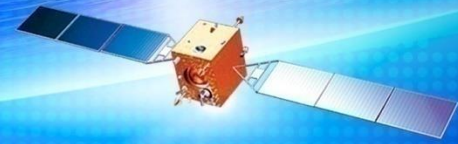
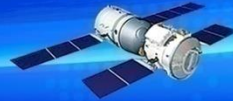
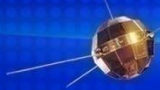




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# Disposal Status and Operation Safety of GNSS/RNSS Satellites

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13<sup>th</sup> 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, 8<sup>th</sup> 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, 36<sup>th</sup> IADC WG4**

China has introduced the situation that the orbits of more than 40 GPS retired spacecraft 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

**1** MEO Space Debris Status

**2** International Guidelines and Execution of BDS

**3** Long Term Evolution of BDS MEO & IGSO

**4** Disposal Safety Restrictions for BDS

**5** Problems and Recommendations

# MEO Space Debris Status

# GNSS/RNSS Satellites in Orbit

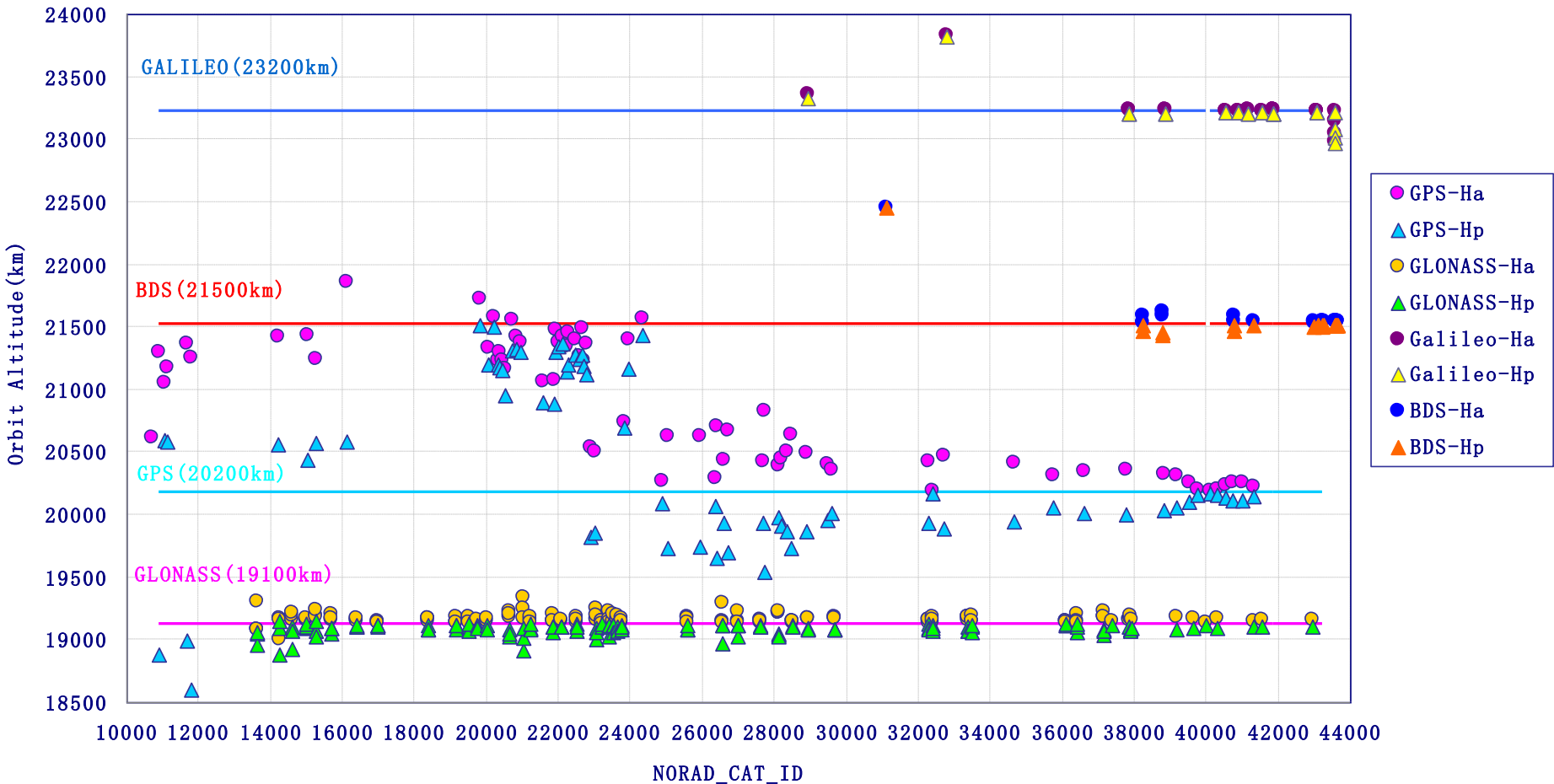


Constellation	Nation/Area	Number of SVs *			
		GEO	IGSO	MEO	Total
GPS	USA	0	0	70	70
GLONASS	Russia	0	0	132	132
Galileo	Europe	0	0	28	28
BDS	China	11	9	24	44
QZSS	Japan	1	3	0	4
NAVIC	India	3	6	0	9

Data collected from [www.space-track.org](http://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.**

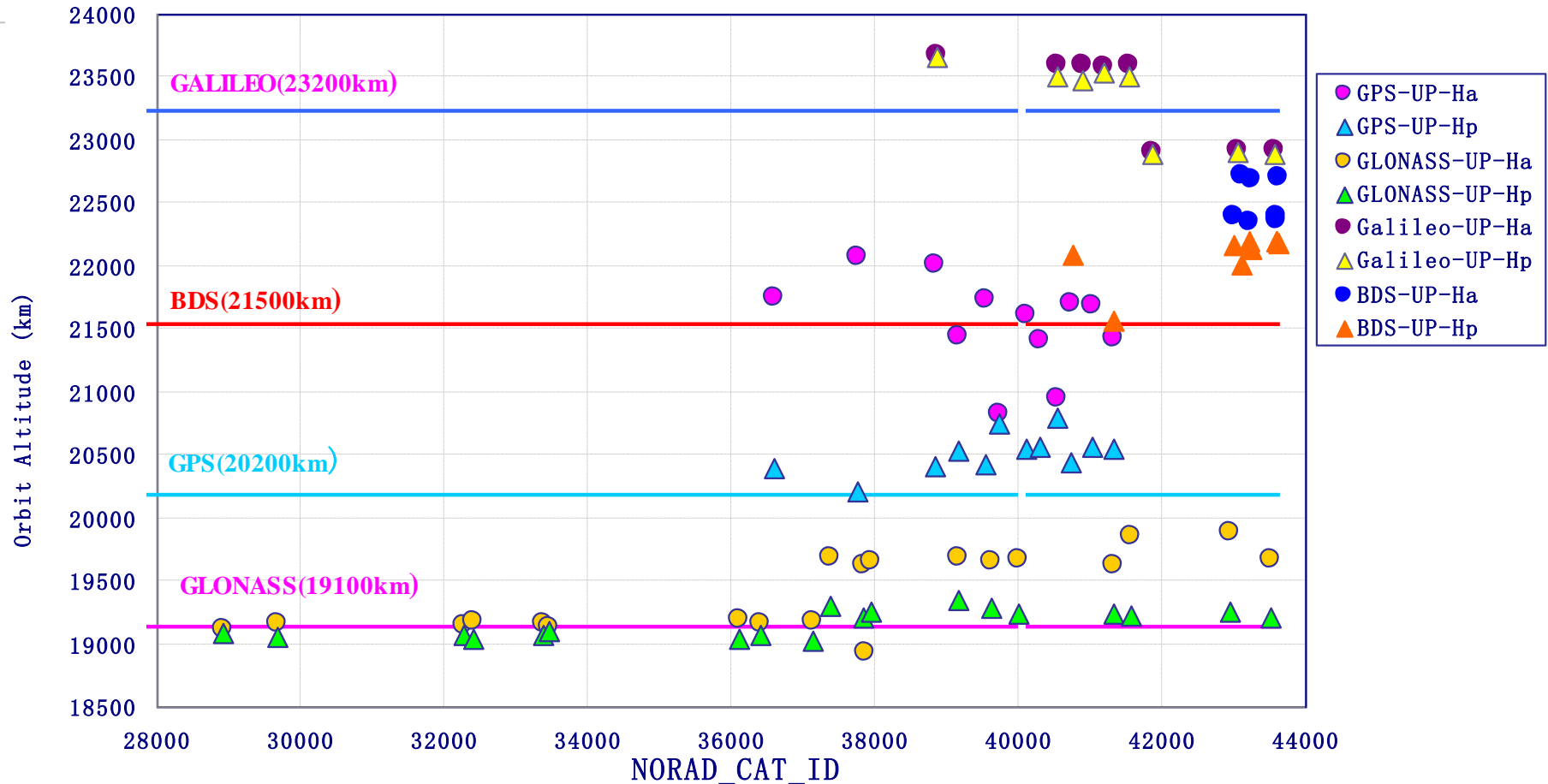
# GNSS Satellites Orbit Altitude



**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](http://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](http://www.space-track.org) by the end of Oct. 2018

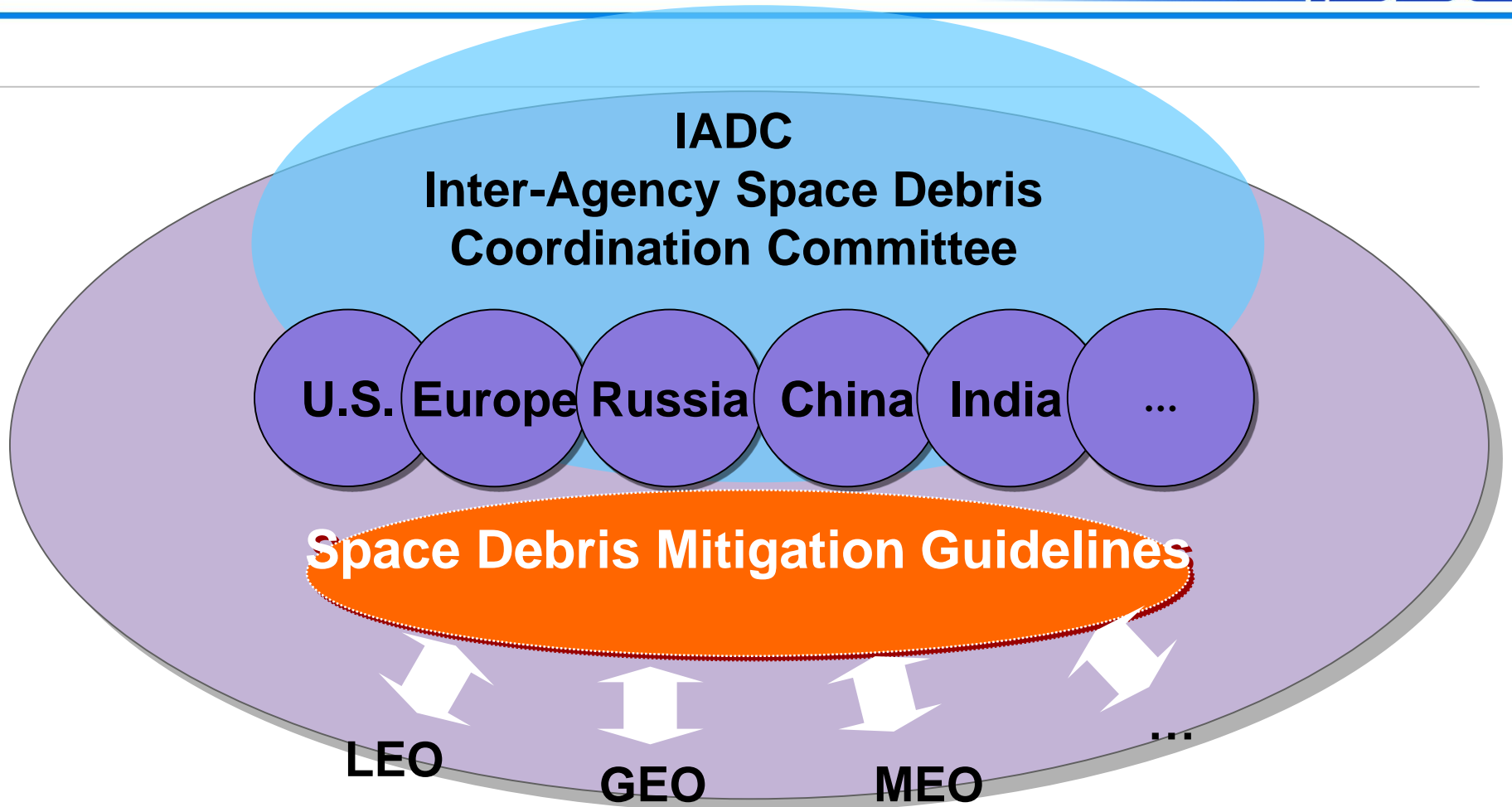
# GNSS Spacecraft Disposal Orbit

Constellation	De-orbited Satellites		De-orbited Upper-stage	
	Number	$\Delta H_a$ (Increase in apogee altitude)	Number	$\Delta H_a$ (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.**

## The requirements for GEO satellites post mission disposal of IADC:

- ◆ A minimum increase in perigee altitude of:  
 $235\text{km} + 1000\text{CR} \cdot A/\text{m}$
- ◆ An eccentricity less than 0.003, or the eccentricity 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 $\Delta V$ required
Disposal orbit	TBC: 1. Minimum long term perigee of 2000km, apogee below MEO 2. Perigee <b>500km above</b> MEO or nearby operational region and <b><math>e \leq 0.003</math></b> ; RAAN and argument of perigee selected for stability
Direct Reentry	Not recommended due to large $\Delta V$ required

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

# Disposal of 3 BDS GEO Satellites

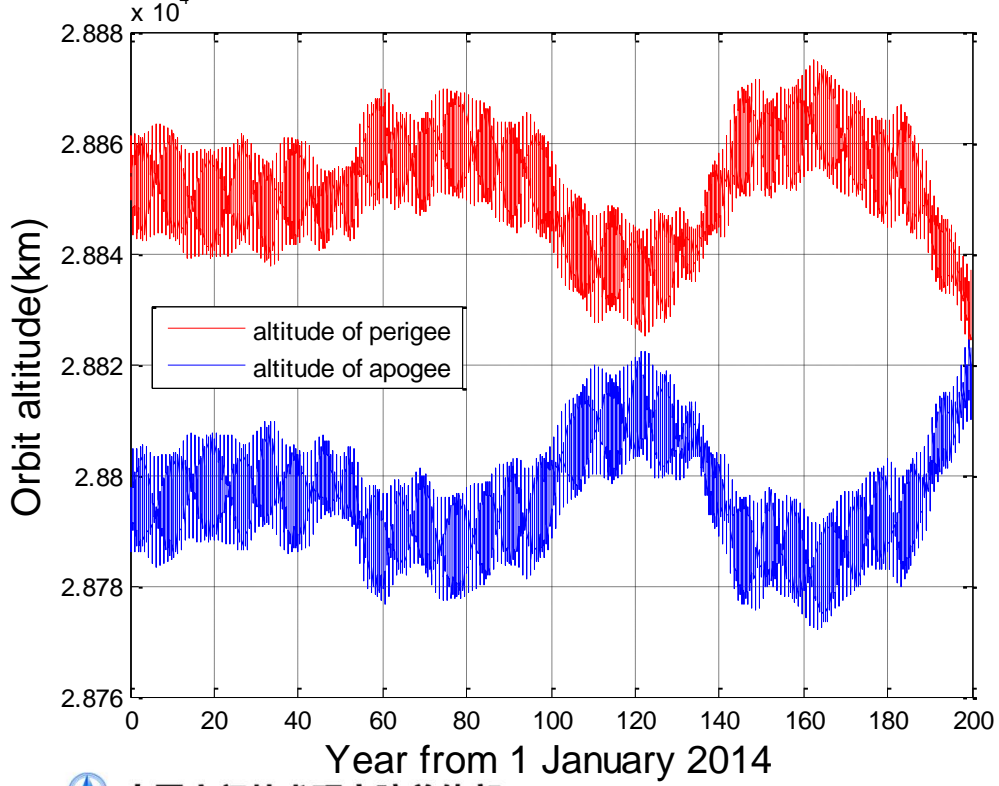
Disposal Satellite	Disposal Date	Increase in Perigee Altitude/km	Meet the Requirement of IADC ?
GEO1	Nov. 11 <sup>st</sup> ~12 <sup>nd</sup> , 2011	328	Y
GEO2	Nov. 23 <sup>rd</sup> , 2011	309	Y
GEO3	Jan. 13 <sup>rd</sup> , 2013	140	N

**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 3<sup>rd</sup> 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

Equation in eccentricity due to third body perturbation:

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

\* 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, =1 for solar perturbation,  
=1/82.3 for lunar perturbation;  
 $\omega$ =argument of perigee of the orbit;  
 $\Delta\Omega$ =RAAN of satellite – RAAN of the third body

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

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

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

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

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

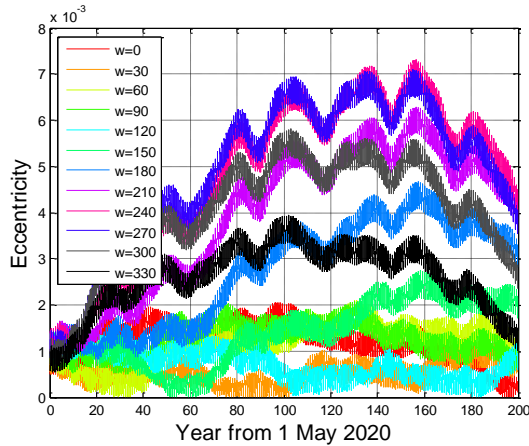


# Stability of MEO Disposal orbit

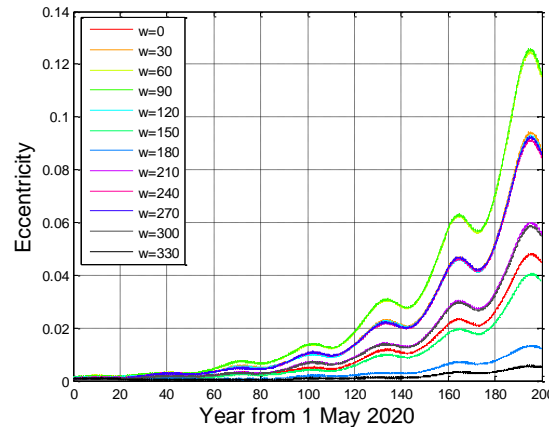
Constellation	Orbit Altitude (km)	Inclination(deg)	$\Omega_{J2}$ (deg/year)	$\omega_{J2}$ (deg/year)	Variation rate of angle in sine function				
					$\omega-\Omega$	$2\omega-\Omega$	$\omega$	$2\omega+\Omega$	$\omega+\Omega$
GLONASS	19100	64	-12.5	-0.56	11.94	11.38	<b>-0.56</b>	-13.62	-13.06
GPS	20180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

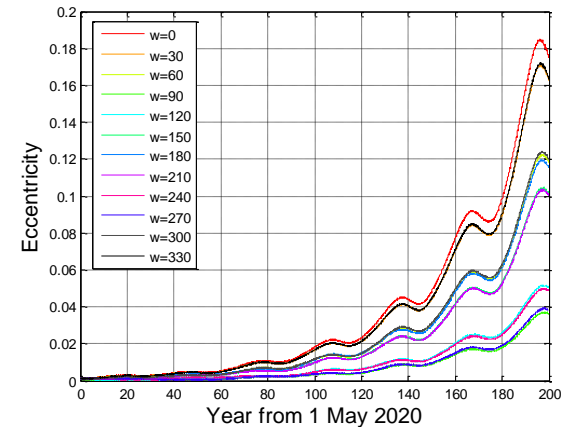
# BDS MEO Evolution with Different Initial Argument of Perigee



$\Omega=18^\circ, e=0.001, \omega=0\sim 360^\circ$



$\Omega=138^\circ, e=0.001, \omega=0\sim 360^\circ$



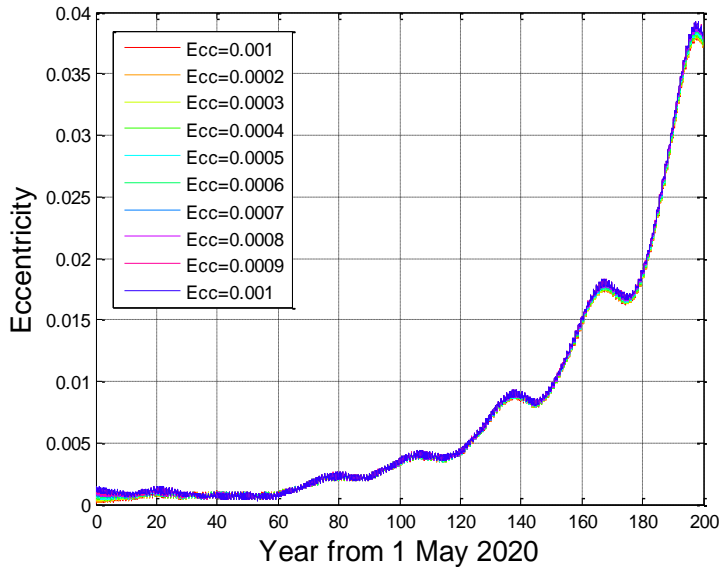
$\Omega=258^\circ, e=0.001, \omega=0\sim 360^\circ$

Recommendations for initial disposal orbit elements of BDS MEO satellites in the 1<sup>st</sup> plane:  
 $\Delta a_1 \geq +300\text{km}, e_1 \leq 0.001, \omega_1 \neq 240 \sim 270^\circ$

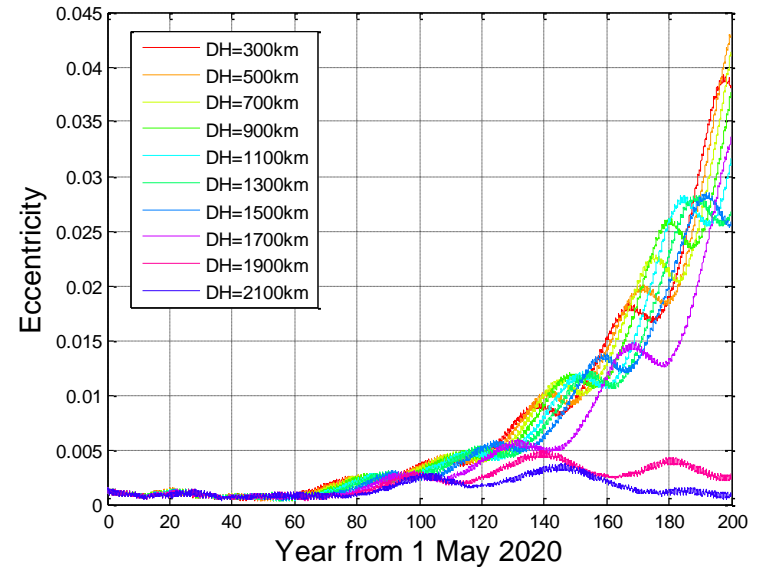
Recommendations for initial disposal orbit elements of BDS MEO satellites in the 2<sup>nd</sup> plane:  
 $\Delta a_2 \geq +300\text{km}, e_2 \leq 0.001, \omega_2 = 330^\circ$

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

## Eccentricity and Altitude in the 3<sup>rd</sup> Plane



$\Omega=258^\circ$  ,  $e=0.0001\sim 0.001$  ,  $\omega=270^\circ$

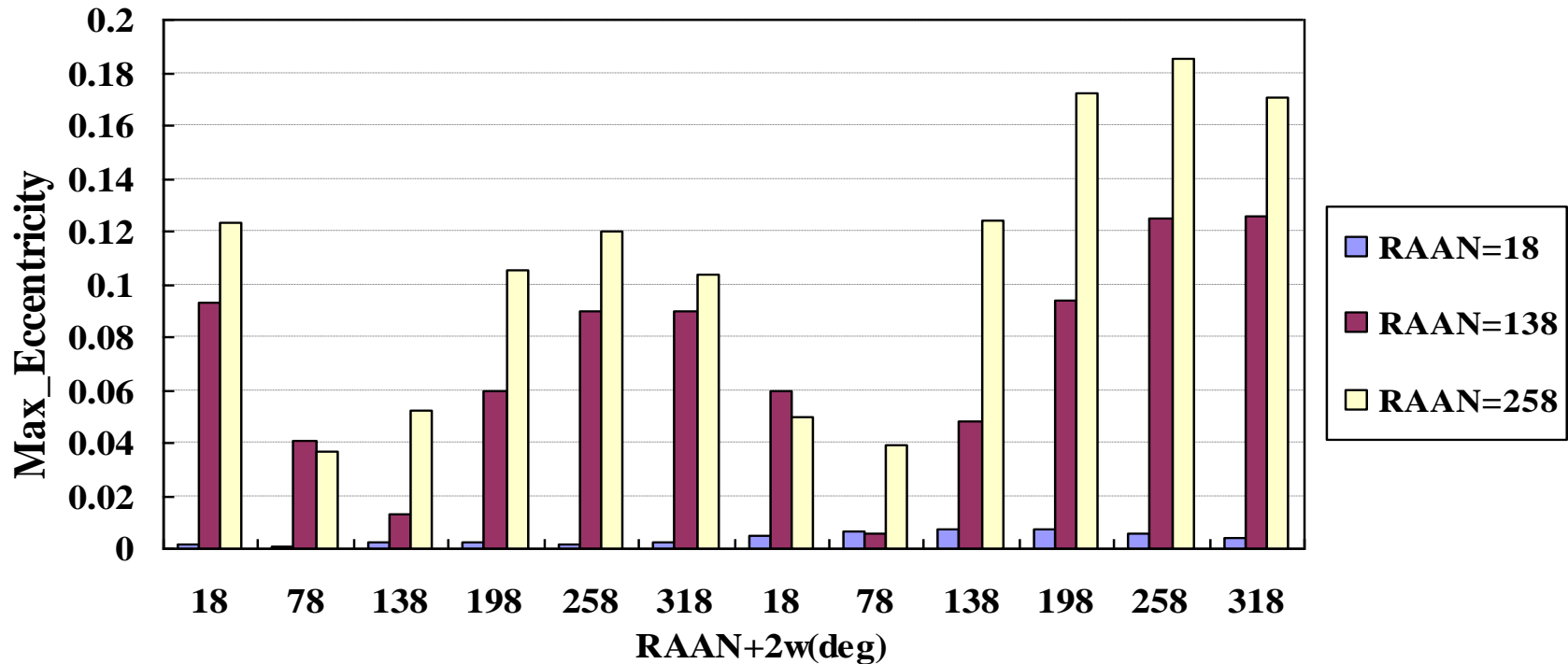


$\Omega=258^\circ$  ,  $e=0.001$  ,  $\omega=270^\circ$  ,  $\Delta a=300\sim 2100\text{km}$

With no propellant limitation, recommendations for initial orbit elements of BDS MEO satellites in the 3<sup>rd</sup> orbit are as following:

$$\Delta a_3 \gg 300\text{km}, e_3 \leq 0.001, \omega_3 \approx 270^\circ$$

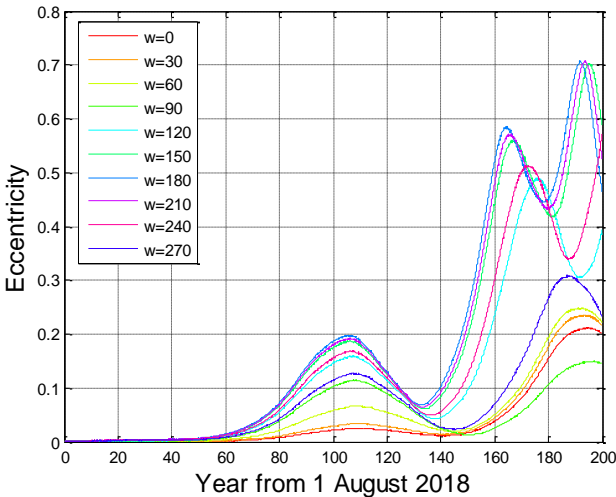
# Stability of BDS MEO Disposal orbit



$2\omega+\Omega=200\sim 320^\circ$  high eccentricity growth, should be avoided.

$2\omega+\Omega=80\sim 140^\circ$  lower eccentricity growth, recommended for MEO satellite initial disposal orbit elements

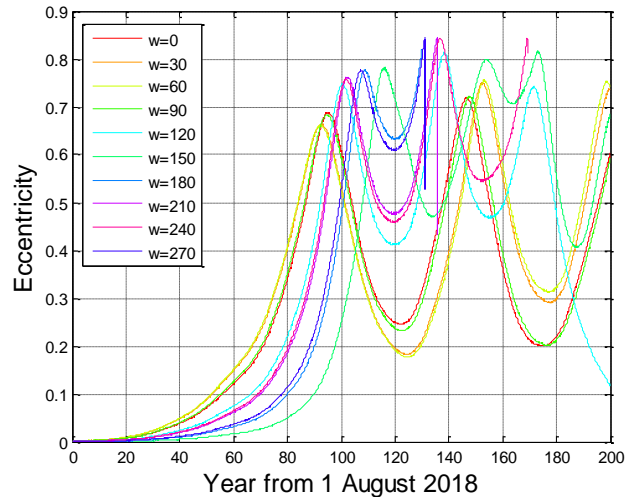
# BDS IGSO Evolution with Different Initial Argument of Perigee



$\Omega_1=69^\circ, e_1=0.001, \omega_1=0\sim 360^\circ$



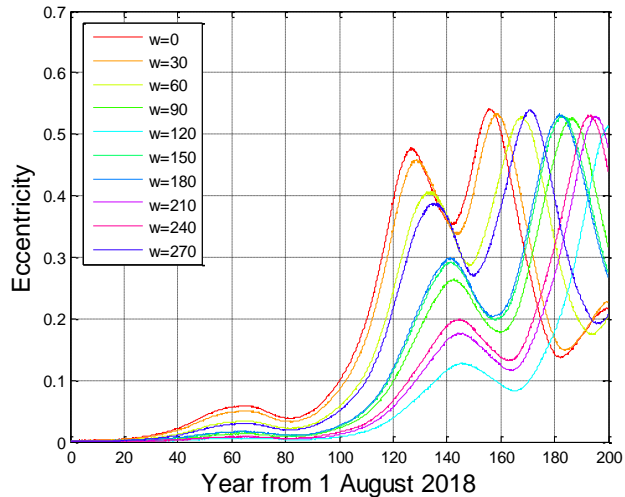
$\omega_1=0$  or  $90^\circ$  to make the max eccentricity less than 0.2 in 200 years



$\Omega_2=189^\circ, e_2=0.001, \omega_2=0\sim 360^\circ$



$\omega_2=120$  or  $330^\circ$  to make the reentry occurs in 130 years

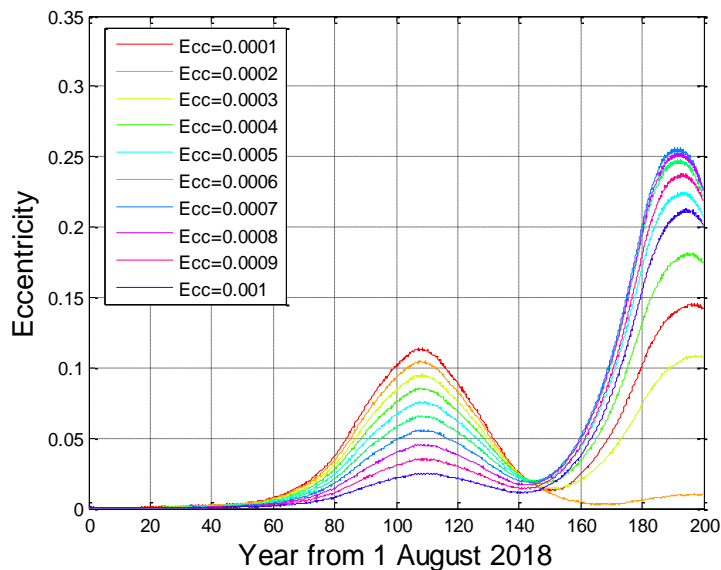


$\Omega_3=309^\circ, e_3=0.001, \omega_3=0\sim 360^\circ$



$\omega_3=60$  or  $270^\circ$  to make the max eccentricity less than 0.2 in 200 years

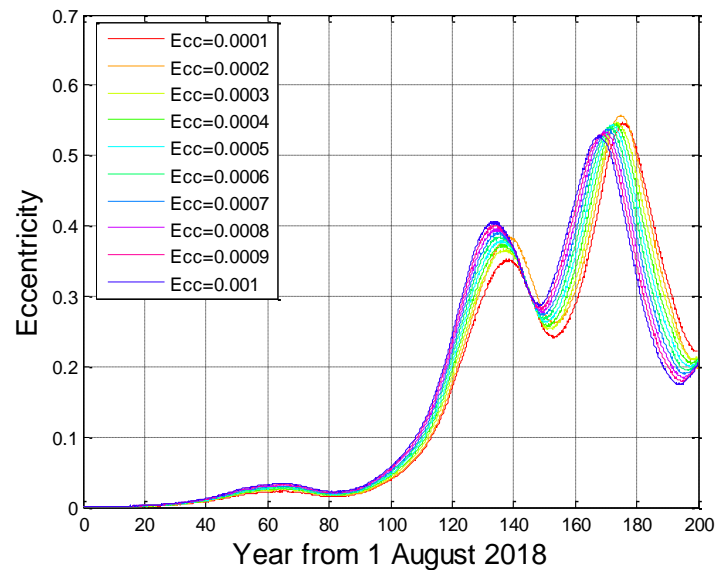
## Eccentricity in the 1<sup>st</sup> and 3<sup>rd</sup> Plane



$\Omega_1=69^\circ$  ,  $e_1=0.0001\sim 0.001$  ,  $\omega_1=0^\circ$



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

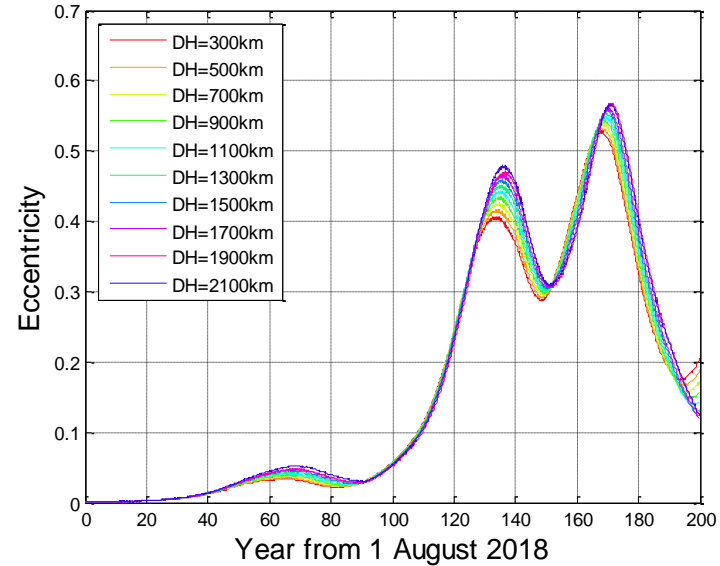
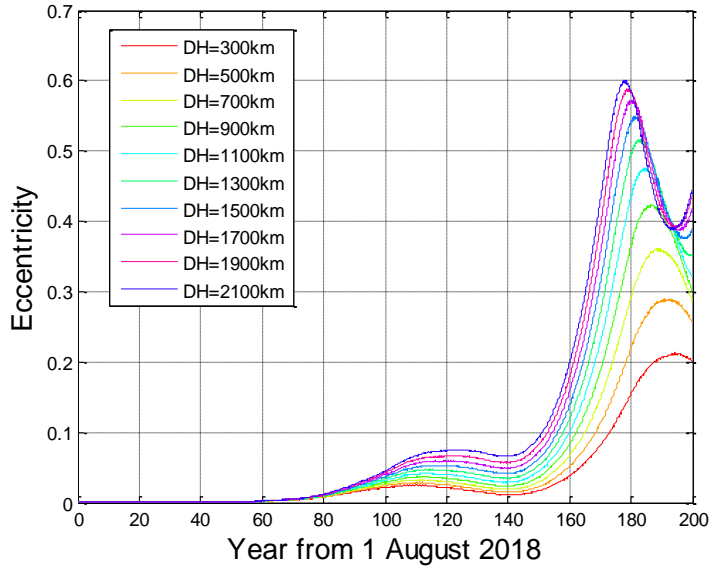


$\Omega_3=309^\circ$  ,  $e_3=0.0001\sim 0.001$  ,  $\omega_3=60^\circ$



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

## Orbit Altitude in the 1<sup>st</sup> and 3<sup>rd</sup> Plane



$\Omega_1=69^\circ$  ,  $e_1=0.001$ ,  $\omega_1=0^\circ$  ,  $\Delta a_1=300\sim 2100$  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

$\Omega_3=309^\circ$  ,  $e_3=0.001$ ,  $\omega_3=60^\circ$  ,  $\Delta a_3=300\sim 2100$  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 .

## 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
1 <sup>st</sup>	300	0.0002	0	No intersection with GEO in 180 years
2 <sup>nd</sup>	300	0.001	120 or 330	Reentry occurs in 130 years
3 <sup>rd</sup>	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

- ◆ 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:

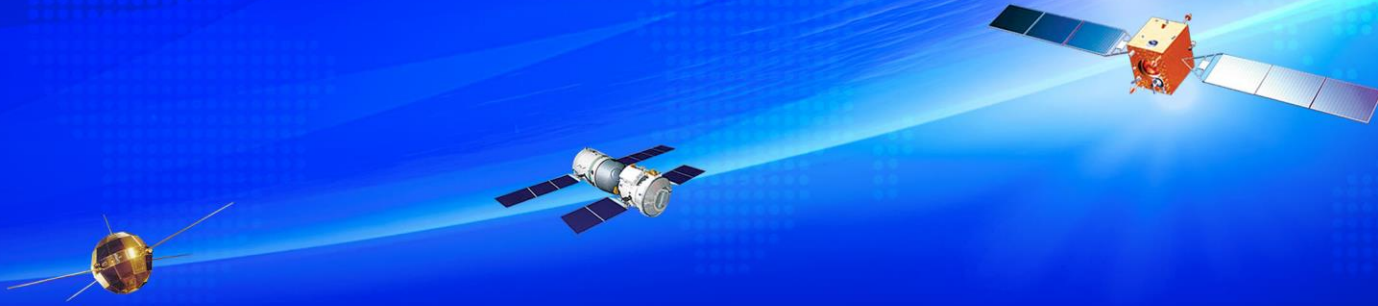
There are guidelines for post-mission disposal for GEO and LEO region, however, there are no specific guidelines for GNSS/RNSS MEO and IGSO satellites post-mission disposal from international organizations.

### 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 be 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 !**