ISO/WD 22639

ISO/TC 20/SC14 22639

Date: 2020-5-15

ISO/WD 22639

ISO/TC 20/SC14/ WG3

Secretariat: ANSI/AIAA

Space systems - Design guidelines for multi-GEO spacecraft collocation

Document type: International standard

Document subtype: if applicable

Document stage: (20) Preparation

Document language: E

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CONTENTS

Foreword

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This ISO standard was prepared by Technical Committee ISO/TC 020, Aircraft and Space Vehicle, Subcommittee SC 14, Space systems and operations.

Introduction

With the widely application of geostationary orbit in satellite navigation, satellite communication and remote sensing, there comes a dramatic increase in the number of geostationary spacecraft while the orbit position of geostationary spacecraft is limited.in order to solve this problem, it is often necessary for spacecraft operators to collocate their spacecraft with spacecraft operated by other agencies in order to deliver their services.

This international standard specifies the design process of a collocation strategy and the basic contents of collocation agreement which including design purpose, working flow, considerations and related requirements. This international standard applies to a particular multi-GEO constellation.

Space systems - Design guidelines for multi-GEO spacecraft collocation

1 Scope

In the increasingly congested GEO region it is often necessary for spacecraft operators to collocate their spacecraft with spacecraft operated by other agencies in order to deliver their services. This international standard specifies the design process of a collocation and the basic contents of collocation design process which including considerations, initial collocation strategy design, simulation evaluation of collocation strategy, optimal collocation strategy selection and collocation agreement.

This international standard gives guidelines for multi-GEO spacecraft collocation, and it applies to a particular multi-GEO constellation.

2 Terms and Definitions, Abbreviations and Acronyms

For the purposes of this Standard, the following terms and definitions, abbreviations and acronyms apply.

2.1 Terms and Definition

2.1.1 Multi-GEO Collocation

Two or more GEO spacecraft collocated at one geostationary orbit slot.

2.1.2 Orbit Maintenance

Orbit control for maintains the spacecraft’s orbit in certain error around the nominal orbit.

2.1.3 Inclination Vector

The magnitude of inclination vector is the orbit inclination. The vector points to the ascending node and measured from the vernal equinox. The expression of the x and y component of the vector can be expressed as:

$$i_x = \sin i \cos(\Omega) \tag{1}$$

$$i_y = \sin i \sin(\Omega) \tag{2}$$

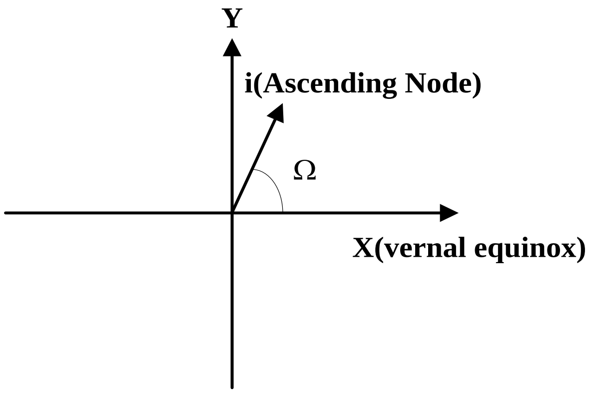

Figure 1 Inclination vector

2.1.4 Eccentricity Vector

The magnitude of eccentricity vector is the orbit eccentricity. The direction of the vector points to the orbit perigee and measured from the vernal equinox as the following figure. The expression of the x and y component of the vector can be expressed as:

$$e_x = e\cos(\Omega + \omega)$$

$$e_y = e\sin(\Omega + \omega)$$

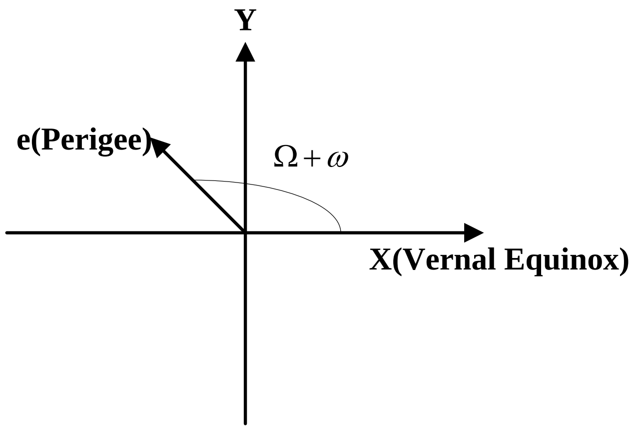

Figure 2 Eccentricity vector

2.1.5 Mean longitude l

The mean longitude is the sum of the right ascension of the ascending node, the augment of perigee and the mean anomaly. it may further be interpreted as the approximate right ascension of the near-circular orbits with small inclination.

2.1.6 J2000 Geocentric Equatorial Coordinate System

The origin is at the Earth's centre. The positive x-axis points in the direction of the mean vernal equinox of Earth at J2000 epoch. The positive z-axis points in the direction of the normal direction of the mean equator at J2000 epoch. The y-axis is orthogonal to both the x-axis and the z-axis and completes a right-handed frame. J2000 epoch: JD=2451545.0, which is 1 Jan 2000 12:00:00 TDB .The coordinate system is shown in Figure 3.

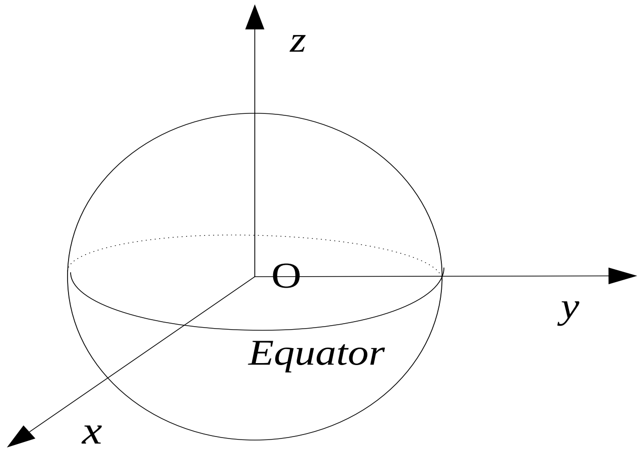

Figure 3 J2000 Geocentric Equatorial Coordinate System

2.1.7 Spacecraft Coordinate System of GEO spacecraft (RTN)

The origin is at the centre of the GEO spacecraft's positioned point. The R axis is outward along radial. The N axis points in the direction of the normal direction of J2000 mean equator. The T axis is constructed as N×R. Figure 4 shows this coordinate system.

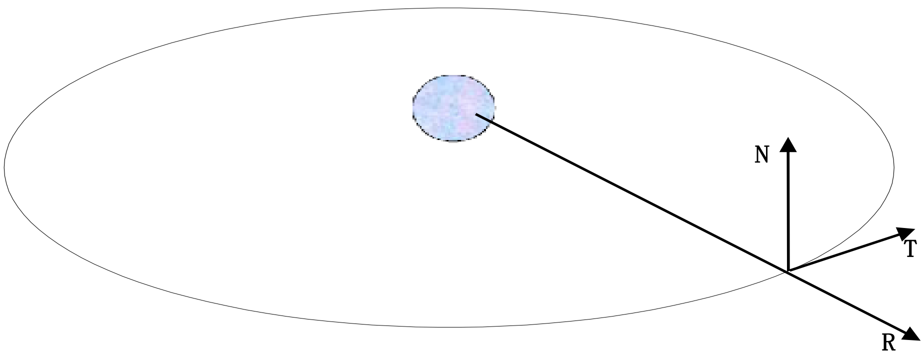

Figure 4 Spacecraft Coordinate System of GEO spacecraft (RTN)

2.2 Abbreviations and Acronyms

GEO geostationary earth orbit

ISO international standardization Organization

RAAN orbit right ascension of the ascending node (the angle between the vernal equinox and the orbit ascending node)

2.3 Symbols

Symbols listed in table 1 are used in this standard.

Table 1 List of Symbols

symbols	name	unit
e_x	x component of eccentricity vector coordinate	—
e_y	y component of eccentricity vector coordinate	—
i_x	x component of inclination vector coordinate	rad
i_y	y component of inclination vector coordinate	rad
δa	semi-major axis difference	km
δr	radial component offset	km
δT	Tangential component offset	
δN	normal component offset	km
a_s	normal semi major axis	km
l	mean longitude	rad
δe_x	x component of eccentricity offset	—
δe_y	y component of eccentricity offset	—
δi_x	x component of inclination offset	rad
δi_y	y component of inclination offset	rad
$d_{\min}$	minimum relative distance	km
α	angle between inclination vector and eccentricity vector	rad

3 Collocation Design Process

Design process of a collocation includes considerations, initial collocation strategy design, simulation evaluation of collocation strategy, initial selection of collocation strategy, optimal collocation strategy selection and collocation agreement.

It should be carried out according to the following steps, which is expressed in Figure 5.

1) Delegations of different spacecraft operators with diversity needs hold an orbit safety consultation meeting. Commonly, the operator of spacecraft that have to collocate with other spacecraft that already

located at the position shall bring forward the consultation meeting, negotiate and organize the meeting. In the consultation meeting each operator should present the operation status, operational issue and then brings forward and confirms the considerations of collocation design.

2) The initial collocation strategy is designed according the considerations. Each collocation spacecraft operator selects and proposes the preferred collocation strategy. The collocation strategy shall include not only the strategy during mission period but also the initial phase strategy to move a satellite into position of collocation configuration and the deorbit strategy.

3) Simulation to evaluate whether the collocation strategies meet the demanded requirements of all parties.

4) If the initial collocation strategy selected can’t meet the demanded requirements then to see if the strategies can be improved. If the answer is yes then revise the collocation strategies and go to the simulation evaluation step④again. If the answer is no then go to the initial design of collocation strategy step ③ again.

5) If the chosen strategy meets all of the defined requirements then the strategy should be confirmed as the final solution.

6) Once the optimal strategy is selected then the collocation agreement should be drafted and signed as defined in Section 5.

7) End the collocation design process.

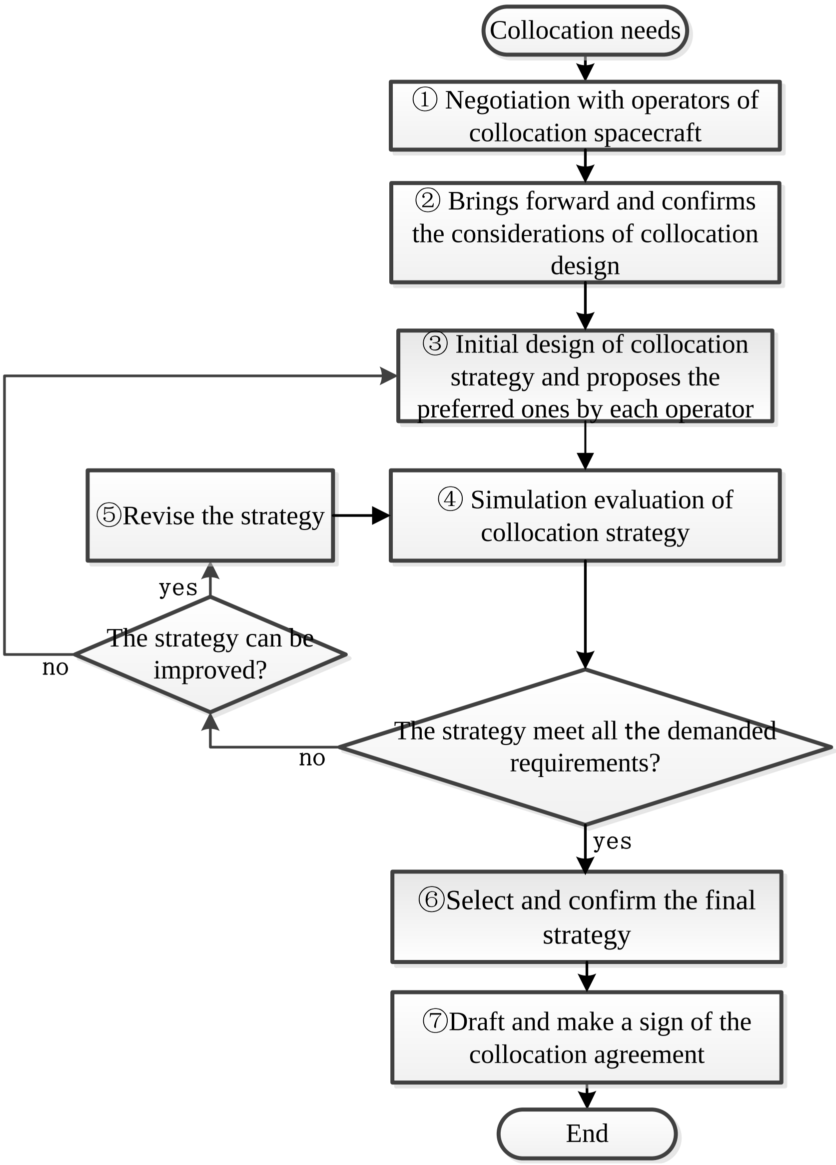

Figure 5 Collocation working flow

4 Basic contents of collocation design process

4.1 Considerations

In the orbit safety consultation meeting each operator presented operation status and operational issue and then brings forward and confirms the considerations of collocation design.

The following considerations shall be involved in the process ：

a) ITU regulations about frequency allocation and assigned orbital slots of the GEO spacecraft;

b) Number of collocated spacecraft ；

c) Safety separation distance between collocated spacecraft ；

d) Orbit maintenance requirements of collocated spacecraft;

e) Precision of orbit determination of collocated spacecraft;

f) Flight dynamics characteristics, e.g. Earth gravity, solar radiation pressure ;

g) Fuel consumption of collocated spacecraft ;

h) Number and ability of central management of collocated spacecraft;

i) Other special restrictions of collocated spacecraft.

4.2 Initial collocation strategy design

4.2.1 Fundamental principle of separation strategy

Assuming d is the relative distance between any two collocated spacecraft, $d_{\min}$ is the required minimum safe separation distance, then the collocation strategy is to make the relative distance d qualify the demanded condition which is $d \geq d_{\min}$. Generally, the value of $d_{\min}$ is 10km based on the successful experience of international collocation cases.

The common method of the relative distance between any two collocated spacecraft is shown in annex C.

4.2.2 The Available Separation Strategy

The fundamental separation strategies are listed as follows and the detailed principle about each strategy has been given in annex A. The characteristics of each separation strategy are shown in annex B.

1. The Complete Longitude Separation Strategy;
2. Coordinated Station Keeping Strategy;
3. The Absolute Eccentricity Separation Strategy ;
4. The Relative Eccentricity Vector Separation Strategy ;
5. The Eccentricity and Inclination Vector Separation Strategy.

4.2.3 Selection of collocation strategy

4.2.3.1 Selection principle

The separation strategy should be one of the fundamental strategies of the section 4.2.2, some other new strategies or the combination of them. However, the selection of separation strategy shall meet the following requirements:

a) Safety Assured : The design shall assure the in-flight safety of the spacecraft involved in the collocation strategy.

b) Operational requirements: The strategy design shall take into account all the operational requirements.

c) Experience-Based : The design shall be based on current operational best practice.

d) Easy Realized : The strategy shall be operationally feasible.

4.2.3.2 Selection method

During the selection process, the selection principle listed in section 4.2.3.1 should always be considered. Annex D listed the common collocation cases as well as the commonly adopted collocation design results.

4.2.4 Simulation Evaluation of Collocation Strategy

The strategy can be evaluated through simulation considering the orbit perturbation, orbit control, OD error and some other error sources. The detailed evaluation items are listed as follows:

1. Evaluate whether the safety separation distances between collocated spacecraft are ensured;
2. Evaluate whether the orbit maintenance period qualifies the perspective requirements;
3. Evaluate whether the fuel consumption of collocation spacecraft is within the budget requirement.

Based on the designed collocation strategy, some factors are considered such as orbit perturbation, orbit maintenance error, orbit determination error and so on to evaluate whether the considerations including the safety separation distance, orbit maintenance period, fuel consumption and some other factors are full filled.

4.3 Final collocation strategy

Once the chosen strategy meets all of the defined requirements then it should be confirmed as the final solution.

4.4 Collocation Agreement

After the optimal collocation strategy is selected and confirmed, the collocation agreement should be drafted and signed by each operator.

The collocation agreement shall contain the following:

1. **Introduction**: Detailing the collocation motivations, the operators and the collocation spacecraft involved;
2. **Summarize**: Summarize all the collocation strategies proposed and illustrate why the final collocation strategy was chosen;
3. **Detail**: A detailed description of the final collocation strategy, e.g. considerations, parameter values and associated data;
4. **Information exchange:** Detailing data to be regularly exchanged and clarify the information exchange mechanism, time, period and formats (use standard formats where possible). Generally, the use of ORBIT DATA MESSAGES – ISO 26900 (CCSDS 502.0-B) is encouraged for orbital data exchange

   (1) **Orbital data information**

   Orbital data content is as follows:

   - Reference coordinate system of orbit data;
   - Cartesian elements (x, y, z, vx, vy, vz);
   - Keplerian osculated elements (Semi-major axis eccentricity inclination RAAN argument of perigee true anomaly);
   - Orbit epoch (Year month day hour minute second(UTC));
   - Other information need to be exchanged.

   The data format shall comply with the following regulations:

   - The naming of the data file shall be clarified as (SSS_yyyymmdd.xls), where SSS stands for spacecraft name and yyyymmdd stands for the date of the data;
   - The file format shall be the same between all operators.

   The information shall be exchanged daily at a conventional period without maneuvers plan.

   (2) Emergency information:

   - Any spacecraft operator shall notify to the other operators before any operator's spacecraft will enter into the guard-band. The duration in the guard-band, time and date of entering-into/going-out the guard-band shall be informed in advance by e-mail basis, but they shall be notified immediately in the case of emergency. For example, If any side finds that the predicted separation distance of any two spacecraft is less than the minimum separation distance, the situation should be informed to the other sides and the relevant parties should discuss the possibility of avoidance maneuver. The essential control should be operated according to the agreed strategy.

(3) Orbit maneuver information: Generally, the maneuver plan shall be given in advance and after each maneuver of collocation spacecraft it shall be also exchanged in time (always two or three days) through the operator of maneuver spacecraft.

(4) De-orbit and replacement plan: Detailing the de-orbit and replacement plan. Generally, the de-orbit plan and orbit manoeuvre strategy shall be inform to the other operators in advance. The replacement plan shall be informed to the other operators at least one year ahead.

5. **Declaration**: Declare the duration of collocation agreement;
6. **Others**:
   The change manner should also be given in the document if the collocation strategy will change with needs. Any other information pertinent to the agreement shall also be included.
7. **Contact Information**: Each operator involved in the collocation scenario shall nominate a contact point for negotiation and information exchange.
8. **Emergency contact information:** Each operator shall nominate an Emergency Contact point (24 hours) in case of emergency. The Emergency Contact point shall at least contain the telephone number and the fax number.
9. **Signature Block:** Signature of an authorized person of each organization involved in the collocation negotiation.

After the creation of collocation agreement draft, it shall be signed by all operators involved in the collocation scenario. A copy of the collocation agreement shall be held by each operator involved in the collocation scenario. The collocation agreement shall be regular reviewed and updated when required.

Annex A

(Informative)

Fundamental principle of available separation strategy

A.1 A The complete Longitude Separation Strategy

This strategy ensures minimum separation between two spacecraft by the use of longitude separation. Assuming that the minimum safety separation distance is $d_{\min}$, then the minimum longitude dead bands can be expressed as:

$$\min \delta\lambda = \min|\lambda_2 - \lambda_1| = \frac{d_{\min}}{a_s} \tag{3}$$

λ_i (i=1,2) is the osculating longitude of the collocated spacecraft. The complete longitude separation strategy is a simple method of splitting the longitude dead band into smaller dead bands. Each spacecraft performs station keeping maneuvers independently within its reduced longitude dead bands。 The working principle can be seen in Figure 6.

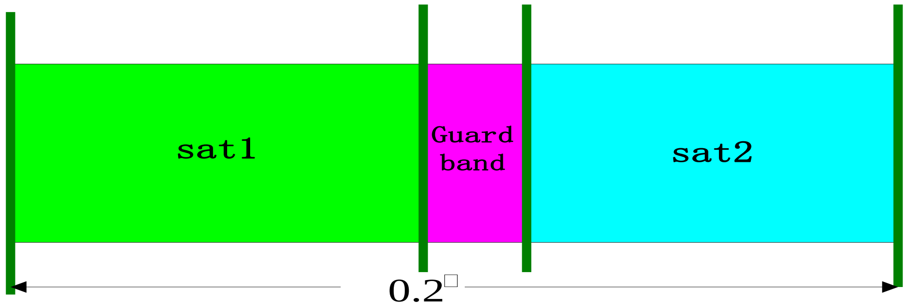

Figure 6 Working principle of the complete Longitude Separation Strategy

A.2 B Coordinated Station Keeping Strategy

With this method, the longitude dead-band is split into several overlap longitude bands and the collocated spacecraft domains different area in different station keeping stages.

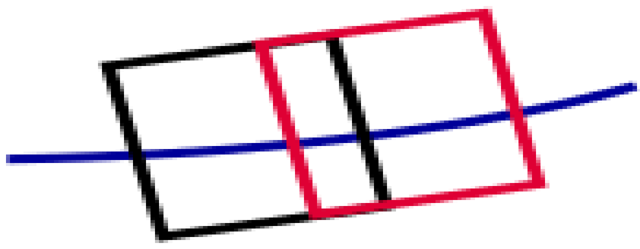

Figure 7 Coordinated Station Keeping Strategy

A.3 C The Absolute Eccentricity Separation Strategy

The absolute eccentricity separation strategy is based on the period motion of eccentricity. The relative motion of one spacecraft respect to the other is an ellipse whose semi-minor axis is $a_s \cdot e$ and points to the radial direction. The semi-major axis is twice the semi-minor axis and points to the tangential direction. The strategy is expressed in Figure 8.

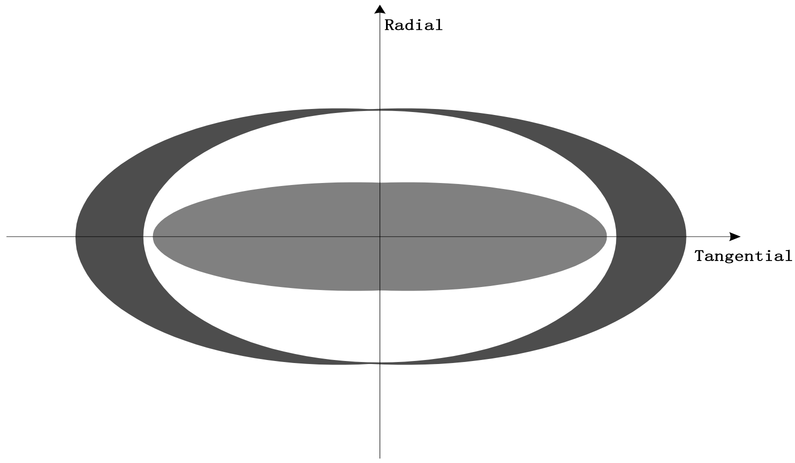

Figure 8 The Absolute Eccentricity Separation Strategy

A.4 D The Relative Eccentricity Vector Separation Strategy

The relative eccentricity vector separation strategy can induce not only the radial but also the tangential separation distance. This strategy can deal with the circumstances that the orbits of collocated spacecraft are on the same orbit plane or not. The radial component offset and normal component offset is expressed as:

$$\delta r = -a_s(\delta e_x \cos(l) + \delta e_y \sin(l)) \quad (4)$$

$$\delta T = 2 a_s (\delta e_x \sin(l) - \delta e_y \ \mathrm{c\,c} \quad (5)$$

From the above equation it can be concluded that the radial component offset and tangential component offset will never equal zero simultaneously which ensures the distance separation between different spacecraft. The separation method has been shown in Figure 9. it is proved that the eccentricity offset is the maximum in any time. When the radial component offset is zero the tangential component offset reaches the max. While the tangential component offset is zero the radial component offset reaches the max.

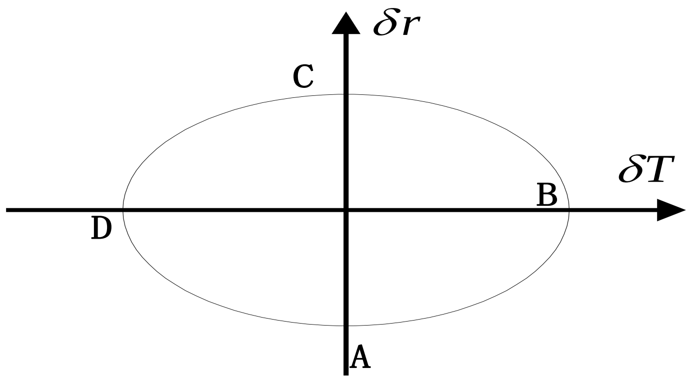

Figure 9 The Relative Eccentricity Vector Separation Strategy

A.5 E The Eccentricity and Inclination Vector Separation Strategy

An inclination offset itself is not sufficient to maintain minimal allowable distance because that there may be collision at the orbit intersection points. In order to solve this problem, the eccentricity separation is introduced to create the relative radial offset to finally realize the separation of collocated spacecraft. The combined eccentricity and inclination separation should follow the constraint equation as follows:

$$\delta r = \delta a - a_s(\delta e_x \cos(l) + \delta e_y \sin(l)) \tag{6}$$

$$\delta N = a_s(\delta i_x \sin(l) - \delta i_y \cos(l)) \tag{7}$$

The relative radial distance at orbit intersection points can be expressed as:

$$\delta r = \delta a - \frac{a_s}{\delta i}(\delta\vec{e} \cdot \delta\vec{i}) \tag{8}$$

When the relative normal distance is zero in order to maximum the relative radial distance the following conditions should be qualified.

$$\left|\cos(\delta\vec{e}, \delta\vec{i})\right| = 1 \tag{9}$$

Which means the angle between the relative eccentricity vector and the relative inclination vector should be 0 °or 180°to make a maximum relative radial distance at the orbit intersection points. Then we can derive the condition of eccentricity and inclination separation combined strategy:

$$\delta e \geq \frac{d_{\min} + |\delta a|}{a_s}, \quad \delta i \geq \frac{d_{\min}}{a_s} \tag{10}$$

In which δa is the offset of semi major axis, a_s is the normal semi major axis of geostationary orbit. Through the above equation we can see that when the relative eccentricity vector is parallel or antiparallel to the relative inclination vector the maximum relative distance can be less than the demanded minimum separation distance by set the relative eccentricity vector and inclination vector to an appropriate numerical value.

Annex B

(Informative)

Characteristics of separation strategy

Separation strategy	Characteristics
The Complete Longitude Separation Strategy	(1). Collocation operation is simple; (2). Each spacecraft can perform station keeping maneuvers independently without orbit data exchange； (3). E/W station keeping maneuver is frequent； (4). It is only fit for two spacecraft's collocation； (5). There is no special request of station keeping;
Coordinated Station Keeping Strategy	(1) Collocation operation is a little complex； (2) Orbit data exchange is needed during operation； (3) E/W station keeping maneuver is a little frequent； (4) It can be used in two or more spacecraft's collocation; (5) The collocation spacecraft operate at different area at different stages. Furthermore, E/W station keeping maneuver of each collocation spacecraft should be strictly synchronous; (6) The area to mass ratio of collocation spacecraft should be small.
The Absolute Eccentricity Separation Strategy	(1) Collocation operation is simple; (2) Each spacecraft can perform station keeping maneuvers independently without orbit data exchange； (3) E/W station keeping maneuver is frequent since that the daily change of the eccentricity vector along longitude direction is large.； (4) It cannot effectively collocate more than three spacecraft in the same control box with a ±0.1 deg limit; (5) There is no special request of station keeping.
The Relative Eccentricity Vector Separation Strategy	(1) Collocation operation is a little complex； (2) Orbit data exchange is needed during operation； (3) E/W station keeping maneuver is less frequent .The relative longitude drift rate and difference between collocation spacecraft during E/W station keeping maneuver must be approximate zero; (4) It is fit for multiple spacecraft collocation. (5) The eccentricity vector control method of collocation spacecraft must be the same.
The Eccentricity and Inclination Vector Separation Strategy	(1) Collocation operation is complex； (2) Each spacecraft can perform station keeping maneuvers independently with orbit data exchange； (3) E/W station keeping maneuver is not that frequent; (4) It is fit for multiple spacecraft's collocation; (5) All collocated spacecraft can share the same orbit slot； (6) During the station keeping maneuver, the angle between eccentricity difference and inclination difference between collocated spacecraft should be well maintained.

Annex C

(Informative)

Fundamental principle of separation strategy

Assuming that two GEO spacecraft's named spacecraft 1 and spacecraft 2 whose orbits can be represented by ($\lambda_{01}, D_1, \vec{e}_1, \vec{i}_1$) and ($\lambda_{02}, D_2, \vec{e}_2, \vec{i}_2$) separately, then the deviation of the orbit elements can be expressed as:

$$\delta\lambda = \lambda_{01} - \lambda_{02} \tag{11}$$

$$\delta D = D_1 - D_2 \tag{12}$$

$$\delta\vec{e} = \vec{e}_1 - \vec{e}_2 \tag{13}$$

$$\delta\vec{i} = \vec{i}_1 - \vec{i}_2 \tag{14}$$

Through the linearization of motion equation of the considered spacecraft the relative distance in radial, tangent and normal direction can be derived as below:

$$\delta r = \delta a - a_s(\delta e_x \cos(l) + \delta e_y \sin(l)) \tag{15}$$

$$\delta T = a_s \cdot \delta\lambda + 2a_s(\delta e_x \sin(l) - \delta e_y \cos(l)) \tag{16}$$

$$\delta N = a_s(\delta i_x \sin(l) - \delta i_y \cos(l)) \tag{17}$$

The instantaneous relative distance can be expressed as:

$$d = \sqrt{\delta r^2 + \delta T^2 + \delta N^2} \tag{18}$$

The collocation strategy is to make the relative distance between any two collocated spacecraft qualify the demanded condition which is $d > d_{\min}$.

Through equation of relative motion, it can be concluded that relative motion normal components is relatively independent with radial and tangent component. The motion in radial and tangent can be expressed as an ellipse with l as an independent variable. The longitude deviation between the collocated spacecraft introduces the relative motion in tangent direction. The eccentricity deviation can both influence the relative motion in radial and tangent direction. The inclination deviation between collocated spacecraft can only affect the relative motion in normal direction.

Annex D

(Informative)

Sample of Collocation Evaluation strategy

Table 2 Form used in the strategy selection step

Separation strategy	Safety separation distance(km)	Orbit Determination Precision of accuracy	Fuel Consumption	Operating Complexity	Feasibility	others
A						
B						
C						
…						

Annex E

(Informative)

Common Collocation Cases and Strategies

I. Two spacecraft collocation strategy

- If the eccentricity of two spacecraft is small (always less than 0.0003) and there is no special requirement about the E/W station keeping period, the complete longitude separation strategy is commonly adopted.
- Assuming that the inclination vector difference between the two spacecraft is large (always larger than 0.1°)， the sun-pointing eccentricity control strategy is already adopted and at least one spacecraft's E/W station keeping period is demanded to be as long as possible, then the Eccentricity and Inclination Separation Strategy is commonly adopted.

II. Triple spacecraft Collocation strategy

Assuming that there are three collocated spacecraft are named as s1,s2 and s3 separately and the following condition is full filled, then Eccentricity and Inclination Separation Strategy is commonly adopted between s1 and other two spacecraft.Meanwhile the complete longitude separation strategy is adopted between s2 and s3.

(1) Three spacecraft all use the sun-pointing eccentricity control strategy.
(2) The S/N station keeping area of s2 is the same as s3.
(3) The inclination vector difference of sa1 with s2 and s3 is large.
(4) E/W station keeping period of sa1 is long compare to the period of s2 and s3.

III. More than three spacecraft collocation strategy

- If the collocated spacecraft belong to the same control center, the eccentricity are small and the control manner is the same, then Eccentricity and Inclination Separation Strategy is commonly used collocation strategy.
- If the collocated spacecraft belong to different control center, the eccentricity are small and the control manner is the same, then the Eccentricity and Inclination Separation Strategy, one or combination of the strategies listed in section 4.2.2 is always adopted. The final collocation strategy is related to the E/W station keeping periods and the magnitude of the eccentricity. First the collocation spacecraft can be classified into several groups and the final strategy can be chosen refers to situation I and II.