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Space systems — Design guidelines for multi-geo spacecraft collocation

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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

With the wide application of geostationary orbit in spacecraft navigation, spacecraft 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.

Space systems — Design guidelines for multi-geo spacecraft collocation

1 Scope

This document addresses the design process of a collocation and the basic contents of collocation design process which include considerations, initial collocation strategy design, simulation evaluation of collocation strategy, optimal collocation strategy selection and collocation agreement.

This document gives guidelines for multi-geo spacecraft collocation, and it applies in particular to multi-geo constellation.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1.1
orbit maintenance
orbit control for maintaining the spacecraft's orbit in certain prediction error around the nominal orbit

3.1.2
inclination vector
vector which points to the ascending node and which is measured from the vernal equinox

Note 1 to entry: The x and y components of the vector can be expressed as Formulae (1) and (2).

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

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

where

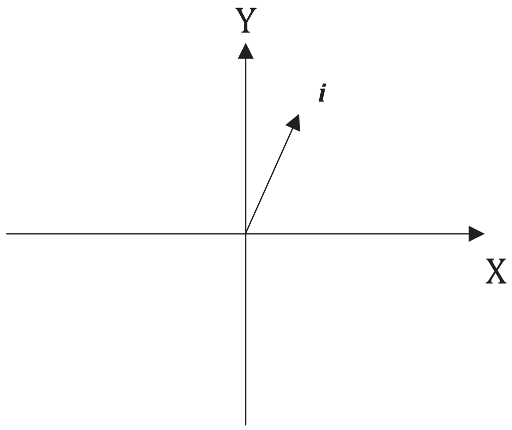
i is the magnitude of the inclination vector;

Ω is the raan in J2000 *geocentric equatorial coordinate system* (3.1.5);

i_x is the x component of the inclination vector coordinate;

i_y is the y component of the inclination vector coordinate.

Note 2 to entry: Figure 1 shows the definition of the inclination vector.



Key

i inclination vector which points to the ascending node

X direction of vernal equinox

Figure 1 — Inclination vector

3.1.3
eccentricity vector
vector which points to the orbit perigee and which is measured from the vernal equinox

Note 1 to entry: The *x* and y components of the vector can be expressed as Formulae (3) and (4).

$$e_x = e\cos(\Omega + \omega) \tag{3}$$

$$e_y = e\sin(\Omega + \omega) \tag{4}$$

where

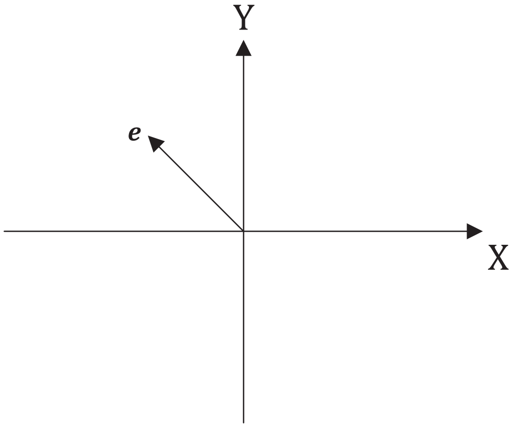
e is the magnitude of the eccentricity vector;

e_x is the *x* component of the eccentricity vector coordinate;

e_y is the y component of the eccentricity vector coordinate;

ω is the argument of perigee.

Note 2 to entry: Figure 2 shows the definition of the eccentricity vector.



Key

e eccentricity vector which points to the orbit perigee

X direction of the vernal equinox

Figure 2 — Eccentricity vector

3.1.4
mean longitude
l
sum of the right ascension of the ascending node, the augment of perigee and the mean anomaly

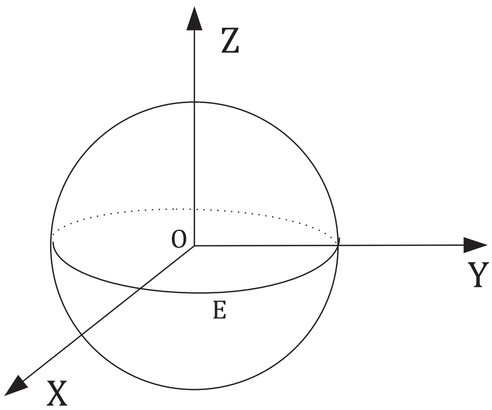
Note 1 to entry: It can further be interpreted as the approximate right ascension of the near-circular orbits with small inclination.

3.1.5
J2000 geocentric equatorial coordinate system
coordinate system with origin at the Earth's centre

Note 1 to entry: 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.

Note 2 to entry: J2000 epoch: JD=2451545,0, which is 1 Jan 2000 12:00:00 TDB.

Note 3 to entry: Figure 3 shows this coordinate system.



Key

E earth equator plane

Figure 3 — J2000 geocentric equatorial coordinate system

3.1.6
spacecraft coordinate system of geo spacecraft
RTN
coordinate system with origin at the centre of the geo spacecraft's positioned point

Note 1 to entry: 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.

Note 2 to entry: Figure 4 shows this coordinate system.

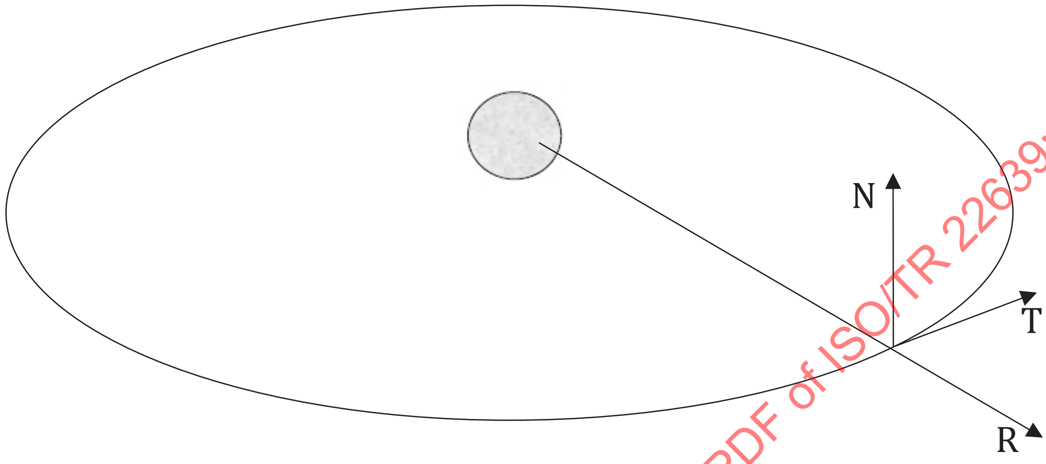


Figure 4 — Spacecraft coordinate system of geo spacecraft (RTN)

3.2 Abbreviated terms

E/W east/west

geo geostationary earth orbit

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

OD orbit determination

4 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.

The collocation design process is basically carried out according to the following steps, which are represented in the collocation working flow (see Figure 5).

a) Delegations of different spacecraft operators with diversity needs hold an orbit safety consultation meeting. Commonly, the operator of spacecraft that has to collocate with other spacecraft that is already located at the position brings forward the consultation meeting, negotiates and organizes the meeting.

b) In the consultation meeting, each operator presents the operation status, operational issue and then brings forward and confirms the considerations of collocation design.

c) The initial collocation strategy is designed according to the considerations. Each collocation spacecraft operator selects and proposes the preferred collocation strategy. The collocation strategy includes the strategy during mission period and the initial phase strategy to move a spacecraft into position of collocation configuration and the deorbit strategy.

d) Simulation is carried out to evaluate whether the collocation strategies meet the demanded requirements of all parties.

e) If the selected initial collocation strategy can't meet the specified requirements, the collocation strategies are reviewed in order to identify what can be improved. If improvements are identified, the collocation strategies are revised and the simulation evaluation step d) is carried out again. Else, the initial design of collocation strategy step c) is carried out again.

f) If the chosen strategy meets all the specified requirements then the strategy can be confirmed as the decided solution.

g) Once the optimal strategy is selected then the collocation agreement formalized and signed in accordance with Clause 5.

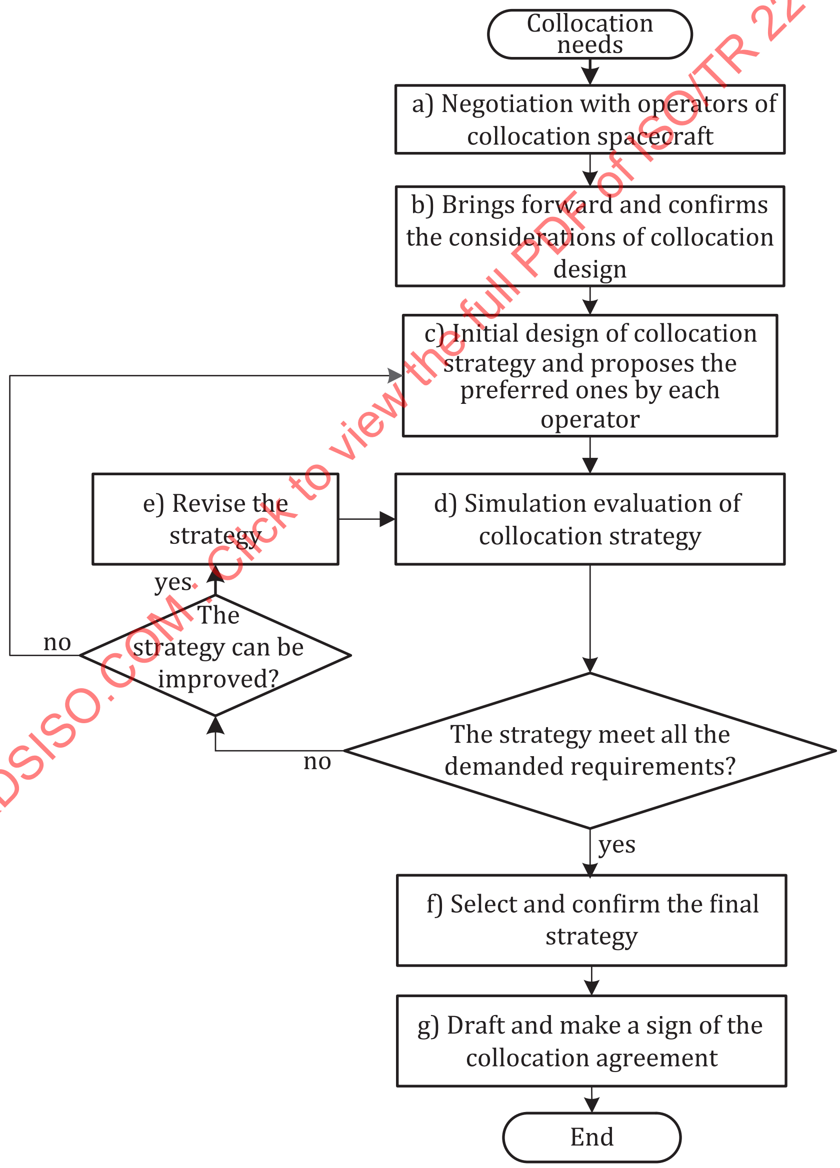


Figure 5 — Collocation working flow

5 Basic contents of collocation design process

5.1 Considerations

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

The following considerations are at least 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.

5.2 Initial collocation strategy design

5.2.1 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 $d \geq d_{\mathrm{min}}$. Generally, the value of d_{min} is 10 km 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.

5.2.2 The available separation strategy

The fundamental separation strategies are listed as follows and the detailed principle about each strategy is given in Annex A. The characteristics of each separation strategy are shown in Annex B (see Table B.1).

a) the complete longitude separation strategy;

b) coordinated station keeping strategy;

c) the absolute eccentricity separation strategy;

d) the relative eccentricity vector separation strategy;

e) the eccentricity and inclination vector separation strategy.

5.2.3 Selection of collocation strategy

5.2.3.1 Selection principle

The separation strategy is one of the fundamental strategies of 5.2.2, some other new strategies or the combination of them. In any case, the separation strategy to be selected meets the following design considerations:

a) safety assured: the design ensures that the in-flight safety of the spacecraft involved in the collocation strategy;

b) operational mission: the design takes into account all the operational specifications;

c) experience-based: the design is based on current operational best practices and return of experience (lessons learned); for the common collocation cases and strategies, refer to Annex E;

d) easily realized: the designed separation strategy is operationally feasible.

5.2.3.2 Selection method

During the selection process, the selection principle listed in 5.2.3.1 is always applied. Annex D (see Table D.1) provides common collocation cases as well as commonly adopted collocation design results.

5.2.4 Simulation Evaluation of Collocation Strategy

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

a) evaluate whether the safety separation distances between collocated spacecraft are ensured;

b) evaluate whether the orbit maintenance period qualifies the perspective requirements;

c) 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, to evaluate whether the considerations including the safety separation distance, orbit maintenance period, fuel consumption and other factors are sufficiently taken into account.

5.3 Final collocation strategy

Once the selected strategy meets all specifications, it is confirmed as the decided optimal collocation strategy.

5.4 Collocation agreement

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

The collocation agreement contains at least the following.

a) Introduction: Details the collocation motivations, the operators and the collocation spacecraft involved.

b) Summary: Summarizes all the collocation strategies proposed and illustrate why the final collocation strategy was chosen (justifications).

c) Detail: Describes the final collocation strategy, including considerations, parameter values and associated data.

d) Information exchange: Details data to be regularly exchanged and clarifies the information exchange mechanism, time, period and formats (standard formats are used where possible). In particular, the use of ORBIT DATA MESSAGES – ISO 26900 (CCSDS 502.0-B-2) is encouraged for addressing 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 which needs to be exchanged.

The data format can comply with the following international conventions:

— clarified naming of the data file as (SSS_yyyymmdd.xls), where SSS stands for spacecraft name and yyyymmdd stands for the date of the data;

— same file format between all operators.

The information can be exchanged daily at a conventional period without manoeuvres plan.

2) Emergency information: Any spacecraft operator can notify the other operators before any operator's spacecraft enters into the guard-band. The other operators can be informed of the duration in the guard-band, time and date of entering-into/going-out the guard-band in advance by e-mail, but they can 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 other sides can be informed of the situation; and the relevant parties can discuss the possibility of avoidance manoeuvre. The essential control can be operated according to the agreed strategy.

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

4) De-orbit and replacement plan: Details the de-orbit and replacement plan. Generally, the other operators can be informed of the de-orbit plan and orbit manoeuvre strategy in advance. The other operators can be informed of the replacement plan at least one year ahead.

e) Declaration: Declares the duration of collocation agreement.

f) Others: The change manner can also be given in the document if the collocation strategy will change with needs. Any other information pertinent to the agreement can also be included.

g) Contact information: Each operator involved in the collocation scenario can nominate a contact point for negotiation and information exchange.

h) Emergency contact information: Each operator can nominate an emergency contact point (24 hours) in case of emergency. The emergency contact point can at least contain the telephone number and the fax number.

i) Signature block: Signature of an authorized person of each organization involved in the collocation negotiation.

Once the collocation agreement is reached, it is formalized and signed by all operators involved in the collocation scenario. A copy of the collocation agreement can be held by each operator involved in the collocation scenario. The collocation agreement is regularly reviewed and updated when necessary.

Annex A
(informative)

Fundamental principle of available separation strategy

A.1 The complete longitude separation strategy

The complete longitude separation strategy is a simple method of splitting the longitude dead band into smaller dead bands. Each spacecraft performs station keeping manoeuvres within its reduced longitude dead bands. It ensures minimum separation distance between two spacecraft through the longitude separation. Assuming that the minimum separation distance is d_{min}, then the minimum longitude dead bands $\delta_{\lambda\mathrm{min}}$ can be expressed as:

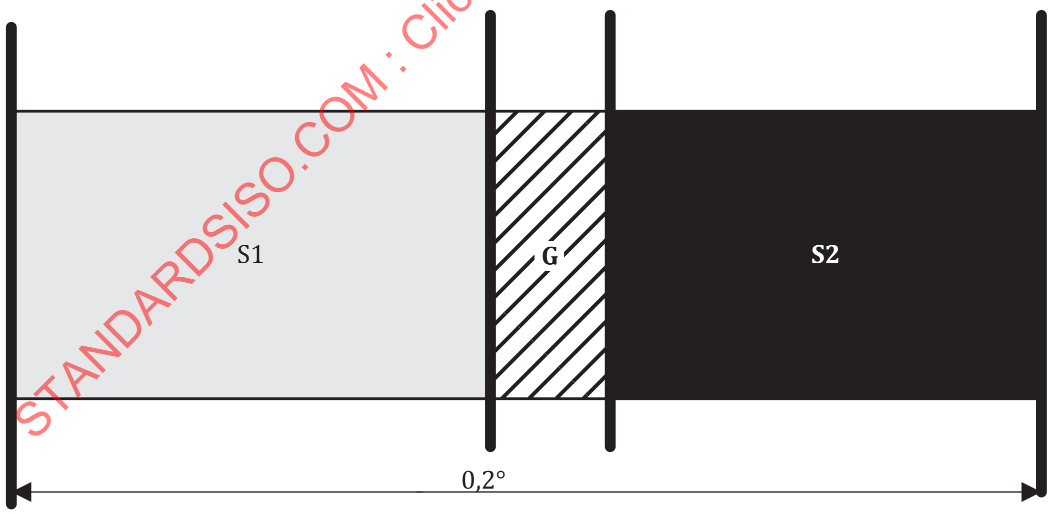
$$\delta_{\lambda\,\mathrm{min}} = \left|\lambda_2 - \lambda_1\right|_{\mathrm{min}} = \frac{d_{\mathrm{min}}}{a_{\mathrm{s}}} \qquad \text{(A.1)}$$

where

λ_i $(i=1,2)$ is the osculating longitude of the collocated spacecraft 1 and 2;

a_{s} is the normal semi-major axis.

For the working principle of the two satellites collocation within the 0,2 degree control dead band based on the complete longitude separation strategy, refer to Figure A.1; the station keeping manoeuvres of satellite 1 are limited to the S1 zone while the station keeping manoeuvres of satellite 2 is limited to the S2 zone. Both satellites are forbidden to come into the guard band which is marked by the G zone.



Key

S1 satellite 1

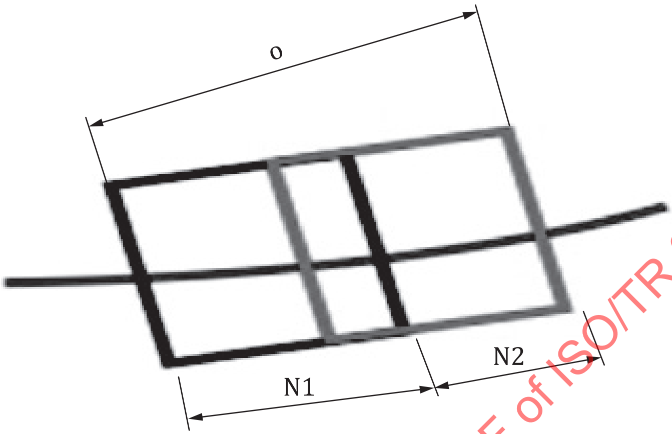
S2 satellite 2

G guard band

Figure A.1 — Working principle of the complete longitude separation strategy

A.2 Coordinated station keeping strategy

The strategy is to ensure a safe minimum distance along the radial and cross-track directions between station keeping manoeuvres with coordination in manoeuvre planning. It is similar with the complete longitude separation strategy that the original dead band is equally divided into several new dead bands. It is different from the complete separation strategy that the new dead band overlaps with each other and that each spacecraft comes into the overlap zone in different time to keep safety (see Figure A.2).



Key

o original dead band

N1 new dead band 1

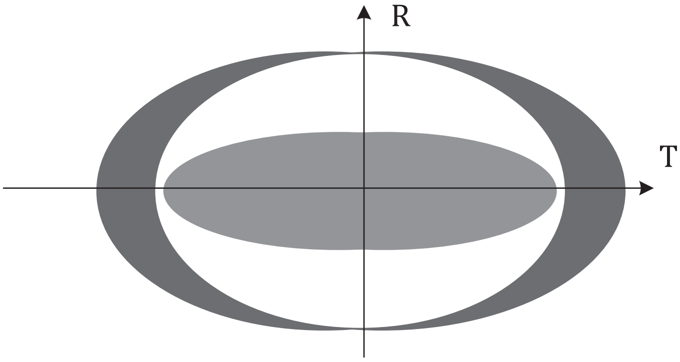
N2 new dead band 2

Figure A.2 — Coordinated station keeping strategy

A.3 The absolute eccentricity separation strategy

The absolute eccentricity separation strategy is based on the period motion of eccentricity. The in plane motion of each spacecraft is an ellipse with its semi-minor axis pointing to the radial direction and the magnitude equal to $a_s \cdot e$. The semi-major axis is twice the semi-minor axis and points to the tangential direction. e refers to the eccentricity of the collocation spacecraft.

Through the intentionally set of the eccentricity of the collocation spacecraft, one spacecraft's in orbit plane motion can be limited to the black area and the other's is limited to the central area. Then the separation is achieved by ensuring the separation of the absolute value of the collocation spacecraft's eccentricity. The relative motion ellipse is showed in Figure A.3.



Key

T tangential direction

R radio direction

Figure A.3 — Relative motion ellipse of the Absolute Eccentricity Separation Strategy

A.4 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 δ_r and normal component offset δ_T are expressed as:

$$\delta_r = -a_s(\delta_{e_x}\cos(l) + \delta_{e_y}\sin(l)) \tag{A.2}$$

$$\delta_T = 2a_s(\delta_{e_x}\sin(l) - \delta_{e_y}\cos(l)) \tag{A.3}$$

where

δ_{e_x} is the x component of the eccentricity offset;

δ_{e_y} is the y component of the eccentricity offset;

l is the mean longitude.

From Formulae (A.2) and (A.3), 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 is shown in Figure A.4. 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 maximum. While the tangential component offset is zero, the radial component offset reaches the maximum.

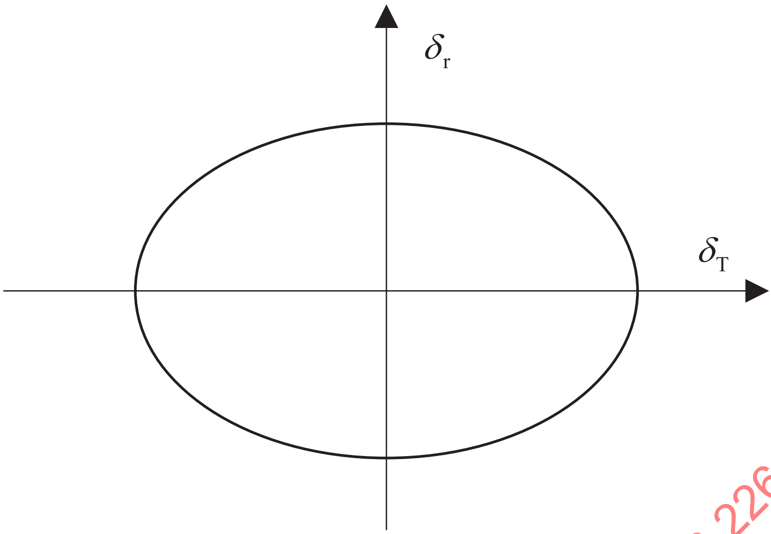


Figure A.4 — The relative eccentricity vector separation strategy

A.5 The eccentricity and inclination vector separation strategy

An inclination offset itself is not sufficient to maintain minimal allowable distance because there can 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 can follow the constraint Formulae (A.4) and (A.5):

$$\delta_\mathrm{r} = \delta_a - a_\mathrm{s}(\delta_{e_x}\cos(l) + \delta_{e_y}\sin(l)) \tag{A.4}$$

$$\delta_\mathrm{N} = a_\mathrm{s}(\delta_{i_x}\sin(l) - \delta_{i_y}\cos(l)) \tag{A.5}$$

where

δ_a is the semi-major axis difference;

δ_N is the normal component offset;

δ_{i_x} is the x component of the inclination offset;

δ_{i_y} is the y component of the inclination offset.

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

$$\delta_\mathrm{r} = \delta_a - \frac{a_\mathrm{s}}{\delta_i}(\delta_{\vec{e}} \cdot \delta_{\vec{i}}) \tag{A.6}$$

where

δ_a is the semi-major axis difference;

$\delta_{\vec{i}}$ is the inclination offset vector;

δ_i is the magnitude of the inclination offset vector;

$\delta_{\vec{e}}$ is the eccentricity offset vector.

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

$$\left|\cos(\delta_{\vec{e}},\delta_{\vec{i}})\right|=1 \tag{A.7}$$

Which means the angle between the relative eccentricity vector and the relative inclination vector can be 0°or 180° to make a maximum relative radial distance at the orbit intersection points.

Then the condition of eccentricity and inclination separation combined strategy can be derived:

$$\delta_e \geq \frac{d_{\min}+|\delta_a|}{a_s}, \delta_i \geq \frac{d_{\min}}{a_s} \tag{A.8}$$

where

δ_e is the magnitude of the eccentricity offset vector;

$d_{\min}$ is the minimum relative distance.

Through Formulae (A.4) to (A.7), it can be seen 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 setting the relative eccentricity vector and inclination vector to an appropriate numerical value.

Annex B
(informative)

Characteristics of separation strategy

Table B.1 — Characteristics of separation strategy

Separation strategy	Characteristics
The complete longitude separation strategy	a) Collocation operation is simple. b) Each spacecraft can perform station keeping manoeuvres independently without orbit data exchange. c) E/W station keeping manoeuvre is frequent. d) It is only fit for two spacecraft's collocation. e) There is no special request of station keeping.
The coordinated station keeping strategy	a) Collocation operation is a little complex. b) Orbit data exchange is needed during operation. c) E/W station keeping manoeuvre is a little frequent. d) It can be used in two or more spacecraft's collocation. e) The collocation spacecraft operate at different area at different stages. Furthermore, E/W station keeping manoeuvre of each collocation spacecraft can be strictly synchronous. f) The area to mass ratio of collocation spacecraft is small.
The absolute eccentricity separation strategy	a) Collocation operation is simple. b) Each spacecraft can perform station keeping manoeuvres independently without orbit data exchange. c) E/W station keeping manoeuvre is frequent since that the daily change of the eccentricity vector along longitude direction is large. d) It cannot effectively collocate more than three spacecraft in the same control box with a ±0,1° limit. e) There is no special request of station keeping.
The relative eccentricity vector separation strategy	a) Collocation operation is a little complex. b) Orbit data exchange is needed during operation. c) E/W station keeping manoeuvre is less frequent. The relative longitude drift rate and difference between collocation spacecraft during E/W station keeping manoeuvre must be approximately zero. d) It is fit for multiple spacecraft collocation. e) The eccentricity vector control method of collocation spacecraft must be the same.

Table B.1 *(continued)*

Separation strategy	Characteristics
The eccentricity and inclination vector separation strategy	a) Collocation operation is complex. b) Each spacecraft can perform station keeping manoeuvres independently with orbit data exchange. c) E/W station keeping manoeuvre is not that frequent. d) It is fit for multiple spacecraft's collocation. e) All collocated spacecraft can share the same orbit slot. f) During the station keeping manoeuvre, the angle between eccentricity difference and inclination difference between collocated spacecraft can be well maintained.