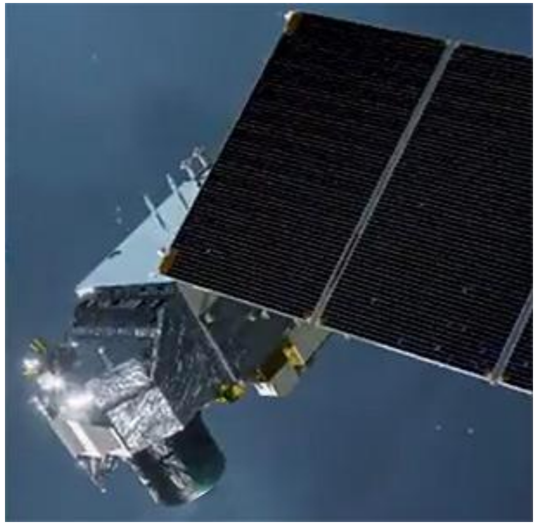
The Tianhe space station core module

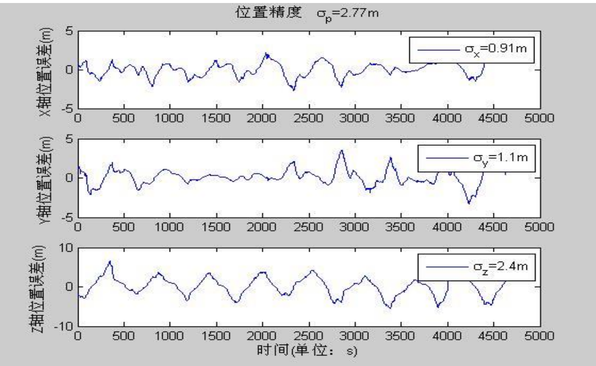


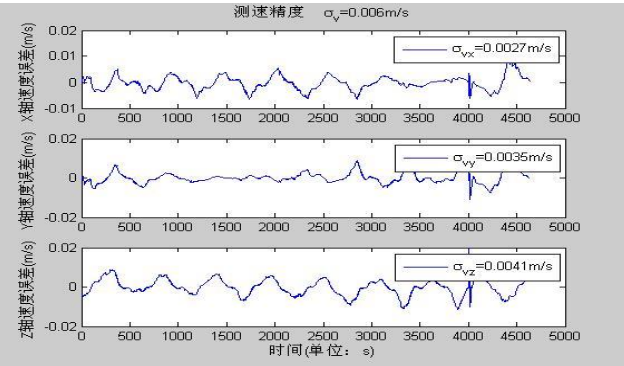


BDS/GNSS Space Applications

Atmospheric Environment Monitoring Satellite (Daqi-1)
Launch Date: : 2022-4-16
Mission Description: Environments, gaseous pollutants, fine particulate matter and CO2 detection
Mission Orbit: LEO
GNSS Mission Need:
Receive BDS and GPS dual frequency signals and provide real-time PVT , orbit determination result , time and PPS
GNSS Signals Used: BDS B1&B3、GPS L1&L2
On-Orbit Results:
positioning accuracy 2.77m, velocity accuracy 6mm/s

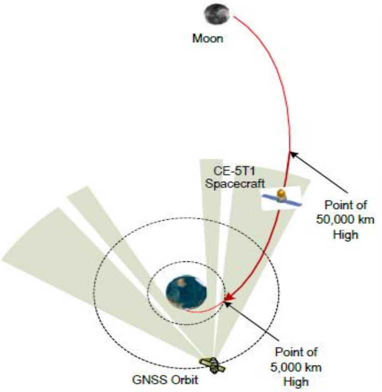


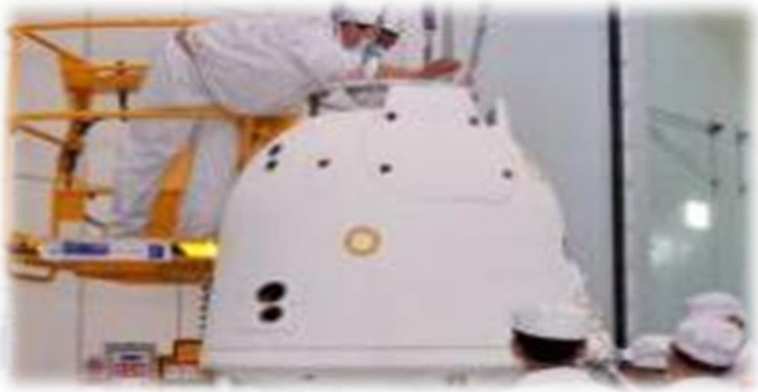




BDS/GNSS Space Applications

CHANG'E 5-T1
Launch Date: 2014-10-25
Re-entry date: 2014-11-1
Mission Description: Lunar sampling and return mission flight test
Mission Orbit: Moon-earth transfer, CLO
GNSS Mission Need:
Provide PVT information when the return module conducted atmospheric re-entry at 50,000 to 5000km altitude.
GNSS Signals Used: GPS、GLONASS
On-Orbit Results:
Time of first fixed at 61,808km.
positioning accuracy better than 100m, velocity accuracy better than 0.1m/s





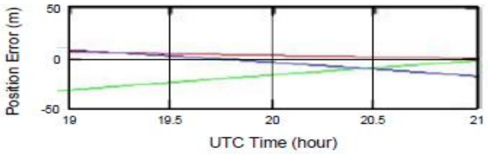
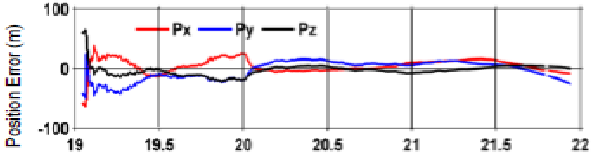
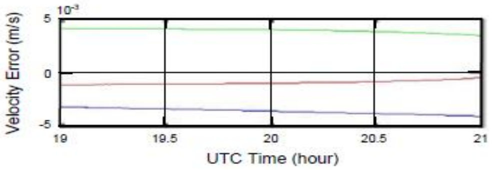
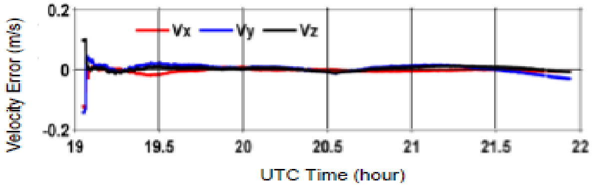


Fig.11 Position error in external accord assessment

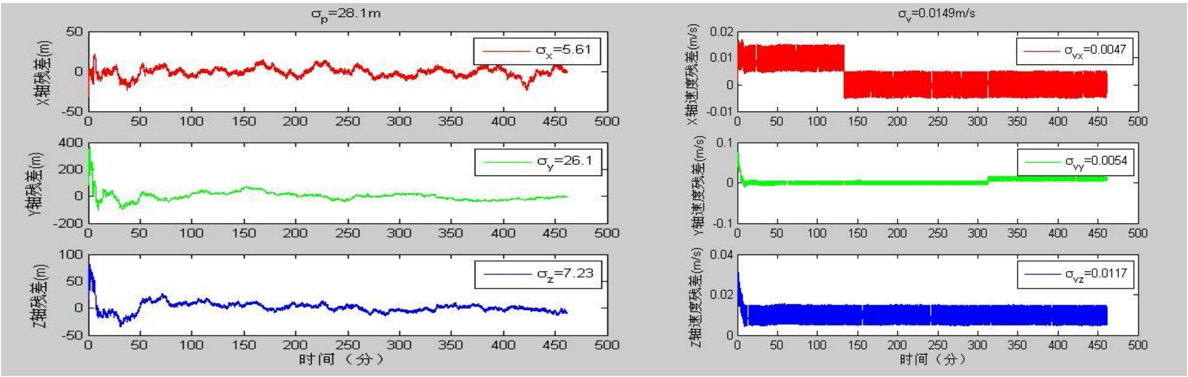


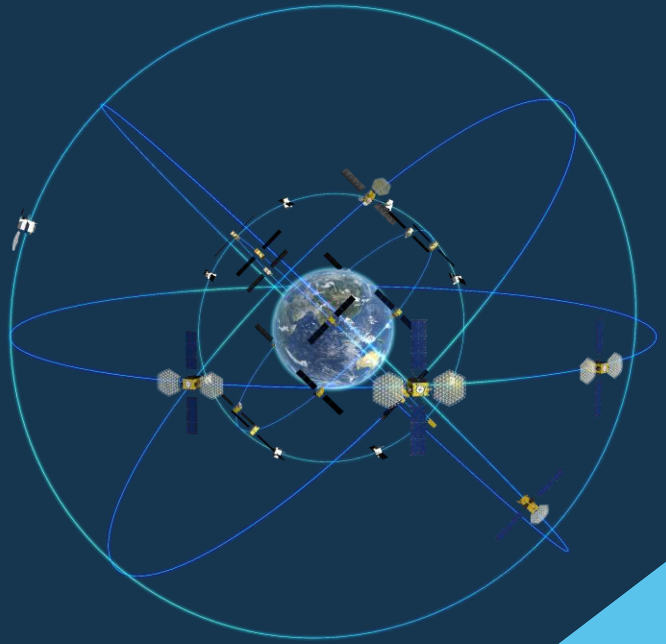




BDS/GNSS Space Applications

Land Exploration-4 01(L-SAR4 01) Satellite
Launch Date: : 2023-8-13
Mission Description: High earth orbit SAR for disaster prevention and reduction, resource prospecting and exploration , water conservancy, meteorology, agriculture, environmental protection and forestry.
Mission Orbit: IGSO
GNSS Mission Need:
support SAR payload mission by providing on-board orbit determination and POD measurements.
GNSS Signals Used: BDS B1 , GPS L1
On-Orbit Results:
positioning accuracy better than 30m, velocity accuracy better than 0.02m/s





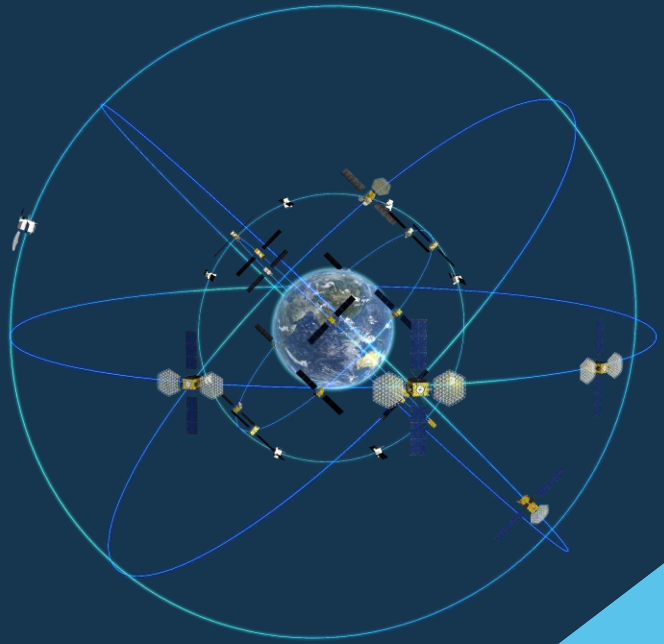
05 Conclusions and Future Visions

Conclusions

- **BDS supports interoperable GNSS SSV** through constellation, signals, time and coordination systems.
- In response to ICG recommendations, **BDS is carrying out analysis of all constellation satellites pre-flight antenna pattern test data (including side-lobes)**
  - the in-orbit antenna gain pattern test results indicates ground test data well reflected the actual performance in-orbit.
  - For users flying below 3000km, the antenna gain min-model can be adopted for mission analysis
- GEO users simulation results shows, with the use of antenna pattern data ,signal visibility can be improved significantly compared to use only minimum received power and reference off-boresight angle data from the SSV Booklet, showing the importance of antenna pattern data with side-lobe for GEO and higher altitude mission analysis .
- four typical BDS/GNSS space application cases are given, covering various orbit types from LEO to moon-earth transfer.

Future Visions

- **BDS will continue to improve it constellation to ensure support to interoperable GNSS SSV.**
- On the basis of maintaining existing space service capabilities, future generation of BDS should further enhance service performance in space service volume and cis-lunar space.
- In the next decade, there will be a new upsurge in space. Tens of thousands of space missions, including the space station, lunar and deep space exploration and LEO networks, will be carried out. BDS will work with all GNSSs in building the interoperable GNSS SSV and contribute to cis-lunar PNT capabilities.



Thank you