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Disposal Status and Operation Safety of GNSS/RNSS Satellites

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13th Meeting of the International Committee on Global Navigation Satellite System(ICG-13)
November 4-9, 2018,Xi’an,China

Study Progress Related to the Issue of Space Debris

- **May 2018, 8th Meeting on WG C&I of CRSNC**

  Both parties agree to jointly propose a recommendation related to GNSS satellites End-of-life disposal safety under the framework of ICG.

- **June 2018, ICG WG-S Intersessional Meeting**

  BDS has proposed a recommendation related to "GNSS/RNSS MEO and IGSO satellites EOL Disposal Strategy and Operation".

- **June 2018, 36th IADC WG4**

  China has introduced the situation that the orbits of more than 40 GPS retired spacraft are very close to the operational orbit of BDS MEO.

- **July 2018, ICG WG-S Intersessional Meeting**

  The recommendation has been proposed related to "IADC MEO/IGSO Study".

Contents

MEO Space Debris Status

GNSS/RNSS Satellites in Orbit

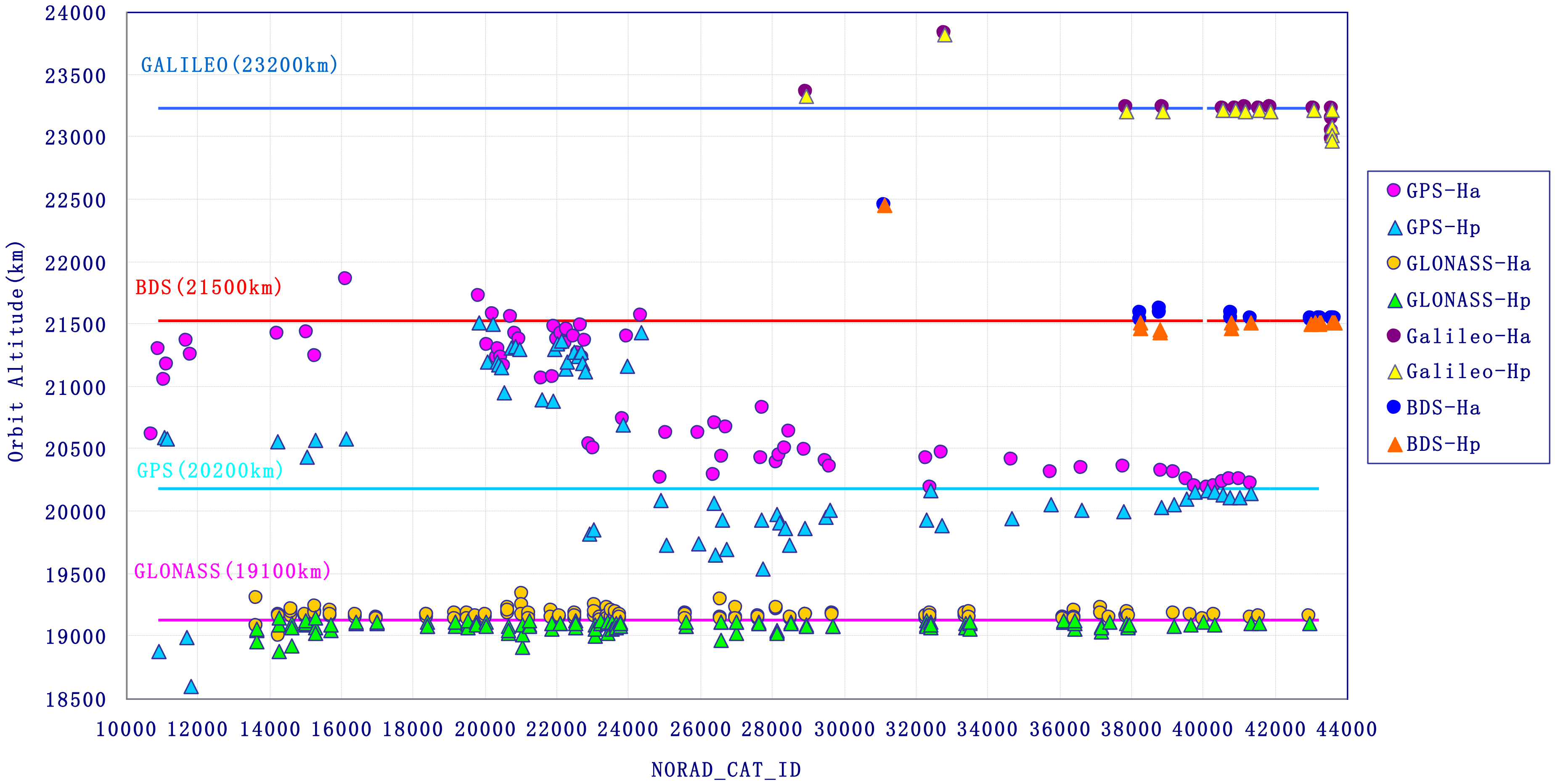
Constellation	Nation/Area	Number of SVs *			
		GEO	IGSO	MEO	Total
GPS	USA	0	0	70	70
GLONASS	Russia	0	0	132	132
Galileo	Europe	0	0	28	28
BDS	China	11	9	24	44
QZSS	Japan	1	3	0	4
NAVIC	India	3	6	0	9

Data collected from www.space-track.org by the end of Oct. 2018

There are more than 274 GNSS satellites stay in MEO orbit, 33 RNSS satellites in GEO and IGSO orbit.

GNSS Satellites Orbit Altitude

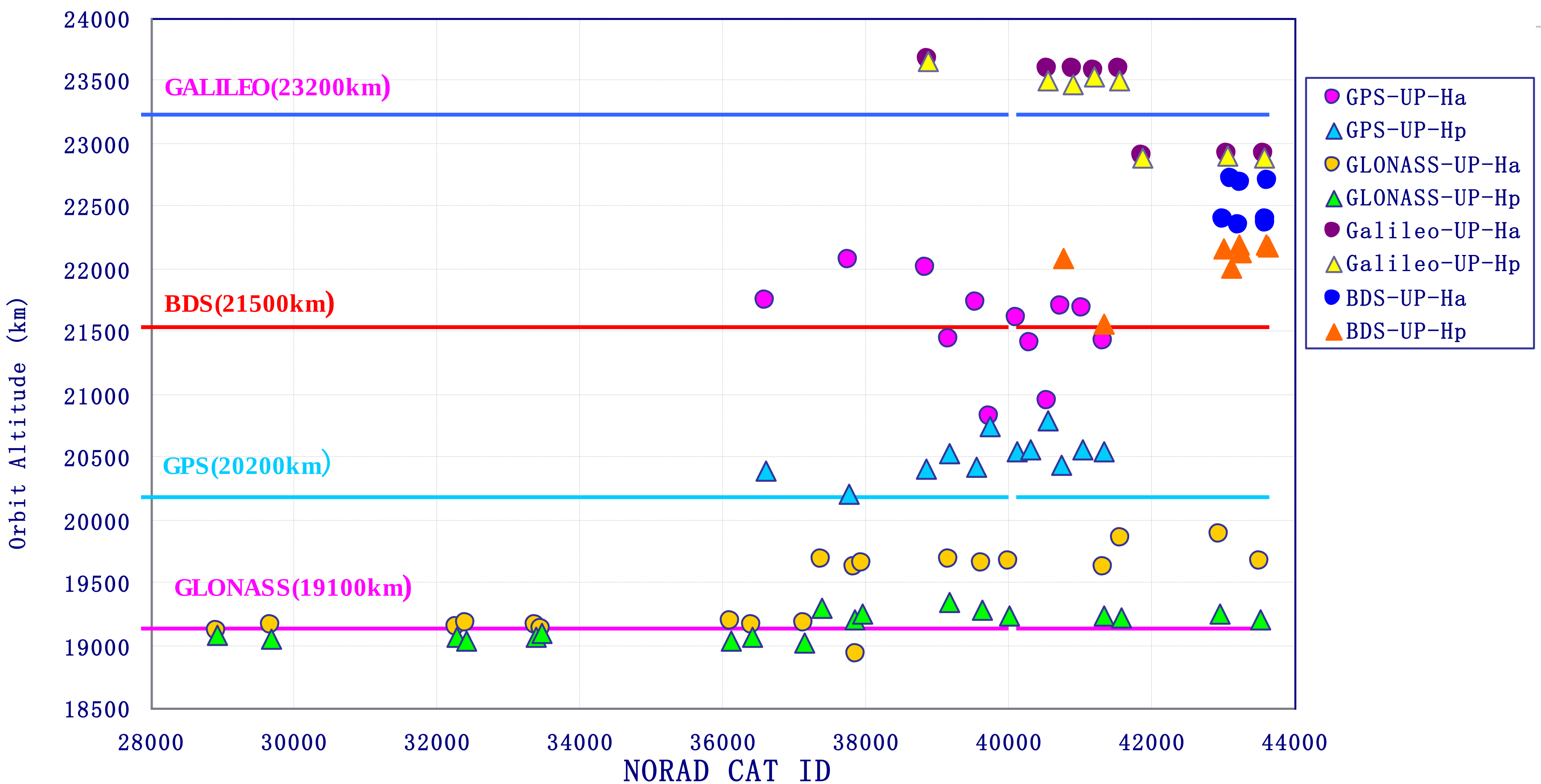
ISSE



The post-mission satellites of GPS,Galileo and BDS have increase in orbit altitude, while Glonass satellites at the end of life stay in operational orbit.

Data collected from www.space-track.org by the end of Oct. 2018

GNSS Upper-stage Orbit Altitude



Most of the Upper-stage of GPS have crossed the BDS operational orbit, while two Upper-stages of Galileo is very close to the Upper-stage of BDS.Accordingly, we should also pay more attention to the safety of the GNSS Upper-stage.

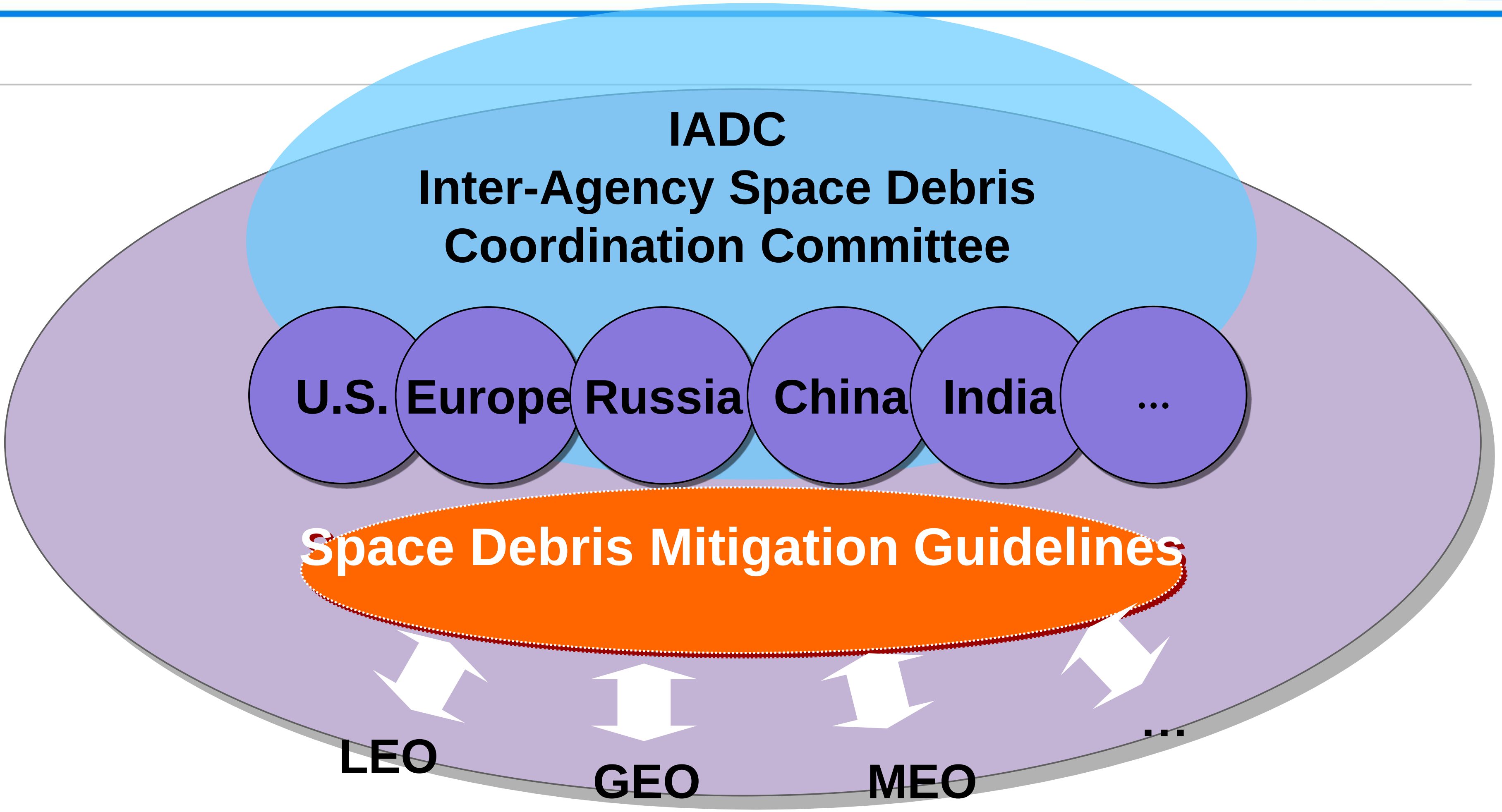
Data collected from www.space-track.org by the end of Oct. 2018

GNSS Spacecraft Disposal Orbit

Constellation	De-orbited Satellites		De-orbited Upper-stage	
	Number	△Ha (Increase in apogee altitude)	Number	△Ha (Increase in apogee altitude) /km
GPS	36	+350~+1700	12	+600~+1900
GLONASS	0*	0*	20	0~+700
Galileo	2	+120~+600	9	+350~+2900 -300
BDS	4(3GEO/1 MEO)	GEO:+140~+300 MEO:+900	10	+200~+6000
QZSS	—	—	—	—
NAVIC	—	—	—	—

The increase in apogee altitude of GPS satellite post-mission is between 350km and 1700km. As there will be more BDS satellites deployed in MEO orbit, and it would have a higher risk of collision.

International Guidelines and Execution of BDS



Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines was established since 2002 which describe efficient practice for limiting the generation of space debris.Members of the IADC includes national agencies and official organizations in China, the U.S., Europe, Russia, India and etc.

GEO Disposal Requirements

The requirements for GEO satellites post misssion disposal of IADC:

- A minimum increase in perigee altitude of: 235km+1000CR·A/m
- An eccentricity less than 0.003,or the ecccentricity vector should be pointed such that $\Omega+\omega\approx 90$ or 270 with the magnitude of eccentricity set to insure the perigee not drop into GEO protection.

Requirements from IADC document 'IADC Space Debris Guidelines'

MEO Disposal Requirements(TBC)

Disposal Action	MEO Navigation Satellite Orbit
25-year decay	Not recommended due to large ΔV required
Disposal orbit	TBC: 1.Minimum long term perigee of 2000km,apogee below MEO 2. Perigee **500km above** MEO or nearby operational region and **e≤0.003**;RAAN and argument of perigee selected for stability
Direct Reentry	Not recommended due to large ΔV required

Requirements from IADC document 'Support to the IADC Space Debris Guidelines'

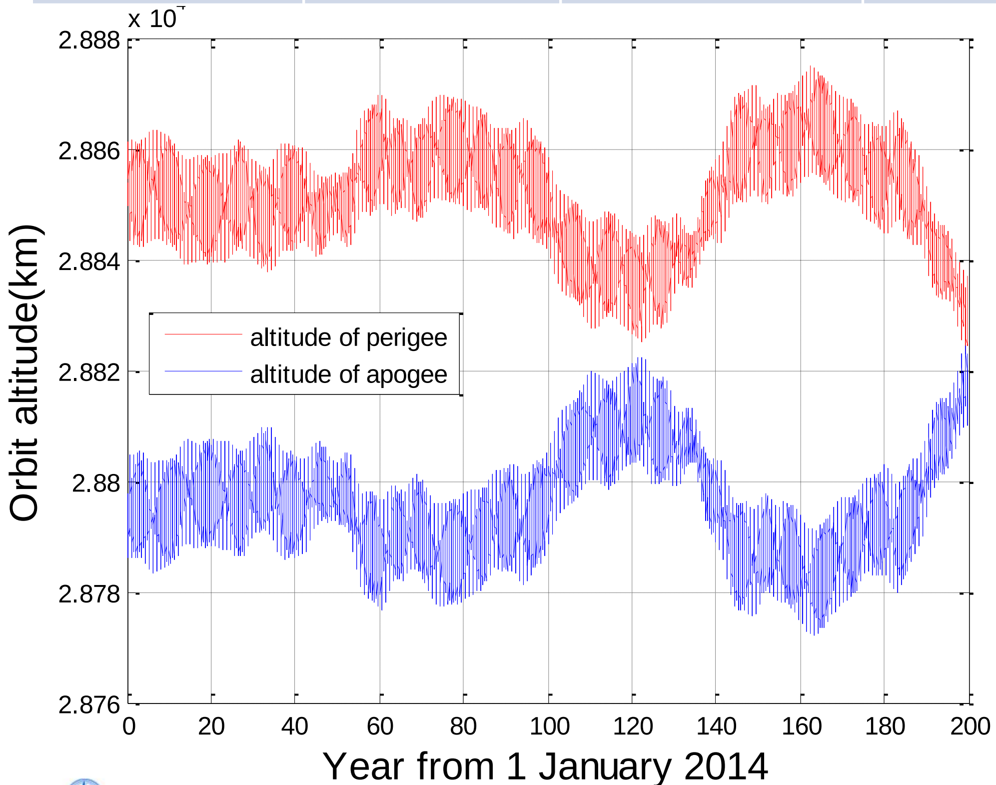
Disposal of 3 BDS GEO Satellites

Disposal Satellite	Disposal Date	Increase in Perigee Altitude/km	Meet the Requirement of IADC ?
GEO1	Nov. 11st ~12nd , 2011	328	Y
GEO2	Nov. 23rd , 2011	309	Y
GEO3	Jan. 13rd , 2013	140	N

EOL disposal of 3 BDS GEO satellites were carried out since 2011.The perigee altitude of the first 2 satellites met the requirement of IADC, and the perigee of the 3rd satellite was increased by 140km due to the limitation of propellant.

Disposal of BDS MEO Satellite

Disposal Satellite	Launch Year	Disposal Date	Increase in Orbit Altitude/km	Eccentricity	Meet the Requirement of IADC ?
MEO1	Apr.2007	Aug. 2013	920	<0.001	Y



200-years Disposal Orbit Evolution of the First BDS MEO Satellite indicates that there will be no collision with own satellites and nearby constellations.

Long Term Evolution of BDS MEO & IGSO

Stability of MEO Disposal orbit

Equation in eccentricity due to third body perturbation:

$$de/dt = -(15/8)e\gamma s[C_1 \sin 2(\omega - \Delta\Omega) + C_2 \sin(2\omega - \Delta\Omega) + C_3 \sin 2\omega + C_4 \sin(2\omega + \Delta\Omega) + C_5 \sin 2(\omega + \Delta\Omega)]$$

* Function is derived from C.C.Chao

e=eccentricity $\gamma = n_3^2 R_m / n$ $s = (1 - e^2)^{1/2}$

n=mean motion of the orbit;

n_3=mean motion of the third body;

R_m=mass ratio，=1for solar perturbation，=1/82.3 for lunar perturbation;

ω=argument of perigee of the orbit;

ΔΩ=RAAN of satellite – RAAN of the third body

$$C_1 = 1/2 \sin^2 i_3 (\cos i + 1/2 \sin^2 i - 1)$$

$$C_2 = 1/2 \sin i \sin 2i_3 (\cos i - 1)$$

$$C_3 = \sin^2 i (3/2 \sin^2 i_3 - 1)$$

$$C_4 = 1/2 \sin i \sin 2i_3 (\cos i + 1)$$

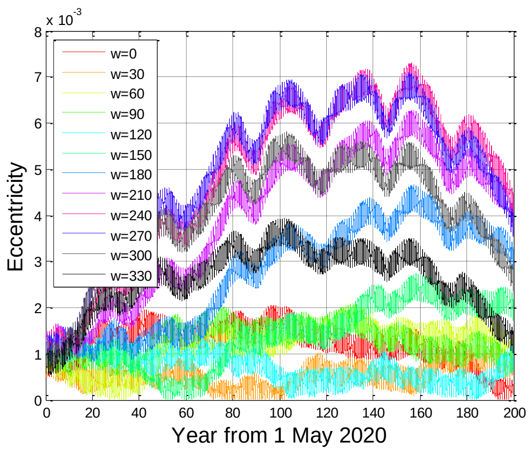
$$C_5 = 1/2 \sin^2 i_3 (1/2 \sin^2 i - \cos i - 1)$$

Stability of MEO Disposal orbit

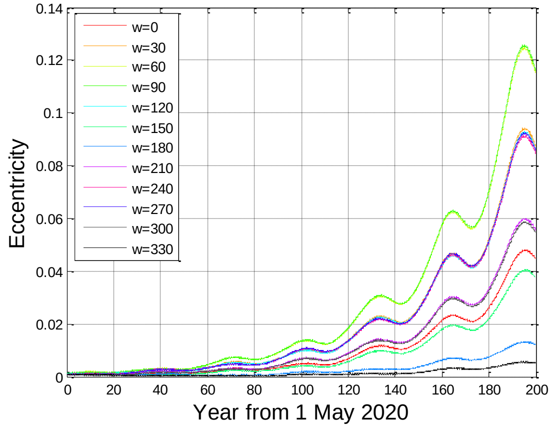
Constellation	Orbit Altitude (km)	Inclination(deg)	Ω_{J2} (deg/year)	ω_{J2} (deg/year)	Variation rate of angle in sine function				
					$\omega-\Omega$	$2\omega-\Omega$	ω	$2\omega+\Omega$	$\omega+\Omega$
GLONASS	19100	64	-12.5	-0.56	11.94	11.38	**-0.56**	-13.62	-13.06
GPS	20180	55	-14.15	7.99	22.14	30.13	7.99	**1.83**	-6.16
BDS	21528	55	-11.9	6.72	18.62	25.34	6.72	**1.54**	-5.18
GALILEO	23222	55	-9.68	5.47	15.15	20.62	5.47	**1.26**	-4.21

For MEO satellites of GPS,BDS and Galileo, the change rate of $2\omega+\Omega$ is slow, the resonances effect may drive the eccentricity to a very large value if the initial eccentricity is not small and the angle is close to 270 deg.

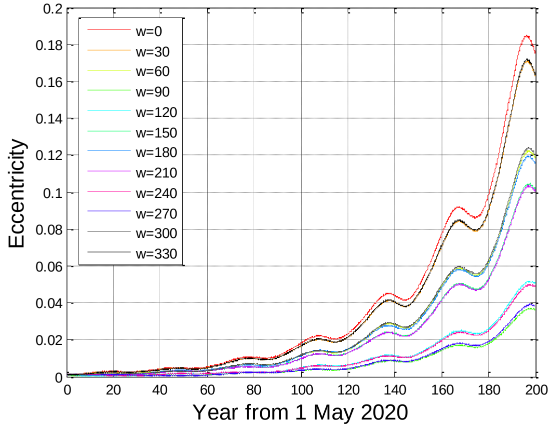
BDS MEO Evolution with Different Initial Argument of Perigee



Ω=18° ,e=0.001,ω=0~360°



Ω=138° ,e=0.001,ω=0~360°



Ω=258° ,e=0.001,ω=0~360°

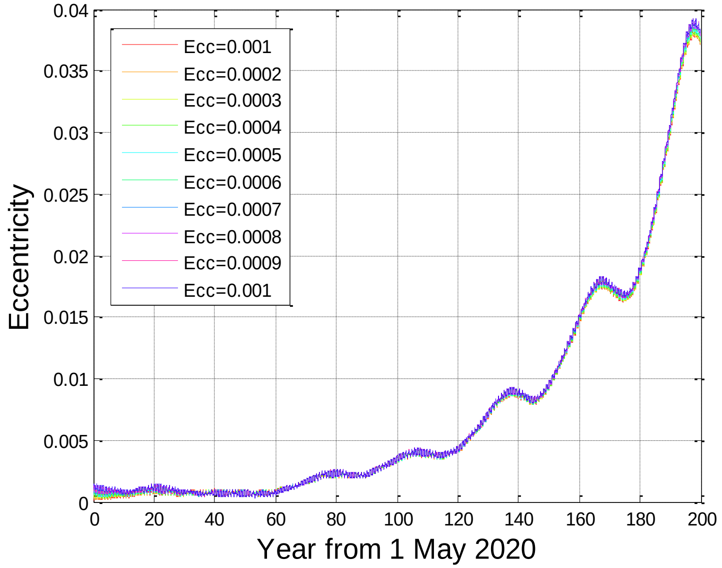
Recommendations for initial disposal orbit elements of BDS MEO satellites in the 1st plane: $\triangle a_1 \geq +300$km, $e_1 \leq 0.001$, $\omega_1 \neq 240 \sim 270°$

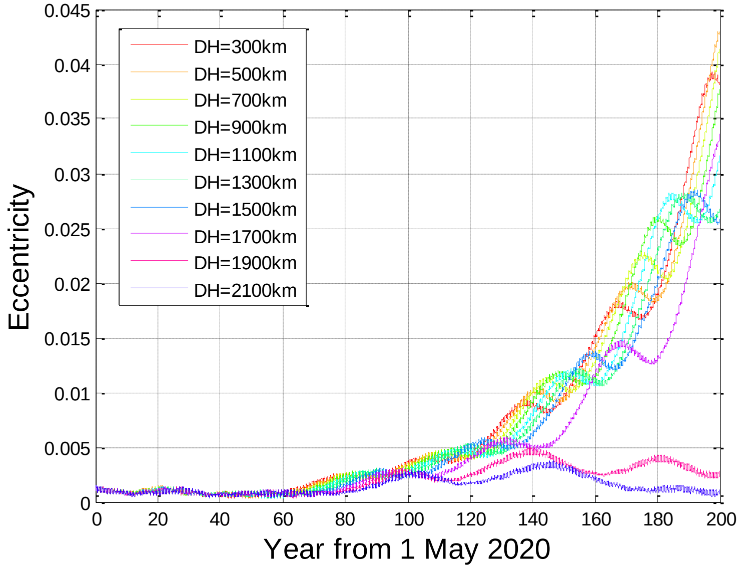
Recommendations for initial disposal orbit elements of BDS MEO satellites in the 2nd plane:

$\triangle a_2 \geq +300$km, $e_2 \leq 0.001$, $\omega_2 = 330°$

BDS MEO satellites in the 3rd orbit plane can **not** realize long-term post mission stable operation within 200 years, by setting proper initial value of **argument of perigee.**

BDS MEO with Different Initial Eccentricity and Altitude in the 3rd Plane





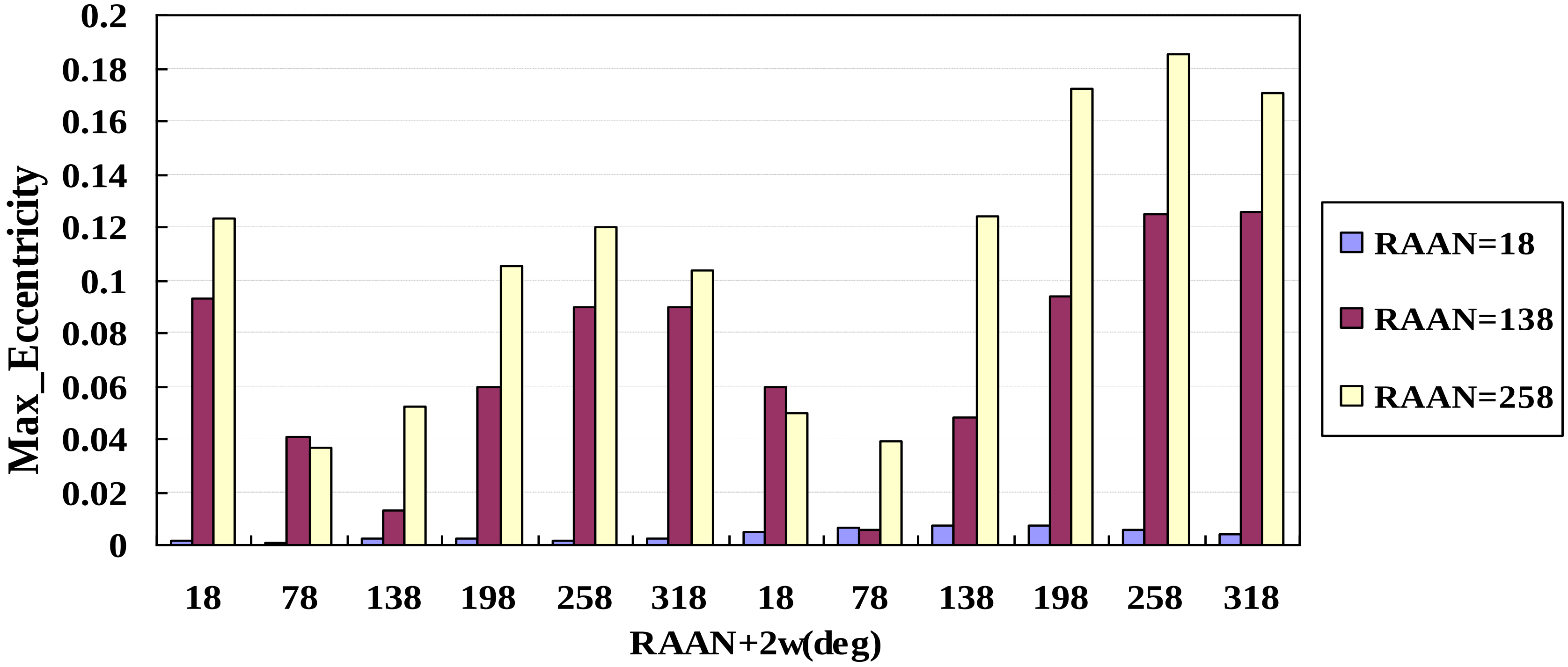
Ω=258°, e=0.0001~0.001, ω=270°

Ω=258°, e=0.001, ω=270°, △a=300~2100km

With no propellant limitation, recommendations for initial orbit elements of BDS MEO satellites in the3rd orbit are as following:

$\triangle a_3 >> 300km, e_3 \leq 0.001, \omega_3 \approx 270^\circ$

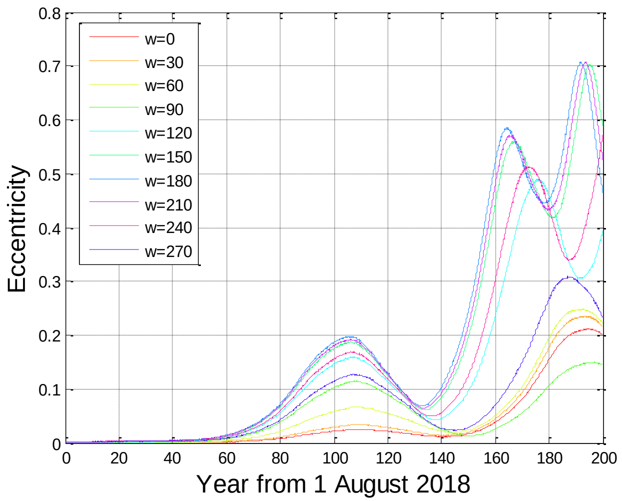
Stability of BDS MEO Disposal orbit



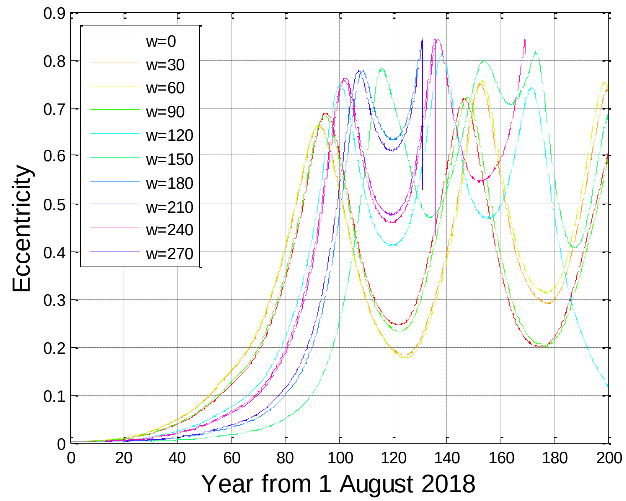
2ω+Ω=200~320° high eccentricity growth, should be avoided.

2ω+Ω=80~140° lower eccentricity growth, recommended for MEO satellite initial disposal orbit elements

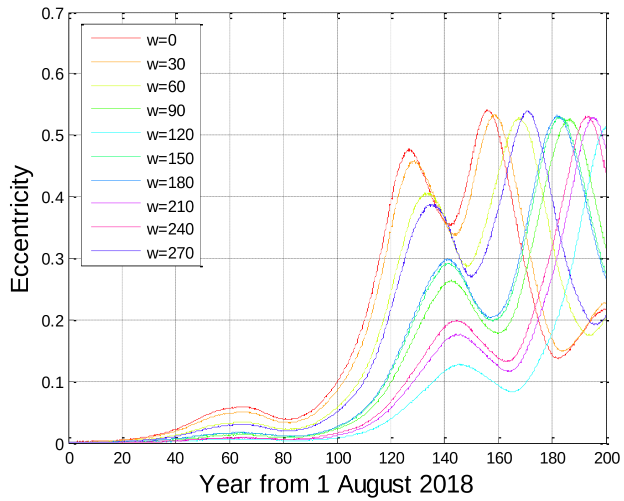
BDS IGSO Evolution with Different Initial Argument of Perigee



$\Omega_1=69°\ ,e_1=0.001,\omega_1=0\sim360°$



$\Omega_2=189°\ ,e_2=0.001,\omega_2=0\sim360°$



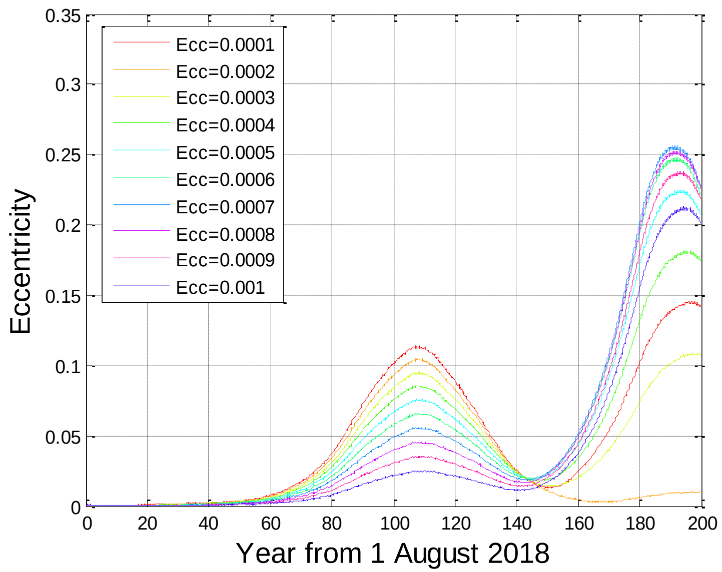
$\Omega_3=309°\ ,e_3=0.001,\omega_3=0\sim360°$

ω_1=0 or 90° to make the max eccentricity less than 0.2 in 200 years

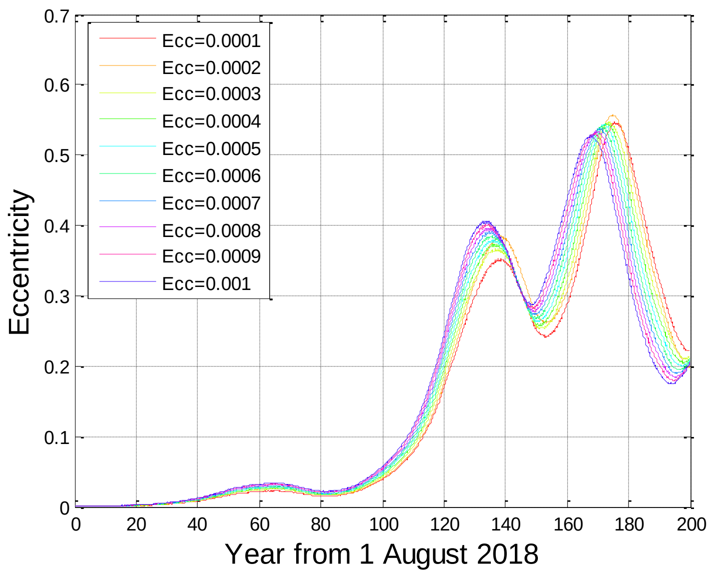
ω2=120 or 330° to make the reentry occurs in 130 years

ω_3=60 or 270° to make the max eccentricity less than 0.2 in 200 years

BDS IGSO with Different Initial Eccentricity in the 1st and 3rd Plane



$\Omega_1=69°$,$e_1=0.0001\sim0.001$,$\omega_1=0°$

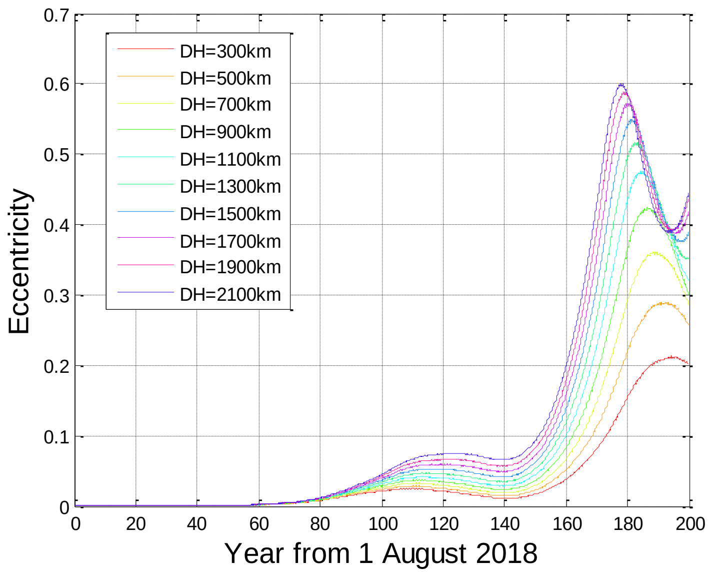


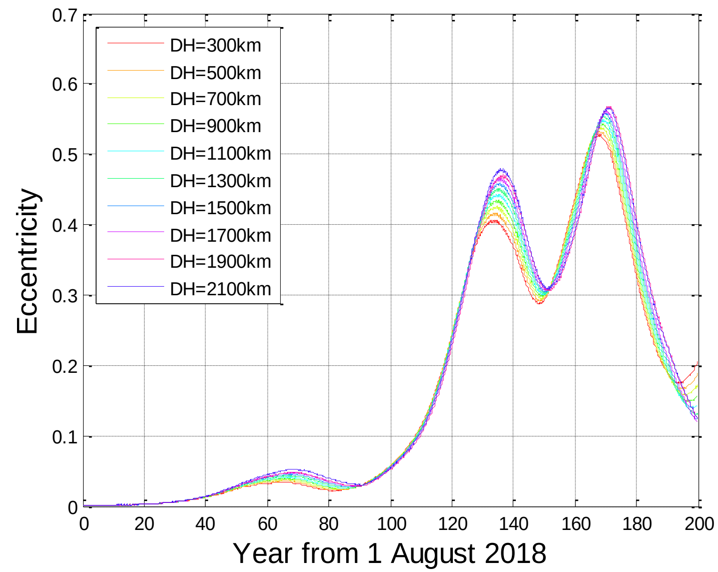
$\Omega_3=309°$,$e_3=0.0001\sim0.001$,$\omega_3=60°$

e=0.0002 to make the max eccentricity less than 0.007 in 180 years

The eccentricity changes significantly no matter how to choose the initial value of eccentricity, the max value is near 0.055 in 200 years .

BDS IGSO with Different Initial Orbit Altitude in the 1st and 3rd Plane





$\Omega_1=69°$, $e_1=0.001$, $\omega_1=0°$, $\Delta a_1= 300\sim 2100$ km

Orbit altitude the higher, the eccentricity greater.

$\Delta a_1=300$km to make the max eccentricity less than 0.2 in 180 years

$\Omega_3=309°$, $e_3=0.001$, $\omega_3=60°$, $\Delta a_3= 300\sim 2100$ km

The eccentricity changes significantly no matter how to choose the initial value of altitude, the max value is near 0.055 in 200 years .

Recommendations for BDS IGSO Disposal Orbit Elements

To keep the disposal orbit stable as long as possible, recommendations for initial disposal orbit elements of BDS IGSO satellites are as following:

Orbit Plane	Increase in orbit altitude/km	Eccentricity	Argument of perigee/deg	Max Eccentricity in 200 years
1st	300	0.0002	0	No intersection with GEO in 180 years
2nd	300	0.001	120 or 330	Reentry occurs in 130 years
3rd	300	0.001	120	No intersection with GEO in 100 years

Disposal Safety Restrictions for BDS

Disposal Safety Restrictions for BDS MEO satellites

To protect nearby constellation and follow-up MEO satellites operational safety, restrictions for EOL disposal of BDS MEO satellites are suggested as follows:

- Based on research of NASA and other organizations, disposal for post mission MEO satellites should ensure no collision risk with operational orbit and nearby constellations within **200 years**.
- Considering propellant limitation and isolation from nearby MEO satellite orbits, the increase in altitude at the end of re-orbiting maneuver of MEO satellites should be **more than 300km**.
- The variation of altitude after satellite re-orbit should be minimized over 200 years, and the variation of orbit altitude should be **less than 200 km within 200 years**.

Disposal Safety Restrictions for BDS IGSO satellites

To protect geosynchronous orbit and follow-up IGSO satellites operational safety, restrictions for EOL disposal of BDS IGSO satellites are suggested as follows:

- Disposal orbits of IGSO satellites should not cross geosynchronous orbit within 200 years.
- The increase in altitude at the end of re-orbiting maneuver of IGSO satellites should be more than 300km to avoid geosynchronous protect region.
- Altitude difference of re-orbiting IGSO satellites and follow-up IGSO satellites should be more than 300km to avoid interference with other space vehicle in the same orbit.

Problems and Recommendations

Problems

- There are **no final guidelines** for navigation system MEO satellites post-mission disposal from international organizations, while conclusions from study on stability of satellites disposal orbit and safety restrictions are not exactly the same.

- The maximum increase in apogee altitude of GPS satellite and upper-stage post-mission is **more than 1900km**. There are more than **40** GPS EOL spacecraft that have been nearby or even intersected the BDS operating orbit.

- As there will be more BDS MEO satellites deployed in the future, there will be higher collision risk and the collision probability after disposal of GNSS/RNSS satellites with own satellites and nearby constellation should be studied.

Issue Title: GNSS/RNSS MEO and IGSO satellites End-of-life Disposal Strategy and Operation

Background/Brief Description of the Issue:

There are guidelines for post-mission disposal for GEO and LEO region, however, there are no specific guidelines for GNSS/RNSS MEO and IGSO satellites post-mission disposal from international organizations.

Discussion/Analyses:

In the past few meetings of WG-S, reports on GNSS satellites disposal orbit for space debris mitigation were presented. Observation shows some GNSS retired spacecrafts are very likely close to other GNSS operational orbit. For system orbit safety, information on orbital debris mitigation plans need to exchanged on a regular basis, and it requires the service providers to develop guidelines for GNSS MEO and IGSO satellite disposal together.

Recommendation of Committee Action:

WG-S will establish a coordination mechanism for GNSS satellites post-mission disposal to raise the attention to MEO and IGSO space debris mitigation and to establish the GNSS/RNSS space debris mitigation guidelines along with IADC. System Providers are invited to exchange information on GNSS/RNSS satellites post-mission disposal plans and implementation in WG-S.

Thank you for your attention！