
**Space systems — Disposal of satellites
operating at geosynchronous altitude**

Systèmes spatiaux — Élimination des satellites opérant à une altitude géostionnaire

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 26872 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

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Introduction

This International Standard prescribes requirements for planning and executing manoeuvres and operations to remove an operating satellite from geosynchronous orbit at the end of its mission and place it in an orbit for final disposal where it will not pose a future hazard to satellites operating in the geosynchronous ring.

This International Standard includes requirements related to the following:

- when the disposal action needs to be initiated,
- selecting the final disposal orbit,
- executing the disposal action successfully, and
- depleting all energy sources to prevent explosions after disposal.

End-of-mission disposal of an Earth-orbiting satellite broadly means the following:

- a) removing the satellite from the region of space where other satellites are operating, so as not to interfere or collide with these other users of space in the future, and
- b) ensuring that the disposed object is left in an inert state and is incapable of generating an explosive event that could release debris which might threaten operating satellites¹⁾.

For satellites operating in the geosynchronous belt, the most effective means of disposal is first to re-orbit the satellite to a super-synchronous orbit above the region of operating spacecraft and the manoeuvre corridor used for relocating operating satellites to new longitudinal slots, and then to discharge batteries and vent propellants and take other actions to preclude a debris-producing event.

1) Further information will be provided in the future International Standard, ISO 16127.

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Space systems — Disposal of satellites operating at geosynchronous altitude

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1 Scope

This International Standard specifies requirements for the following:

- planning for disposal of satellites operating at geosynchronous altitude to ensure that final disposal is sufficiently characterized and that adequate propellant will be reserved for the manoeuvre;
- selecting final disposal orbits where the satellite will not re-enter the operational region within the next 100 years;
- executing the disposal manoeuvre successfully;
- depleting all energy sources on board the vehicle before the end of its life to minimize the possibility of an event that can produce debris.

This International Standard provides techniques for planning and executing the disposal of space hardware that reflect current internationally accepted guidelines and consider current operational procedures and best practices.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 24113:2010 *Space systems — Space debris mitigation requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 24113 and the following apply.

3.1

inclination excursion region

region in space occupied either by a non-operational geostationary satellite or by an operational geosynchronous satellite without inclination station-keeping

3.2

re-orbit manoeuvre

action of moving a satellite to a new orbit

3.3

satellite

manufactured object or vehicle intended to orbit the earth, the moon or another celestial body

4 Symbols and abbreviated terms

4.1 Symbols

a	semi-major axis
C_R	solar radiation pressure coefficient of the spacecraft ²⁾ ($0 < C_R < 2$)
e	eccentricity
h_p	perigee altitude
i	inclination
I_{sp}	specific impulse
L_S	solar longitude
M	mean anomaly
p	semilatus rectum or semi-parameter [$p = a(1 - e^2)$]
r	radius of orbit
v	true anomaly
μ	Earth gravitational constant
σ	standard deviation or the positive root of the variance, which measures the dispersion of the data
Ω	right ascension of ascending node (RAAN)
ω	argument of perigee
A/m	effective area-to-mass ratio: projected area of the spacecraft perpendicular to the sun's ray divided by the mass of the spacecraft
ΔH	change in altitude
ΔV	delta velocity or total velocity change

4.2 Abbreviated terms

EGM	Earth gravitational model
EOMDP	end-of-mission disposal plan
GEO	geosynchronous (geostationary) Earth orbit
RAAN	right ascension of ascending node

2) In some references, the C_R is defined as the index of surface reflection.

5 Geosynchronous region

The geosynchronous region is a circular ring around the Earth in the equatorial plane. Within this region, an object in space moves along the ring at a mean angular rate that is equal or very close to the Earth's rotation, meaning that the satellite appears to be positioned over a fixed location on the ground.

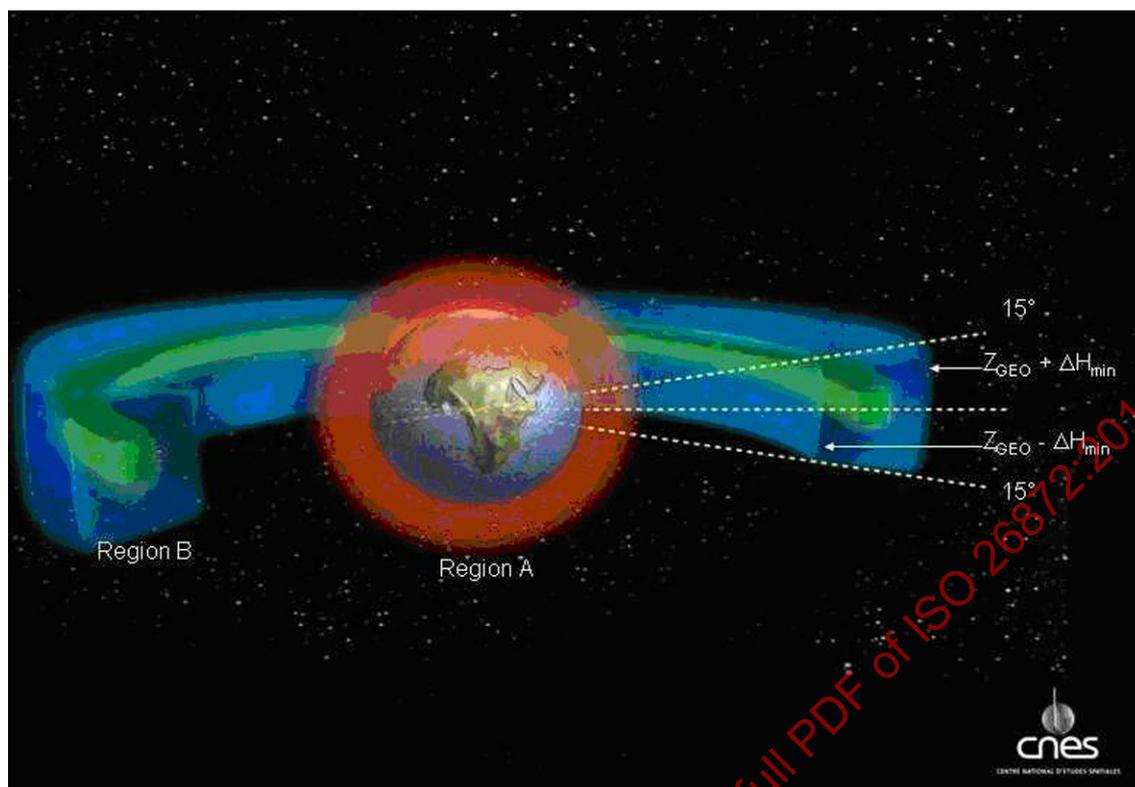
Without so-called north-south station-keeping, the inclination of a GEO satellite will gradually cycle between 0° (equatorial orbit) and a maximum of approximately 14,6° and back again. In addition to maintaining the accuracy of its inclination, a GEO satellite must execute station-keeping manoeuvres to maintain longitudinal accuracy, so as to prevent a naturally occurring drift to the east or to the west caused by asymmetries in the Earth's gravitational field, unless the satellite is located at one of the two "gravity wells" on the geostationary arc.

Figure 1 shows a three-dimensional view of the geosynchronous ring with a cross-section defining the approximate size of the ring. Figure 2 gives the dimensions of three regions of the cross-section. The cross-section is defined by two axes: the latitudinal axis and radial axis. This plane of the cross-section is perpendicular to the Earth's equatorial plane.

The three concentric boxes shown in Figure 2 give the approximate boundaries for three types of orbits. The smallest box represents the region where a geostationary satellite will be confined under station-keeping, and the next larger box approximates the region where a geosynchronous satellite may be located when its inclination is not controlled but it remains under a mission-specified value. For example, the upper value for some specific geosynchronous missions may range from 3° to 5° depending on the ground user's antenna design. The largest box represents the inclination excursion region for a non-operational GEO satellite and the ± 200 km protected region. For most communication satellites, the longitude station-keeping limit is $\pm 0,1^\circ$.

6 Protected region

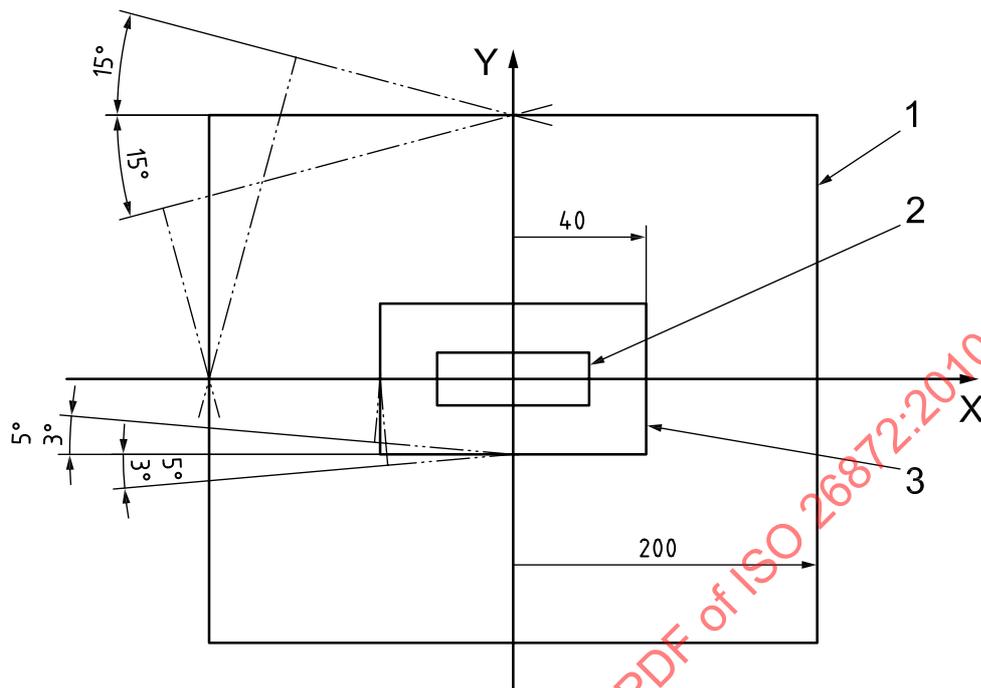
The GEO protected region, defined by ISO 24113 and indicated by Region B in Figure 1, includes the rectangular toroid centred on geostationary altitude, with an extent 200 km above and below this altitude and with inclination limits of +15° to -15°. While operations are usually conducted within about 75 km of geostationary altitude, the GEO protected region is extended in altitude to create a manoeuvre corridor for relocating spacecraft. Passivation of the disposed spacecraft is necessary to ensure that accidental explosions from on-board energy sources do not create debris that could re-enter the protected region.



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Figure 1 — Three-dimensional view of geosynchronous ring

Dimensions in kilometres

**Key**

- X radial (away from Earth)
- Y latitude (north)
- 1 protected region
- 2 geostationary control box ($\pm 37,5 \text{ km} \times \pm 37,5 \text{ km}$)
- 3 geosynchronous control box ($\pm 40 \text{ km}$ radial; $\pm 3^\circ$ to $\pm 5^\circ$ in inclination)

NOTE The dimensions in the figure are not to scale.

Figure 2 — Cross-section of the geosynchronous ring

7 Primary requirements

7.1 Disposal manoeuvre planning

An EOMDP shall be developed, maintained and updated in all phases of mission and spacecraft design and operation. The EOMDP shall be an integral part of the space debris mitigation plan specified by ISO 24113. The EOMDP shall include the following:

- a) details of the nominal mission orbit;
- b) details of the targeted disposal orbit;
- c) estimates of the propellant required for the disposal action;
- d) identity of systems and capabilities required for successful completion of the disposal action;
- e) criteria that, when met, shall dictate initiation of the disposal action;
- f) identities of energy sources required to be depleted before end of life;

- g) timeline for initiating and executing the disposal action;
- h) timeline for depleting the remaining energy sources;
- i) those individuals or entities, or individuals and entities to be notified of the end of mission and disposal and a timeline for notification.

7.2 Probability of successful disposal

In accordance with the requirements of ISO 24113:2010, 6.3.1, a spacecraft shall be designed such that the joint probability of having sufficient energy (propellant) remaining to achieve the final disposal orbit and successfully executing commands to deplete energy sources equals or exceeds 0,9 at the time disposal is executed. ISO 24113:2010, 6.3.1, also requires that the disposal success probability shall be evaluated as conditional probability (weighted on the mission success). Annex E provides a discussion of the conditional probability. Details of the design that provide the basis for the probability estimate shall be included in the EOMDP.

7.3 Criteria for executing disposal action

Specific criteria for initiating the disposal action shall be developed, included in the EOMDP and monitored throughout the mission life.

EXAMPLE Propellant amount remaining; redundancy remaining; status of electrical power; status of systems critical to a successful disposal action; time required to execute disposal action.

Projections of mission life based on these criteria shall be made as a regular part of mission status reviews.

7.4 Contingency planning

Independent of the success or failure of other aspects of a disposal action, a contingency plan shall be developed to deplete all energy sources and secure the vehicle before the final demise of the spacecraft. The objective shall be to ensure that actions necessary to secure the vehicle are taken before end of life. The contingency plan shall include criteria that define when the securing actions are to be taken, the rationale for each criterion, and a schedule for securing actions. The contingency plan shall be included in the EOMDP.

8 Disposal planning requirements

8.1 General

Planning activities for end-of-mission disposal shall start in the mission design phase. Planning for the actual disposal action should begin at least six months before the date of re-orbit manoeuvres. The steps described in 8.2 to 8.8 shall be followed in all mission phases and shall be documented in the EOMDP.

8.2 Estimating propellant reserves

The amount of fuel necessary to perform spacecraft disposal shall be estimated from the design phase, in accordance with the needed accuracy level, and reserved for the disposal phase. The minimum ΔV capability ($3-\sigma$) to reach the targeted disposal orbit shall be determined and specified in the EOMDP. The fuel required to provide this ΔV shall be maintained for end-of-life disposal³⁾.

3) Further information will be provided in the future International Standard, ISO 23339.

8.3 Computing the initial perigee increase

In accordance with the requirements of ISO 24113:2010, 6.3.2, a spacecraft operating within the GEO protected region must, after completion of its GEO disposal manoeuvres, have an orbital state that satisfies at least one of the two conditions outlined below.

- a) The orbit has an initial eccentricity of less than 0,003, and a minimum perigee altitude, ΔH , expressed in kilometres, above the geostationary altitude (35 786 km) calculated according to Equation (1):

$$\Delta H = 235 + (1\,000 \times C_R \times Alm) \quad (1)$$

The minimum value of C_R for computing the initial perigee increase shall be no less than 1,5 (a conservative estimate for C_R , so as to adequately predict the solar radiation pressure effect). Justification shall be provided for using a value less than 1,5. Equation (1) was derived to ensure that the long-term perturbations will not cause the GEO debris to re-enter a protected zone of GEO plus 200 km.

- b) The orbit has a perigee altitude sufficiently above the geostationary altitude that the spacecraft will not enter the GEO protected region within 100 years, irrespective of long-term perturbation forces.

8.4 Developing basic manoeuvre requirements for a stable disposal orbit

A stable disposal orbit shall be established by one of the two options described below.

- a) Use Equation (1) and the eccentricity constraint to determine initial disposal orbit conditions.
- b) Perform long-term (100-year) numerical integrations of the selected disposal orbit. The predicted minimum perigee altitude shall be greater than the 200 km protected region (see 8.5). It is recommended that the optimal eccentricity vector be determined from Tables A.1 to A.3, as a function of the date of orbital insertion and the value of $C_R \times Alm$.

The altitude stability will be improved for either method if the following apply:

- the initial disposal perigee points toward the sun (perigee is sun-pointing);
- the disposal manoeuvres are performed in the most favourable season of the year, such that the same amount of perigee altitude increase will give the largest clearance over 100 years.

NOTE 1 The true optimal direction will differ slightly from the actual sun-pointing direction as a result of lunar perturbations.

NOTE 2 See Annex A for the optimal eccentricity and argument of perigee as a function of time for various values of $C_R \times Alm$. Disposal orbits defined in accordance with Equation (1) are stable if the final eccentricity is less than 0,003. Tables A.1 to A.3 can be used to select the initial guess if option b) is used to determine the initial orbit parameters.

Should the intention be to operate the vehicle after placing it in a disposal orbit, the effects of such operation on the orbit shall be estimated, and this estimate and computations verifying that the operations will not compromise the long-term stability of the orbit (i.e. perigee shall remain above the protected region for 100 years) shall be included in the EOMDP. In all cases, the spacecraft shall be passivated (see 8.7) prior to end of life.

8.5 Developing long-term (100-year) disposal orbit characteristics

Long-term (100-year) orbit histories are needed only when the second option [see 8.4 b)] is chosen to establish a stable disposal orbit. If 8.4 b) is chosen, orbit propagation results developed by a reliable orbit propagator, either semi-analytic or numerical, shall be used to predict histories of perigee heights above GEO for a period of 100 years after initial insertion into the disposal orbit. The orbit propagator shall be of high precision and include as a minimum the perturbing forces of Earth's gravitational harmonics (up to a degree/order of 6 by 6), lunisolar attractions and solar radiation pressure. The precision of long-term

propagation of the propagator shall be verified against another well-established orbit propagator. Details on the orbit propagator used, assumptions made and analysis results shall be included in the EOMDP.

8.6 Determining the manoeuvre sequence

The manoeuvre sequence shall be determined that will place the GEO satellite in the required disposal orbit, have the optimal near-sun-pointing perigee and exhaust all the propellant on board. The disposal orbit is obtained after passivation and complete tank depletion, which can have unpredictable effects on orbital parameters and altitude. See Annex B for examples. The initial conditions of the disposal orbit shall be determined using the steps outlined in 8.4 and 8.5.

8.7 Developing a vehicle securing plan

Depletion of propellant creates forces that can affect a vehicle's orbit. The vehicle securing plan shall specify the following:

- a) steps to deplete on-board energy sources after the satellite has been placed into the disposal orbit;
- b) the effects the depletion action will have on the final orbit of the vehicle (the goal should be either to increase altitude or at least to limit a possible decrease in altitude);
- c) criteria for when the plan will be executed; and
- d) a schedule to be followed.

8.8 Developing a contingency plan

If a malfunction or other circumstance makes it necessary to proceed to the disposal phase earlier than planned, a contingency plan shall be developed that includes provisions for the following:

- a) selecting an alternative orbit that is the least likely to interfere with the protected area (see Annex C): the contingency plan shall include criteria and techniques for selecting this orbit;
- b) manoeuvring the satellite to the alternative orbit;
- c) securing the satellite after the move; and
- d) securing the vehicle if specified criteria are met at any time in the mission.

Annex D provides an example in which the quantity of propellant remaining is uncertain.

Annex A (informative)

Tabulated values of the optimal eccentricity vector

Tables A.1 to A.3 contain the optimal eccentricity vector [eccentricity and argument of perigee plus RAAN (or longitude of periapsis)] as a function of time and a function of ($C_R \times Alm$), expressed in square metres per kilogram, that will yield the highest perigee over the next 100 years. The optimal values were calculated in a brute-force fashion using increments of $2,3 \times 10^{-5}$ in eccentricity and 5° in longitude of periapsis. The benefit gained from using the optimal vector over the sun-pointing strategy varied from 0 km to 20 km (the average was approximately 9 km). However, if the sun-pointing strategy is chosen for the disposed vehicle, then the longitude of periapsis should be set equal to the value of the solar longitude (depicted as L_S in Tables A.1 to A.3) with an eccentricity equal to $0,01 \times C_R \times Alm$. These charts can be interpolated to find the optimal vector for any particular satellite at a given time. However, the following should be noted when using these tables.

The initial conditions used to generate the data assumed a constant semi-major axis of 300 km above GEO (i.e. a constant ΔV was used in the disposal), mean anomaly of 180° (i.e. the last burn occurs at apogee, raising the perigee so that the eccentricity is equal to the tabulated value), an inclination of $7,74^\circ$ (maximum at end of life if inclination drift is allowed) and an epoch of 0:00 Universal Time on the first day of each month. Additional analysis has shown that the optimal vector depends little upon these elements (the minimum perigee altitude may vary by approximately 2 km for each component), but if a high level of accuracy is required for a given disposal, the interpolated values found from the tables should be used as an initial guess so as to find the optimum for a particular disposal situation. The exception is the RAAN: in the search process, the initial RAAN was set to $62,3^\circ$ and the argument of perigee was changed in 5° increments until the optimal value was found. Different RAANs were then checked and it was found that the relevant angular parameter was the argument of perigee plus RAAN; if this value is held constant, then the results will again be consistent with 1 km to 2 km, irrespective of the particular RAAN.

In addition, care should be taken if interpolating the values. In searching for optimal values in the angular argument, it was found that, at times, there was not one pure maximum, but multiple local maximums. As either the time or $C_R \times Alm$ advanced, the true maximum jumped from one peak to another. For example, consider the 2008-05-01 disposal. A $C_R \times Alm$ of $0,015 \text{ m}^2/\text{kg}$ has an optimal eccentricity of $0,000\ 04$ and a longitude of periapsis and $262,3^\circ$, whereas the $C_R \times Alm$ of $0,03 \text{ m}^2/\text{kg}$ has optimal values of $0,000\ 09$ and $37,3^\circ$. Linearly interpolating would imply optimal values of $0,000\ 057$ and $307,3^\circ$ for a $C_R \times Alm$ of $0,02 \text{ m}^2/\text{kg}$. Instead, the $C_R \times Alm = 0,02$ optimal value was actually $0,000\ 015$ and $47,3^\circ$. In this case, the optimal point switched from one maximum to another, and therefore the intermediate maximum would actually be close to one point or the other.

Therefore, when confronted with angular changes greater than 90° , it is recommended that interpolation not be performed. Instead, the closer value should be used either directly or as a starting point for a more refined search.

A few final comments on the general behaviour of the system are warranted. When the Alm was small ($C_R \times Alm < 0,01$), the optimal angle was pointed at the lunar apogee; when the Alm was large ($C_R \times Alm > 0,03$), the solar radiation pressure force became dominant and the optimal angle was directed toward the sun.

**Table A.1 — Optimal eccentricity vector for $C_R \times A/m = 0,00 \text{ m}^2/\text{kg}$,
 $C_R \times A/m = 0,005 \text{ m}^2/\text{kg}$ and $C_R \times A/m = 0,01 \text{ m}^2/\text{kg}$**

Year	Month	L_S (°)	$C_R \times A/m = 0,00 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,005 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2006	1	281	0,000 115	132,3	0,000 065	142,3	0,000 090	177,3
	2	314	0,000 140	112,3	0,000 115	102,3	0,000 065	102,3
	3	341	0,000 140	117,3	0,000 115	117,3	0,000 115	92,3
	4	10	0,000 140	142,3	0,000 115	132,3	0,000 090	117,3
	5	38	0,000 140	162,3	0,000 115	147,3	0,000 090	127,3
	6	68	0,000 115	177,3	0,000 115	167,3	0,000 090	122,3
	7	99	0,000 065	167,3	0,000 090	122,3	0,000 140	117,3
	8	131	0,000 090	142,3	0,000 140	137,3	0,000 190	137,3
	9	160	0,000 115	157,3	0,000 165	157,3	0,000 215	157,3
	10	187	0,000 090	167,3	0,000 140	172,3	0,000 215	177,3
	11	216	0,000 090	187,3	0,000 140	202,3	0,000 215	207,3
	12	246	0,000 165	177,3	0,000 115	207,3	0,000 165	222,3
2007	1	281	0,000 140	187,3	0,000 140	207,3	0,000 140	222,3
	2	314	0,000 165	207,3	0,000 165	217,3	0,000 165	232,3
	3	341	0,000 165	212,3	0,000 115	227,3	0,000 115	242,3
	4	10	0,000 090	217,3	0,000 065	237,3	0,000 040	257,3
	5	37	0,000 040	192,3	0,000 015	167,3	0,000 015	147,3
	6	68	0,000 115	192,3	0,000 090	172,3	0,000 115	162,3
	7	99	0,000 140	202,3	0,000 165	192,3	0,000 140	177,3
	8	130	0,000 190	222,3	0,000 165	212,3	0,000 140	197,3
	9	159	0,000 165	237,3	0,000 165	222,3	0,000 190	207,3
	10	186	0,000 115	207,3	0,000 165	212,3	0,000 240	212,3
	11	215	0,000 190	227,3	0,000 240	227,3	0,000 290	227,3
	12	246	0,000 165	232,3	0,000 215	237,3	0,000 290	242,3
2008	1	280	0,000 115	237,3	0,000 165	252,3	0,000 215	252,3
	2	313	0,000 090	222,3	0,000 115	247,3	0,000 140	262,3
	3	342	0,000 115	227,3	0,000 090	252,3	0,000 115	272,3
	4	10	0,000 140	227,3	0,000 115	242,3	0,000 065	267,3
	5	38	0,000 190	237,3	0,000 115	242,3	0,000 090	252,3
	6	69	0,000 165	247,3	0,000 115	247,3	0,000 040	242,3
	7	100	0,000 140	237,3	0,000 115	227,3	0,000 140	212,3
	8	131	0,000 215	237,3	0,000 240	232,3	0,000 215	222,3
	9	160	0,000 215	252,3	0,000 165	242,3	0,000 165	232,3
	10	187	0,000 140	262,3	0,000 165	247,3	0,000 190	237,3
	11	216	0,000 215	247,3	0,000 115	252,3	0,000 165	242,3
	12	247	0,000 090	237,3	0,000 140	242,3	0,000 190	247,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2009	1	280	0,000 140	242,3	0,000 165	252,3	0,000 265	257,3
	2	313	0,000 165	257,3	0,000 190	267,3	0,000 265	272,3
	3	342	0,000 165	262,3	0,000 190	272,3	0,000 215	287,3
	4	10	0,000 115	262,3	0,000 115	287,3	0,000 140	312,3
	5	38	0,000 115	252,3	0,000 065	267,3	0,000 040	347,3
	6	69	0,000 115	272,3	0,000 065	282,3	0,000 040	287,3
	7	100	0,000 090	287,3	0,000 040	277,3	0,000 015	272,3
	8	131	0,000 015	292,3	0,000 015	342,3	0,000 015	192,3
	9	160	0,000 040	267,3	0,000 040	227,3	0,000 090	222,3
	10	187	0,000 140	297,3	0,000 115	247,3	0,000 115	237,3
	11	216	0,000 115	282,3	0,000 140	272,3	0,000 165	262,3
	12	247	0,000 090	302,3	0,000 115	287,3	0,000 165	277,3
2010	1	280	0,000 040	33 2,3	0,000 040	277,3	0,000 115	282,3
	2	313	0,000 065	282,3	0,000 090	297,3	0,000 165	297,3
	3	341	0,000 040	302,3	0,000 090	312,3	0,000 140	307,3
	4	10	0,000 065	332,3	0,000 090	342,3	0,000 140	347,3
	5	38	0,000 090	352,3	0,000 115	7,3	0,000 165	7,3
	6	68	0,000 090	22,3	0,000 115	27,3	0,000 140	37,3
	7	99	0,000 065	27,3	0,000 090	47,3	0,000 115	57,3
	8	131	0,000 015	337,3	0,000 040	67,3	0,000 065	77,3
	9	160	0,000 065	342,3	0,000 015	352,3	0,000 015	322,3
	10	187	0,000 090	7,3	0,000 040	7,3	0,000 015	7,3
	11	216	0,000 140	37,3	0,000 090	32,3	0,000 040	32,3
	12	246	0,000 140	47,3	0,000 065	32,3	0,000 040	17,3
2011	1	279	0,000 140	27,3	0,000 140	12,3	0,000 140	357,3
	2	313	0,000 215	42,3	0,000 190	27,3	0,000 215	17,3
	3	341	0,000 215	47,3	0,000 215	32,3	0,000 265	27,3
	4	10	0,000 165	57,3	0,000 215	52,3	0,000 240	42,3
	5	37	0,000 115	57,3	0,000 165	57,3	0,000 215	52,3
	6	68	0,000 115	42,3	0,000 165	52,3	0,000 215	57,3
	7	99	0,000 190	37,3	0,000 190	47,3	0,000 215	57,3
	8	130	0,000 265	47,3	0,000 265	57,3	0,000 265	62,3
	9	159	0,000 265	62,3	0,000 265	72,3	0,000 290	77,3
	10	186	0,000 215	62,3	0,000 165	72,3	0,000 140	92,3
	11	215	0,000 265	57,3	0,000 190	57,3	0,000 165	62,3
	12	246	0,000 265	62,3	0,000 190	62,3	0,000 140	62,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2012	1	279	0,000 240	72,3	0,000 190	67,3	0,000 140	57,3
	2	312	0,000 190	67,3	0,000 190	57,3	0,000 165	42,3
	3	342	0,000 190	67,3	0,000 215	52,3	0,000 215	42,3
	4	10	0,000 240	62,3	0,000 265	57,3	0,000 340	52,3
	5	38	0,000 315	67,3	0,000 340	62,3	0,000 415	62,3
	6	69	0,000 315	77,3	0,000 365	77,3	0,000 415	72,3
	7	100	0,000 240	72,3	0,000 290	77,3	0,000 390	82,3
	8	131	0,000 315	72,3	0,000 340	77,3	0,000 365	82,3
	9	160	0,000 340	82,3	0,000 340	87,3	0,000 340	92,3
	10	187	0,000 290	87,3	0,000 290	97,3	0,000 265	107,3
	11	216	0,000 215	87,3	0,000 215	102,3	0,000 190	112,3
	12	247	0,000 215	82,3	0,000 140	82,3	0,000 090	87,3
2013	1	279	0,000 290	77,3	0,000 240	72,3	0,000 190	62,3
	2	312	0,000 340	82,3	0,000 315	77,3	0,000 290	72,3
	3	342	0,000 340	87,3	0,000 340	82,3	0,000 315	77,3
	4	10	0,000 315	97,3	0,000 290	87,3	0,000 315	77,3
	5	38	0,000 290	92,3	0,000 315	87,3	0,000 365	82,3
	6	69	0,000 315	97,3	0,000 390	97,3	0,000 415	92,3
	7	100	0,000 290	107,3	0,000 340	102,3	0,000 390	102,3
	8	131	0,000 240	112,3	0,000 290	112,3	0,000 340	117,3
	9	160	0,000 215	107,3	0,000 240	117,3	0,000 290	122,3
	10	187	0,000 265	97,3	0,000 265	112,3	0,000 290	122,3
	11	216	0,000 340	102,3	0,000 315	112,3	0,000 265	122,3
	12	247	0,000 340	112,3	0,000 290	117,3	0,000 265	127,3
2014	1	280	0,000 265	117,3	0,000 215	127,3	0,000 165	132,3
	2	313	0,000 265	112,3	0,000 215	112,3	0,000 190	102,3
	3	341	0,000 290	117,3	0,000 265	107,3	0,000 240	102,3
	4	10	0,000 315	127,3	0,000 290	122,3	0,000 290	117,3
	5	38	0,000 315	137,3	0,000 290	132,3	0,000 265	122,3
	6	68	0,000 240	142,3	0,000 240	137,3	0,000 290	122,3
	7	99	0,000 190	137,3	0,000 265	127,3	0,000 265	127,3
	8	131	0,000 240	127,3	0,000 315	127,3	0,000 365	127,3
	9	160	0,000 265	137,3	0,000 315	137,3	0,000 365	142,3
	10	187	0,000 290	142,3	0,000 340	152,3	0,000 365	152,3
	11	216	0,000 265	152,3	0,000 290	157,3	0,000 315	167,3
	12	246	0,000 340	162,3	0,000 265	162,3	0,000 265	177,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2015	1	279	0,000 315	162,3	0,000 290	172,3	0,000 265	182,3
	2	313	0,000 265	177,3	0,000 240	182,3	0,000 215	192,3
	3	341	0,000 240	177,3	0,000 215	177,3	0,000 165	182,3
	4	10	0,000 190	172,3	0,000 165	162,3	0,000 090	162,3
	5	37	0,000 215	162,3	0,000 190	152,3	0,000 190	142,3
	6	68	0,000 290	162,3	0,000 315	152,3	0,000 340	142,3
	7	99	0,000 315	172,3	0,000 315	162,3	0,000 340	157,3
	8	130	0,000 315	182,3	0,000 340	177,3	0,000 365	172,3
	9	159	0,000 265	182,3	0,000 290	182,3	0,000 365	177,3
	10	186	0,000 290	187,3	0,000 340	187,3	0,000 415	187,3
	11	215	0,000 315	197,3	0,000 365	202,3	0,000 415	202,3
	12	246	0,000 290	202,3	0,000 340	212,3	0,000 365	212,3
2016	1	279	0,000 215	207,3	0,000 240	217,3	0,000 290	222,3
	2	312	0,000 240	192,3	0,000 215	207,3	0,000 215	217,3
	3	342	0,000 240	192,3	0,000 215	202,3	0,000 165	212,3
	4	10	0,000 290	202,3	0,000 240	202,3	0,000 190	202,3
	5	38	0,000 315	207,3	0,000 265	207,3	0,000 190	202,3
	6	69	0,000 290	217,3	0,000 240	207,3	0,000 190	207,3
	7	100	0,000 290	217,3	0,000 290	202,3	0,000 315	192,3
	8	131	0,000 340	222,3	0,000 365	212,3	0,000 365	207,3
	9	160	0,000 315	232,3	0,000 340	222,3	0,000 365	217,3
	10	187	0,000 265	237,3	0,000 290	232,3	0,000 315	227,3
	11	216	0,000 215	222,3	0,000 265	222,3	0,000 315	222,3
	12	247	0,000 240	222,3	0,000 290	222,3	0,000 340	232,3
2017	1	279	0,000 315	227,3	0,000 340	232,3	0,000 390	237,3
	2	312	0,000 340	237,3	0,000 365	242,3	0,000 390	252,3
	3	342	0,000 340	242,3	0,000 340	247,3	0,000 340	257,3
	4	10	0,000 290	242,3	0,000 265	252,3	0,000 240	257,3
	5	38	0,000 315	242,3	0,000 240	247,3	0,000 190	247,3
	6	69	0,000 315	252,3	0,000 265	252,3	0,000 215	252,3
	7	100	0,000 290	257,3	0,000 240	257,3	0,000 190	257,3
	8	131	0,000 215	257,3	0,000 190	247,3	0,000 190	232,3
	9	160	0,000 240	247,3	0,000 240	237,3	0,000 265	227,3
	10	187	0,000 265	247,3	0,000 315	242,3	0,000 340	237,3
	11	216	0,000 315	257,3	0,000 365	257,3	0,000 415	252,3
	12	247	0,000 290	267,3	0,000 365	262,3	0,000 390	262,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2018	1	280	0,000 240	262,3	0,000 290	267,3	0,000 365	272,3
	2	313	0,000 315	262,3	0,000 340	272,3	0,000 365	277,3
	3	341	0,000 315	272,3	0,000 340	272,3	0,000 340	287,3
	4	10	0,000 290	282,3	0,000 290	292,3	0,000 315	297,3
	5	38	0,000 215	287,3	0,000 240	302,3	0,000 240	312,3
	6	68	0,000 165	287,3	0,000 115	302,3	0,000 090	312,3
	7	99	0,000 190	267,3	0,000 115	277,3	0,000 065	257,3
	8	131	0,000 240	277,3	0,000 215	267,3	0,000 165	267,3
	9	160	0,000 265	287,3	0,000 215	282,3	0,000 215	272,3
	10	187	0,000 240	297,3	0,000 215	277,3	0,000 215	272,3
	11	216	0,000 215	292,3	0,000 265	277,3	0,000 265	272,3
	12	246	0,000 240	302,3	0,000 290	292,3	0,000 315	282,3
2019	1	279	0,000 190	312,3	0,000 240	307,3	0,000 290	302,3
	2	313	0,000 140	327,3	0,000 190	322,3	0,000 240	322,3
	3	341	0,000 140	327,3	0,000 190	332,3	0,000 265	337,3
	4	10	0,000 115	312,3	0,000 140	332,3	0,000 190	337,3
	5	37	0,000 140	307,3	0,000 140	322,3	0,000 140	342,3
	6	68	0,000 190	312,3	0,000 165	327,3	0,000 190	342,3
	7	99	0,000 215	332,3	0,000 190	342,3	0,000 165	352,3
	8	130	0,000 165	347,3	0,000 115	352,3	0,000 140	12,3
	9	159	0,000 140	327,3	0,000 090	327,3	0,000 065	307,3
	10	186	0,000 165	342,3	0,000 115	332,3	0,000 090	322,3
	11	215	0,000 165	2,3	0,000 140	352,3	0,000 115	342,3
	12	246	0,000 165	12,3	0,000 140	357,3	0,000 115	342,3
2020	1	279	0,000 115	17,3	0,000 090	347,3	0,000 115	332,3
	2	312	0,000 090	352,3	0,000 140	342,3	0,000 190	337,3
	3	342	0,000 115	352,3	0,000 165	352,3	0,000 215	347,3
	4	10	0,000 165	7,3	0,000 215	7,3	0,000 265	7,3
	5	38	0,000 165	22,3	0,000 215	22,3	0,000 290	27,3
	6	69	0,000 165	32,3	0,000 190	42,3	0,000 265	47,3
	7	100	0,000 165	32,3	0,000 190	47,3	0,000 215	57,3
	8	131	0,000 240	37,3	0,000 240	52,3	0,000 240	57,3
	9	160	0,000 215	52,3	0,000 215	62,3	0,000 215	72,3
	10	187	0,000 165	62,3	0,000 140	72,3	0,000 140	87,3
	11	216	0,000 115	52,3	0,000 040	47,3	0,000 015	52,3
	12	247	0,000 115	37,3	0,000 090	27,3	0,000 090	12,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2021	1	279	0,000 215	47,3	0,000 215	37,3	0,000 190	22,3
	2	312	0,000 265	62,3	0,000 240	52,3	0,000 190	42,3
	3	342	0,000 265	67,3	0,000 265	57,3	0,000 265	52,3
	4	10	0,000 215	72,3	0,000 240	62,3	0,000 265	47,3
	5	38	0,000 215	67,3	0,000 290	62,3	0,000 365	57,3
	6	69	0,000 265	72,3	0,000 340	72,3	0,000 390	72,3
	7	100	0,000 265	77,3	0,000 290	82,3	0,000 365	82,3
	8	131	0,000 215	77,3	0,000 240	87,3	0,000 265	92,3
	9	160	0,000 190	72,3	0,000 190	87,3	0,000 215	97,3
	10	187	0,000 240	72,3	0,000 190	82,3	0,000 190	92,3
	11	216	0,000 290	77,3	0,000 240	82,3	0,000 215	87,3
	12	247	0,000 290	87,3	0,000 240	92,3	0,000 165	92,3
2022	1	280	0,000 240	87,3	0,000 190	82,3	0,000 140	72,3
	2	313	0,000 290	82,3	0,000 290	72,3	0,000 265	67,3
	3	341	0,000 290	87,3	0,000 290	77,3	0,000 315	67,3
	4	10	0,000 290	97,3	0,000 290	92,3	0,000 290	82,3
	5	38	0,000 240	102,3	0,000 265	92,3	0,000 290	87,3
	6	68	0,000 165	97,3	0,000 215	92,3	0,000 265	92,3
	7	99	0,000 190	87,3	0,000 215	92,3	0,000 290	92,3
	8	131	0,000 240	92,3	0,000 290	97,3	0,000 365	97,3
	9	160	0,000 315	97,3	0,000 340	102,3	0,000 340	112,3
	10	187	0,000 315	102,3	0,000 290	117,3	0,000 315	122,3
	11	216	0,000 240	102,3	0,000 215	107,3	0,000 190	122,3
	12	246	0,000 265	102,3	0,000 240	107,3	0,000 190	112,3
2023	1	279	0,000 215	117,3	0,000 165	117,3	0,000 115	127,3
	2	313	0,000 140	122,3	0,000 090	117,3	0,000 040	107,3
	3	341	0,000 140	122,3	0,000 090	117,3	0,000 090	82,3
	4	10	0,000 165	107,3	0,000 165	97,3	0,000 165	82,3
	5	37	0,000 190	112,3	0,000 240	102,3	0,000 265	87,3
	6	68	0,000 240	117,3	0,000 290	107,3	0,000 315	102,3
	7	99	0,000 190	127,3	0,000 240	122,3	0,000 290	117,3
	8	130	0,000 140	112,3	0,000 190	117,3	0,000 240	117,3
	9	159	0,000 190	117,3	0,000 190	127,3	0,000 265	127,3
	10	186	0,000 190	132,3	0,000 215	142,3	0,000 240	147,3
	11	215	0,000 165	152,3	0,000 190	167,3	0,000 215	172,3
	12	246	0,000 140	177,3	0,000 140	177,3	0,000 165	192,3

Table A.1 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,00 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,005 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,01 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2024	1	279	0,000 090	132,3	0,000 065	177,3	0,000 090	207,3
	2	312	0,000 140	127,3	0,000 090	127,3	0,000 040	127,3
	3	342	0,000 140	137,3	0,000 090	132,3	0,000 065	117,3
	4	10	0,000 140	157,3	0,000 090	147,3	0,000 065	142,3
	5	38	0,000 115	172,3	0,000 090	152,3	0,000 090	117,3
	6	69	0,000 090	177,3	0,000 115	142,3	0,000 165	127,3
	7	100	0,000 115	177,3	0,000 140	162,3	0,000 165	152,3
	8	131	0,000 165	217,3	0,000 190	182,3	0,000 215	172,3
	9	160	0,000 140	207,3	0,000 165	197,3	0,000 215	192,3
	10	187	0,000 090	212,3	0,000 140	202,3	0,000 190	197,3
	11	216	0,000 090	172,3	0,000 115	197,3	0,000 165	202,3
	12	247	0,000 140	182,3	0,000 140	197,3	0,000 140	202,3
2025	1	279	0,000 165	197,3	0,000 165	217,3	0,000 190	222,3
	2	312	0,000 165	217,3	0,000 190	232,3	0,000 190	242,3
	3	342	0,000 190	227,3	0,000 190	242,3	0,000 165	252,3
	4	10	0,000 115	222,3	0,000 040	172,3	0,000 015	152,3
	5	38	0,000 165	217,3	0,000 090	212,3	0,000 040	187,3
	6	69	0,000 190	227,3	0,000 140	217,3	0,000 090	207,3
	7	100	0,000 165	232,3	0,000 140	222,3	0,000 115	212,3
	8	131	0,000 115	227,3	0,000 115	207,3	0,000 115	177,3
	9	160	0,000 115	222,3	0,000 140	207,3	0,000 190	192,3
	10	187	0,000 165	227,3	0,000 215	222,3	0,000 240	212,3
	11	216	0,000 190	237,3	0,000 240	232,3	0,000 315	232,3
	12	247	0,000 190	242,3	0,000 265	247,3	0,000 315	247,3

**Table A.2 — Optimal eccentricity vector for $C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$,
 $C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$ and $C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$**

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2006	1	281	0,000 065	187,3	0,000 090	207,3	0,000 115	237,3
	2	314	0,000 015	247,3	0,000 065	257,3	0,000 140	272,3
	3	341	0,000 090	77,3	0,000 065	67,3	0,000 040	357,3
	4	10	0,000 065	107,3	0,000 040	92,3	0,000 140	32,3
	5	38	0,000 090	127,3	0,000 140	82,3	0,000 215	67,3
	6	68	0,000 140	107,3	0,000 190	102,3	0,000 265	87,3
	7	99	0,000 190	117,3	0,000 240	117,3	0,000 365	107,3
	8	131	0,000 240	137,3	0,000 290	137,3	0,000 390	137,3
	9	160	0,000 265	157,3	0,000 315	162,3	0,000 415	162,3
	10	187	0,000 240	177,3	0,000 315	182,3	0,000 415	182,3
	11	216	0,000 240	207,3	0,000 290	207,3	0,000 415	212,3
	12	246	0,000 215	232,3	0,000 265	232,3	0,000 365	237,3
2007	1	281	0,000 190	232,3	0,000 215	242,3	0,000 290	257,3
	2	314	0,000 165	247,3	0,000 165	267,3	0,000 290	272,3
	3	341	0,000 115	257,3	0,000 140	272,3	0,000 140	312,3
	4	10	0,000 015	287,3	0,000 015	312,3	0,000 090	7,3
	5	37	0,000 040	112,3	0,000 040	87,3	0,000 115	67,3
	6	68	0,000 115	142,3	0,000 115	122,3	0,000 190	102,3
	7	99	0,000 165	172,3	0,000 165	157,3	0,000 215	132,3
	8	130	0,000 165	187,3	0,000 190	172,3	0,000 265	162,3
	9	159	0,000 190	197,3	0,000 265	192,3	0,000 365	177,3
	10	186	0,000 290	207,3	0,000 365	207,3	0,000 440	202,3
	11	215	0,000 340	227,3	0,000 365	222,3	0,000 465	222,3
	12	246	0,000 365	242,3	0,000 415	242,3	0,000 515	247,3
2008	1	280	0,000 265	257,3	0,000 315	262,3	0,000 440	267,3
	2	313	0,000 165	277,3	0,000 215	282,3	0,000 340	287,3
	3	342	0,000 115	287,3	0,000 165	302,3	0,000 265	312,3
	4	10	0,000 040	312,3	0,000 065	312,3	0,000 140	352,3
	5	38	0,000 040	262,3	0,000 015	47,3	0,000 090	37,3
	6	69	0,000 015	172,3	0,000 040	137,3	0,000 090	102,3
	7	100	0,000 140	187,3	0,000 140	172,3	0,000 190	152,3
	8	131	0,000 215	212,3	0,000 265	207,3	0,000 265	182,3
	9	160	0,000 190	222,3	0,000 215	207,3	0,000 290	197,3
	10	187	0,000 215	227,3	0,000 265	222,3	0,000 340	212,3
	11	216	0,000 240	237,3	0,000 290	232,3	0,000 415	232,3
	12	247	0,000 240	247,3	0,000 315	247,3	0,000 415	247,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2009	1	280	0,000 315	262,3	0,000 315	262,3	0,000 440	267,3
	2	313	0,000 315	277,3	0,000 340	282,3	0,000 440	287,3
	3	342	0,000 265	292,3	0,000 290	297,3	0,000 365	307,3
	4	10	0,000 165	317,3	0,000 190	327,3	0,000 290	337,3
	5	38	0,000 090	357,3	0,000 115	7,3	0,000 215	12,3
	6	69	0,000 040	42,3	0,000 090	52,3	0,000 190	62,3
	7	100	0,000 015	102,3	0,000 065	102,3	0,000 190	97,3
	8	131	0,000 065	172,3	0,000 115	157,3	0,000 190	137,3
	9	160	0,000 115	207,3	0,000 115	187,3	0,000 240	187,3
	10	187	0,000 165	227,3	0,000 190	217,3	0,000 290	212,3
	11	216	0,000 215	252,3	0,000 265	247,3	0,000 340	242,3
	12	247	0,000 215	272,3	0,000 265	267,3	0,000 390	262,3
2010	1	280	0,000 165	282,3	0,000 240	282,3	0,000 340	282,3
	2	313	0,000 215	297,3	0,000 240	302,3	0,000 340	307,3
	3	341	0,000 165	332,3	0,000 215	332,3	0,000 340	332,3
	4	10	0,000 190	357,3	0,000 240	357,3	0,000 340	7,3
	5	38	0,000 190	17,3	0,000 240	27,3	0,000 340	32,3
	6	68	0,000 190	42,3	0,000 240	47,3	0,000 365	52,3
	7	99	0,000 190	67,3	0,000 240	72,3	0,000 290	82,3
	8	131	0,000 090	92,3	0,000 140	102,3	0,000 215	112,3
	9	160	0,000 040	142,3	0,000 090	152,3	0,000 190	147,3
	10	187	0,000 015	192,3	0,000 065	192,3	0,000 190	192,3
	11	216	0,000 015	262,3	0,000 065	257,3	0,000 165	242,3
	12	246	0,000 090	312,3	0,000 140	297,3	0,000 215	282,3
2011	1	279	0,000 165	347,3	0,000 215	337,3	0,000 265	322,3
	2	313	0,000 240	12,3	0,000 265	2,3	0,000 340	352,3
	3	341	0,000 290	22,3	0,000 315	17,3	0,000 390	7,3
	4	10	0,000 265	32,3	0,000 315	32,3	0,000 415	27,3
	5	37	0,000 265	47,3	0,000 315	47,3	0,000 440	47,3
	6	68	0,000 240	57,3	0,000 290	57,3	0,000 415	62,3
	7	99	0,000 290	62,3	0,000 290	67,3	0,000 415	77,3
	8	130	0,000 315	72,3	0,000 315	77,3	0,000 415	87,3
	9	159	0,000 290	87,3	0,000 340	97,3	0,000 340	107,3
	10	186	0,000 165	97,3	0,000 190	112,3	0,000 240	132,3
	11	215	0,000 065	62,3	0,000 040	177,3	0,000 090	177,3
	12	246	0,000 090	57,3	0,000 015	242,3	0,000 015	247,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2012	1	279	0,000 090	42,3	0,000 090	12,3	0,000 140	317,3
	2	312	0,000 165	22,3	0,000 190	12,3	0,000 265	357,3
	3	342	0,000 240	32,3	0,000 290	22,3	0,000 390	17,3
	4	10	0,000 390	47,3	0,000 440	42,3	0,000 515	37,3
	5	38	0,000 440	57,3	0,000 515	57,3	0,000 615	57,3
	6	69	0,000 465	72,3	0,000 515	72,3	0,000 640	72,3
	7	100	0,000 415	82,3	0,000 515	87,3	0,000 590	87,3
	8	131	0,000 365	87,3	0,000 415	92,3	0,000 515	97,3
	9	160	0,000 365	102,3	0,000 390	102,3	0,000 465	117,3
	10	187	0,000 290	112,3	0,000 290	122,3	0,000 340	137,3
	11	216	0,000 165	127,3	0,000 190	137,3	0,000 215	162,3
	12	247	0,000 040	87,3	0,000 040	172,3	0,000 090	192,3
2013	1	279	0,000 165	57,3	0,000 115	32,3	0,000 015	247,3
	2	312	0,000 240	62,3	0,000 215	52,3	0,000 215	42,3
	3	342	0,000 340	67,3	0,000 340	62,3	0,000 365	47,3
	4	10	0,000 365	72,3	0,000 365	62,3	0,000 465	52,3
	5	38	0,000 440	77,3	0,000 465	72,3	0,000 565	67,3
	6	69	0,000 490	87,3	0,000 540	87,3	0,000 640	87,3
	7	100	0,000 465	102,3	0,000 515	102,3	0,000 615	102,3
	8	131	0,000 390	117,3	0,000 440	117,3	0,000 540	122,3
	9	160	0,000 315	127,3	0,000 365	132,3	0,000 465	137,3
	10	187	0,000 315	127,3	0,000 315	137,3	0,000 390	147,3
	11	216	0,000 290	127,3	0,000 290	137,3	0,000 290	162,3
	12	247	0,000 240	132,3	0,000 215	142,3	0,000 165	177,3
2014	1	280	0,000 140	142,3	0,000 115	162,3	0,000 090	187,3
	2	313	0,000 140	97,3	0,000 015	202,3	0,000 015	237,3
	3	341	0,000 215	92,3	0,000 215	82,3	0,000 215	62,3
	4	10	0,000 290	107,3	0,000 265	97,3	0,000 315	82,3
	5	38	0,000 290	112,3	0,000 315	102,3	0,000 365	92,3
	6	68	0,000 290	117,3	0,000 315	112,3	0,000 415	102,3
	7	99	0,000 365	117,3	0,000 390	117,3	0,000 515	117,3
	8	131	0,000 415	127,3	0,000 465	127,3	0,000 565	127,3
	9	160	0,000 415	142,3	0,000 490	142,3	0,000 590	147,3
	10	187	0,000 415	157,3	0,000 440	162,3	0,000 540	167,3
	11	216	0,000 365	172,3	0,000 390	177,3	0,000 515	187,3
	12	246	0,000 315	182,3	0,000 315	192,3	0,000 415	207,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2015	1	279	0,000 240	192,3	0,000 265	197,3	0,000 265	217,3
	2	313	0,000 190	202,3	0,000 165	212,3	0,000 165	227,3
	3	341	0,000 140	197,3	0,000 090	217,3	0,000 040	272,3
	4	10	0,000 090	132,3	0,000 065	107,3	0,000 115	72,3
	5	37	0,000 215	127,3	0,000 240	117,3	0,000 265	97,3
	6	68	0,000 340	137,3	0,000 315	127,3	0,000 390	117,3
	7	99	0,000 390	152,3	0,000 415	147,3	0,000 465	137,3
	8	130	0,000 390	167,3	0,000 415	162,3	0,000 465	157,3
	9	159	0,000 390	177,3	0,000 465	177,3	0,000 565	172,3
	10	186	0,000 465	187,3	0,000 515	187,3	0,000 615	187,3
	11	215	0,000 440	207,3	0,000 490	207,3	0,000 640	207,3
	12	246	0,000 415	217,3	0,000 465	222,3	0,000 565	227,3
2016	1	279	0,000 315	232,3	0,000 365	237,3	0,000 440	242,3
	2	312	0,000 215	232,3	0,000 215	242,3	0,000 290	262,3
	3	342	0,000 140	222,3	0,000 140	257,3	0,000 165	282,3
	4	10	0,000 140	202,3	0,000 090	207,3	0,000 015	332,3
	5	38	0,000 140	202,3	0,000 090	197,3	0,000 040	87,3
	6	69	0,000 190	182,3	0,000 165	167,3	0,000 240	142,3
	7	100	0,000 315	187,3	0,000 315	177,3	0,000 340	162,3
	8	131	0,000 365	202,3	0,000 390	192,3	0,000 440	182,3
	9	160	0,000 365	217,3	0,000 390	207,3	0,000 465	197,3
	10	187	0,000 365	217,3	0,000 390	217,3	0,000 490	212,3
	11	216	0,000 365	222,3	0,000 440	222,3	0,000 540	222,3
	12	247	0,000 390	232,3	0,000 440	232,3	0,000 540	237,3
2017	1	279	0,000 415	242,3	0,000 465	247,3	0,000 565	252,3
	2	312	0,000 415	257,3	0,000 440	262,3	0,000 540	267,3
	3	342	0,000 365	267,3	0,000 390	272,3	0,000 440	282,3
	4	10	0,000 240	277,3	0,000 240	282,3	0,000 265	302,3
	5	38	0,000 140	252,3	0,000 115	277,3	0,000 115	322,3
	6	69	0,000 165	252,3	0,000 015	252,3	0,000 015	37,3
	7	100	0,000 140	237,3	0,000 065	217,3	0,000 065	157,3
	8	131	0,000 190	207,3	0,000 190	202,3	0,000 215	182,3
	9	160	0,000 290	222,3	0,000 315	212,3	0,000 390	202,3
	10	187	0,000 365	232,3	0,000 415	227,3	0,000 515	222,3
	11	216	0,000 465	247,3	0,000 515	247,3	0,000 615	242,3
	12	247	0,000 440	262,3	0,000 490	262,3	0,000 640	257,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2018	1	280	0,000 415	272,3	0,000 465	272,3	0,000 565	272,3
	2	313	0,000 415	277,3	0,000 440	282,3	0,000 565	287,3
	3	341	0,000 365	287,3	0,000 390	297,3	0,000 465	302,3
	4	10	0,000 315	307,3	0,000 340	312,3	0,000 390	327,3
	5	38	0,000 215	317,3	0,000 215	332,3	0,000 265	347,3
	6	68	0,000 090	332,3	0,000 115	352,3	0,000 140	22,3
	7	99	0,000 015	247,3	0,000 015	22,3	0,000 065	62,3
	8	131	0,000 140	262,3	0,000 115	232,3	0,000 015	122,3
	9	160	0,000 190	257,3	0,000 190	247,3	0,000 215	217,3
	10	187	0,000 215	262,3	0,000 265	247,3	0,000 340	227,3
	11	216	0,000 315	267,3	0,000 390	257,3	0,000 465	252,3
	12	246	0,000 365	282,3	0,000 415	277,3	0,000 515	272,3
2019	1	279	0,000 340	302,3	0,000 390	297,3	0,000 515	297,3
	2	313	0,000 290	317,3	0,000 340	317,3	0,000 465	317,3
	3	341	0,000 315	337,3	0,000 365	337,3	0,000 465	337,3
	4	10	0,000 215	347,3	0,000 265	352,3	0,000 390	357,3
	5	37	0,000 190	357,3	0,000 215	2,3	0,000 315	17,3
	6	68	0,000 165	352,3	0,000 165	7,3	0,000 215	32,3
	7	99	0,000 140	7,3	0,000 115	17,3	0,000 140	47,3
	8	130	0,000 140	27,3	0,000 115	37,3	0,000 115	67,3
	9	159	0,000 040	302,3	0,000 040	82,3	0,000 065	117,3
	10	186	0,000 065	307,3	0,000 015	147,3	0,000 040	162,3
	11	215	0,000 090	317,3	0,000 065	302,3	0,000 140	252,3
	12	246	0,000 090	317,3	0,000 115	302,3	0,000 215	277,3
2020	1	279	0,000 165	307,3	0,000 215	307,3	0,000 315	302,3
	2	312	0,000 265	337,3	0,000 315	327,3	0,000 415	322,3
	3	342	0,000 265	347,3	0,000 340	347,3	0,000 440	347,3
	4	10	0,000 315	12,3	0,000 365	12,3	0,000 490	12,3
	5	38	0,000 365	32,3	0,000 415	32,3	0,000 490	32,3
	6	69	0,000 315	52,3	0,000 365	57,3	0,000 490	57,3
	7	100	0,000 290	62,3	0,000 290	67,3	0,000 390	77,3
	8	131	0,000 215	72,3	0,000 240	77,3	0,000 340	92,3
	9	160	0,000 215	82,3	0,000 240	92,3	0,000 265	107,3
	10	187	0,000 115	107,3	0,000 115	112,3	0,000 140	137,3
	11	216	0,000 015	117,3	0,000 015	137,3	0,000 040	177,3
	12	247	0,000 090	357,3	0,000 090	337,3	0,000 115	302,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2021	1	279	0,000 165	12,3	0,000 165	2,3	0,000 190	332,3
	2	312	0,000 215	27,3	0,000 240	17,3	0,000 290	357,3
	3	342	0,000 290	42,3	0,000 315	32,3	0,000 415	22,3
	4	10	0,000 315	47,3	0,000 390	42,3	0,000 465	37,3
	5	38	0,000 390	57,3	0,000 440	57,3	0,000 540	52,3
	6	69	0,000 440	72,3	0,000 490	72,3	0,000 615	72,3
	7	100	0,000 390	87,3	0,000 440	87,3	0,000 565	87,3
	8	131	0,000 315	102,3	0,000 365	102,3	0,000 465	107,3
	9	160	0,000 240	107,3	0,000 265	112,3	0,000 340	127,3
	10	187	0,000 165	112,3	0,000 190	122,3	0,000 240	142,3
	11	216	0,000 190	97,3	0,000 140	117,3	0,000 115	157,3
	12	247	0,000 140	102,3	0,000 115	102,3	0,000 015	272,3
2022	1	280	0,000 090	57,3	0,000 090	27,3	0,000 115	2,3
	2	313	0,000 240	57,3	0,000 240	47,3	0,000 240	32,3
	3	341	0,000 315	62,3	0,000 340	52,3	0,000 340	42,3
	4	10	0,000 315	72,3	0,000 340	67,3	0,000 415	57,3
	5	38	0,000 340	82,3	0,000 365	77,3	0,000 465	67,3
	6	68	0,000 315	87,3	0,000 365	87,3	0,000 490	82,3
	7	99	0,000 340	92,3	0,000 415	92,3	0,000 490	97,3
	8	131	0,000 390	102,3	0,000 465	102,3	0,000 515	112,3
	9	160	0,000 365	117,3	0,000 440	117,3	0,000 490	127,3
	10	187	0,000 315	132,3	0,000 365	137,3	0,000 440	147,3
	11	216	0,000 190	142,3	0,000 215	162,3	0,000 290	172,3
	12	246	0,000 140	132,3	0,000 090	157,3	0,000 140	197,3
2023	1	279	0,000 065	127,3	0,000 015	232,3	0,000 040	267,3
	2	313	0,000 040	67,3	0,000 040	32,3	0,000 115	352,3
	3	341	0,000 090	62,3	0,000 090	42,3	0,000 190	27,3
	4	10	0,000 190	77,3	0,000 240	67,3	0,000 290	52,3
	5	37	0,000 315	82,3	0,000 390	77,3	0,000 440	72,3
	6	68	0,000 365	102,3	0,000 415	97,3	0,000 515	92,3
	7	99	0,000 340	117,3	0,000 390	112,3	0,000 490	112,3
	8	130	0,000 290	117,3	0,000 365	117,3	0,000 465	122,3
	9	159	0,000 315	127,3	0,000 365	137,3	0,000 440	142,3
	10	186	0,000 265	152,3	0,000 315	162,3	0,000 415	167,3
	11	215	0,000 240	182,3	0,000 265	182,3	0,000 365	192,3
	12	246	0,000 215	207,3	0,000 240	212,3	0,000 340	222,3

Table A.2 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,015 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,02 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,03 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2024	1	279	0,000 090	227,3	0,000 140	237,3	0,000 215	247,3
	2	312	0,000 015	97,3	0,000 040	287,3	0,000 140	297,3
	3	342	0,000 015	97,3	0,000 015	317,3	0,000 115	337,3
	4	10	0,000 040	117,3	0,000 090	52,3	0,000 165	37,3
	5	38	0,000 165	87,3	0,000 190	82,3	0,000 290	67,3
	6	69	0,000 190	122,3	0,000 265	112,3	0,000 315	102,3
	7	100	0,000 240	142,3	0,000 290	137,3	0,000 365	127,3
	8	131	0,000 240	162,3	0,000 290	162,3	0,000 365	152,3
	9	160	0,000 240	182,3	0,000 290	182,3	0,000 390	177,3
	10	187	0,000 240	197,3	0,000 290	197,3	0,000 390	192,3
	11	216	0,000 215	207,3	0,000 240	207,3	0,000 365	212,3
	12	247	0,000 215	222,3	0,000 240	222,3	0,000 340	232,3
2025	1	279	0,000 215	232,3	0,000 240	237,3	0,000 315	252,3
	2	312	0,000 215	252,3	0,000 240	257,3	0,000 290	272,3
	3	342	0,000 190	262,3	0,000 165	277,3	0,000 240	292,3
	4	10	0,000 015	142,3	0,000 065	317,3	0,000 165	327,3
	5	38	0,000 015	187,3	0,000 015	352,3	0,000 065	17,3
	6	69	0,000 065	212,3	0,000 065	102,3	0,000 115	87,3
	7	100	0,000 065	187,3	0,000 090	147,3	0,000 215	127,3
	8	131	0,000 165	177,3	0,000 215	167,3	0,000 290	152,3
	9	160	0,000 215	192,3	0,000 265	182,3	0,000 365	182,3
	10	187	0,000 265	207,3	0,000 340	207,3	0,000 440	202,3
	11	216	0,000 390	232,3	0,000 390	227,3	0,000 515	227,3
	12	247	0,000 365	247,3	0,000 440	247,3	0,000 540	247,3

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**Table A.3 — Optimal eccentricity vector for $C_R \times Alm = 0,04 \text{ m}^2/\text{kg}$,
 $C_R \times Alm = 0,05 \text{ m}^2/\text{kg}$ and $C_R \times Alm = 0,06 \text{ m}^2/\text{kg}$**

Year	Month	L_S (°)	$C_R \times Alm = 0,04 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,05 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2006	1	281	0,000 215	252,3	0,000 315	257,3	0,000 415	267,3
	2	314	0,000 190	297,3	0,000 315	297,3	0,000 415	302,3
	3	341	0,000 165	352,3	0,000 265	347,3	0,000 390	347,3
	4	10	0,000 215	22,3	0,000 315	17,3	0,000 440	17,3
	5	38	0,000 315	57,3	0,000 415	52,3	0,000 540	52,3
	6	68	0,000 390	87,3	0,000 490	82,3	0,000 615	82,3
	7	99	0,000 465	107,3	0,000 590	107,3	0,000 665	107,3
	8	131	0,000 515	132,3	0,000 615	132,3	0,000 715	132,3
	9	160	0,000 515	162,3	0,000 615	162,3	0,000 715	157,3
	10	187	0,000 490	187,3	0,000 615	187,3	0,000 715	187,3
	11	216	0,000 515	212,3	0,000 615	217,3	0,000 715	217,3
	12	246	0,000 515	242,3	0,000 590	242,3	0,000 715	242,3
2007	1	281	0,000 390	262,3	0,000 490	267,3	0,000 615	267,3
	2	314	0,000 365	282,3	0,000 415	292,3	0,000 515	297,3
	3	341	0,000 265	322,3	0,000 365	327,3	0,000 465	332,3
	4	10	0,000 190	7,3	0,000 315	12,3	0,000 415	12,3
	5	37	0,000 215	57,3	0,000 315	52,3	0,000 415	47,3
	6	68	0,000 290	92,3	0,000 390	87,3	0,000 515	82,3
	7	99	0,000 315	117,3	0,000 440	112,3	0,000 515	112,3
	8	130	0,000 390	142,3	0,000 490	142,3	0,000 565	142,3
	9	159	0,000 465	177,3	0,000 565	177,3	0,000 640	172,3
	10	186	0,000 540	197,3	0,000 665	197,3	0,000 790	197,3
	11	215	0,000 590	222,3	0,000 690	222,3	0,000 815	222,3
	12	246	0,000 615	247,3	0,000 740	247,3	0,000 865	247,3
2008	1	280	0,000 540	267,3	0,000 665	272,3	0,000 765	272,3
	2	313	0,000 440	292,3	0,000 540	297,3	0,000 640	297,3
	3	342	0,000 365	317,3	0,000 465	322,3	0,000 565	327,3
	4	10	0,000 240	357,3	0,000 365	2,3	0,000 490	7,3
	5	38	0,000 215	42,3	0,000 315	42,3	0,000 440	42,3
	6	69	0,000 140	92,3	0,000 315	82,3	0,000 390	82,3
	7	100	0,000 240	132,3	0,000 340	127,3	0,000 440	117,3
	8	131	0,000 315	167,3	0,000 390	162,3	0,000 465	152,3
	9	160	0,000 365	187,3	0,000 440	182,3	0,000 540	172,3
	10	187	0,000 440	207,3	0,000 540	202,3	0,000 665	202,3
	11	216	0,000 490	227,3	0,000 615	227,3	0,000 740	227,3
	12	247	0,000 540	247,3	0,000 690	252,3	0,000 790	252,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times A/m = 0,04 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,05 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2009	1	280	0,000 565	272,3	0,000 665	272,3	0,000 790	272,3
	2	313	0,000 515	292,3	0,000 640	297,3	0,000 740	297,3
	3	342	0,000 465	312,3	0,000 540	322,3	0,000 640	322,3
	4	10	0,000 390	347,3	0,000 490	352,3	0,000 590	357,3
	5	38	0,000 290	22,3	0,000 415	27,3	0,000 540	32,3
	6	69	0,000 315	62,3	0,000 415	67,3	0,000 515	67,3
	7	100	0,000 290	97,3	0,000 390	97,3	0,000 515	97,3
	8	131	0,000 290	137,3	0,000 390	137,3	0,000 490	137,3
	9	160	0,000 315	177,3	0,000 415	172,3	0,000 515	172,3
	10	187	0,000 390	207,3	0,000 465	202,3	0,000 590	202,3
	11	216	0,000 415	237,3	0,000 490	232,3	0,000 615	232,3
	12	247	0,000 515	262,3	0,000 615	257,3	0,000 715	257,3
2010	1	280	0,000 465	282,3	0,000 565	282,3	0,000 690	282,3
	2	313	0,000 440	312,3	0,000 565	307,3	0,000 665	312,3
	3	341	0,000 440	337,3	0,000 540	337,3	0,000 615	342,3
	4	10	0,000 465	7,3	0,000 565	7,3	0,000 665	7,3
	5	38	0,000 440	32,3	0,000 565	32,3	0,000 665	37,3
	6	68	0,000 465	57,3	0,000 590	62,3	0,000 715	62,3
	7	99	0,000 440	82,3	0,000 515	87,3	0,000 590	87,3
	8	131	0,000 315	117,3	0,000 440	117,3	0,000 540	122,3
	9	160	0,000 290	152,3	0,000 390	152,3	0,000 490	152,3
	10	187	0,000 290	192,3	0,000 390	192,3	0,000 490	192,3
	11	216	0,000 290	237,3	0,000 390	232,3	0,000 490	232,3
	12	246	0,000 290	272,3	0,000 440	267,3	0,000 515	267,3
2011	1	279	0,000 340	312,3	0,000 490	302,3	0,000 515	302,3
	2	313	0,000 440	342,3	0,000 515	337,3	0,000 615	332,3
	3	341	0,000 490	2,3	0,000 615	2,3	0,000 690	357,3
	4	10	0,000 515	22,3	0,000 615	22,3	0,000 740	22,3
	5	37	0,000 540	47,3	0,000 665	47,3	0,000 790	47,3
	6	68	0,000 565	67,3	0,000 665	67,3	0,000 765	67,3
	7	99	0,000 490	82,3	0,000 565	87,3	0,000 665	87,3
	8	130	0,000 465	97,3	0,000 540	102,3	0,000 640	107,3
	9	159	0,000 415	117,3	0,000 490	122,3	0,000 590	127,3
	10	186	0,000 290	142,3	0,000 365	152,3	0,000 465	162,3
	11	215	0,000 165	197,3	0,000 265	202,3	0,000 365	207,3
	12	246	0,000 140	247,3	0,000 265	247,3	0,000 390	247,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,04 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,05 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2012	1	279	0,000 240	307,3	0,000 340	297,3	0,000 440	297,3
	2	312	0,000 365	347,3	0,000 465	337,3	0,000 540	337,3
	3	342	0,000 440	7,3	0,000 565	7,3	0,000 665	2,3
	4	10	0,000 615	32,3	0,000 715	32,3	0,000 815	27,3
	5	38	0,000 715	52,3	0,000 840	52,3	0,000 965	52,3
	6	69	0,000 740	72,3	0,000 865	72,3	0,000 965	72,3
	7	100	0,000 665	87,3	0,000 815	92,3	0,000 915	92,3
	8	131	0,000 615	102,3	0,000 715	107,3	0,000 790	107,3
	9	160	0,000 540	122,3	0,000 590	132,3	0,000 690	132,3
	10	187	0,000 415	142,3	0,000 490	152,3	0,000 565	157,3
	11	216	0,000 265	177,3	0,000 340	187,3	0,000 440	197,3
	12	247	0,000 140	217,3	0,000 215	222,3	0,000 315	232,3
2013	1	279	0,000 090	302,3	0,000 165	302,3	0,000 340	292,3
	2	312	0,000 240	12,3	0,000 315	347,3	0,000 415	342,3
	3	342	0,000 390	27,3	0,000 465	17,3	0,000 565	7,3
	4	10	0,000 565	47,3	0,000 640	37,3	0,000 740	37,3
	5	38	0,000 665	62,3	0,000 815	62,3	0,000 865	57,3
	6	69	0,000 740	82,3	0,000 840	82,3	0,000 940	82,3
	7	100	0,000 715	102,3	0,000 815	102,3	0,000 915	102,3
	8	131	0,000 640	122,3	0,000 765	122,3	0,000 865	122,3
	9	160	0,000 565	142,3	0,000 665	142,3	0,000 740	147,3
	10	187	0,000 465	157,3	0,000 565	162,3	0,000 665	167,3
	11	216	0,000 340	177,3	0,000 415	187,3	0,000 515	192,3
	12	247	0,000 215	192,3	0,000 265	212,3	0,000 340	222,3
2014	1	280	0,000 090	222,3	0,000 140	242,3	0,000 240	257,3
	2	313	0,000 015	287,3	0,000 115	317,3	0,000 215	317,3
	3	341	0,000 240	42,3	0,000 290	27,3	0,000 365	22,3
	4	10	0,000 340	67,3	0,000 365	52,3	0,000 465	47,3
	5	38	0,000 440	82,3	0,000 515	72,3	0,000 615	67,3
	6	68	0,000 515	97,3	0,000 665	92,3	0,000 740	87,3
	7	99	0,000 615	112,3	0,000 765	107,3	0,000 865	107,3
	8	131	0,000 665	127,3	0,000 790	127,3	0,000 890	127,3
	9	160	0,000 690	147,3	0,000 740	152,3	0,000 865	152,3
	10	187	0,000 640	172,3	0,000 765	172,3	0,000 890	172,3
	11	216	0,000 590	192,3	0,000 690	197,3	0,000 815	202,3
	12	246	0,000 490	217,3	0,000 590	222,3	0,000 690	227,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times A/m = 0,04 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,05 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2015	1	279	0,000 315	237,3	0,000 390	247,3	0,000 515	257,3
	2	313	0,000 190	272,3	0,000 240	277,3	0,000 340	287,3
	3	341	0,000 065	327,3	0,000 190	332,3	0,000 290	337,3
	4	10	0,000 190	52,3	0,000 265	37,3	0,000 365	32,3
	5	37	0,000 340	82,3	0,000 415	72,3	0,000 515	67,3
	6	68	0,000 490	112,3	0,000 540	102,3	0,000 640	97,3
	7	99	0,000 540	132,3	0,000 640	127,3	0,000 740	122,3
	8	130	0,000 590	152,3	0,000 715	147,3	0,000 790	147,3
	9	159	0,000 640	172,3	0,000 765	167,3	0,000 865	167,3
	10	186	0,000 740	187,3	0,000 840	187,3	0,000 940	187,3
	11	215	0,000 715	212,3	0,000 840	212,3	0,000 965	212,3
	12	246	0,000 690	227,3	0,000 765	232,3	0,000 890	232,3
2016	1	279	0,000 540	252,3	0,000 665	257,3	0,000 740	257,3
	2	312	0,000 390	272,3	0,000 465	282,3	0,000 565	287,3
	3	342	0,000 215	302,3	0,000 315	312,3	0,000 440	317,3
	4	10	0,000 090	7,3	0,000 190	12,3	0,000 315	12,3
	5	38	0,000 115	72,3	0,000 240	62,3	0,000 340	62,3
	6	69	0,000 265	127,3	0,000 340	112,3	0,000 415	102,3
	7	100	0,000 415	152,3	0,000 490	142,3	0,000 540	137,3
	8	131	0,000 515	177,3	0,000 565	167,3	0,000 665	162,3
	9	160	0,000 540	192,3	0,000 640	187,3	0,000 740	182,3
	10	187	0,000 615	207,3	0,000 690	207,3	0,000 790	207,3
	11	216	0,000 640	222,3	0,000 765	222,3	0,000 865	222,3
	12	247	0,000 665	242,3	0,000 765	242,3	0,000 890	242,3
2017	1	279	0,000 665	257,3	0,000 740	257,3	0,000 865	262,3
	2	312	0,000 615	277,3	0,000 690	282,3	0,000 765	287,3
	3	342	0,000 490	292,3	0,000 540	297,3	0,000 615	307,3
	4	10	0,000 340	317,3	0,000 390	327,3	0,000 490	337,3
	5	38	0,000 190	352,3	0,000 240	7,3	0,000 340	17,3
	6	69	0,000 090	62,3	0,000 215	67,3	0,000 340	67,3
	7	100	0,000 165	127,3	0,000 265	122,3	0,000 415	117,3
	8	131	0,000 315	167,3	0,000 390	162,3	0,000 465	152,3
	9	160	0,000 440	192,3	0,000 540	187,3	0,000 665	187,3
	10	187	0,000 615	217,3	0,000 715	212,3	0,000 815	207,3
	11	216	0,000 715	237,3	0,000 815	237,3	0,000 915	237,3
	12	247	0,000 740	257,3	0,000 840	257,3	0,000 940	257,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,04 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,05 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2018	1	280	0,000 690	277,3	0,000 815	277,3	0,000 915	277,3
	2	313	0,000 640	292,3	0,000 740	292,3	0,000 840	297,3
	3	341	0,000 565	312,3	0,000 640	317,3	0,000 740	317,3
	4	10	0,000 440	337,3	0,000 515	342,3	0,000 615	347,3
	5	38	0,000 340	2,3	0,000 415	12,3	0,000 540	17,3
	6	68	0,000 215	37,3	0,000 315	47,3	0,000 440	52,3
	7	99	0,000 140	82,3	0,000 240	82,3	0,000 390	107,3
	8	131	0,000 140	152,3	0,000 240	147,3	0,000 340	142,3
	9	160	0,000 290	197,3	0,000 365	187,3	0,000 440	182,3
	10	187	0,000 415	222,3	0,000 515	217,3	0,000 615	212,3
	11	216	0,000 565	247,3	0,000 640	242,3	0,000 740	242,3
	12	246	0,000 615	272,3	0,000 740	267,3	0,000 840	267,3
2019	1	279	0,000 615	292,3	0,000 715	292,3	0,000 840	292,3
	2	313	0,000 565	317,3	0,000 690	317,3	0,000 815	317,3
	3	341	0,000 565	337,3	0,000 665	337,3	0,000 765	337,3
	4	10	0,000 490	2,3	0,000 590	2,3	0,000 690	2,3
	5	37	0,000 440	22,3	0,000 540	27,3	0,000 640	32,3
	6	68	0,000 315	42,3	0,000 415	52,3	0,000 515	57,3
	7	99	0,000 240	62,3	0,000 340	77,3	0,000 440	82,3
	8	130	0,000 165	97,3	0,000 240	102,3	0,000 340	117,3
	9	159	0,000 115	137,3	0,000 190	142,3	0,000 315	152,3
	10	186	0,000 115	182,3	0,000 240	192,3	0,000 365	192,3
	11	215	0,000 265	237,3	0,000 340	232,3	0,000 540	237,3
	12	246	0,000 315	272,3	0,000 440	262,3	0,000 615	267,3
2020	1	279	0,000 415	297,3	0,000 540	292,3	0,000 640	292,3
	2	312	0,000 515	322,3	0,000 615	322,3	0,000 715	317,3
	3	342	0,000 565	347,3	0,000 665	347,3	0,000 790	347,3
	4	10	0,000 590	12,3	0,000 690	12,3	0,000 815	12,3
	5	38	0,000 640	37,3	0,000 740	37,3	0,000 840	37,3
	6	69	0,000 590	62,3	0,000 715	62,3	0,000 865	62,3
	7	100	0,000 515	82,3	0,000 665	82,3	0,000 715	87,3
	8	131	0,000 415	102,3	0,000 515	107,3	0,000 590	112,3
	9	160	0,000 315	117,3	0,000 390	132,3	0,000 465	142,3
	10	187	0,000 215	152,3	0,000 290	167,3	0,000 540	177,3
	11	216	0,000 140	212,3	0,000 240	217,3	0,000 415	217,3
	12	247	0,000 190	272,3	0,000 265	272,3	0,000 490	257,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times A/m = 0,04 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,05 \text{ m}^2/\text{kg}$		$C_R \times A/m = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2021	1	279	0,000 240	312,3	0,000 340	302,3	0,000 465	297,3
	2	312	0,000 365	337,3	0,000 465	337,3	0,000 540	332,3
	3	342	0,000 465	12,3	0,000 565	7,3	0,000 640	2,3
	4	10	0,000 565	32,3	0,000 690	32,3	0,000 790	27,3
	5	38	0,000 665	52,3	0,000 765	52,3	0,000 890	47,3
	6	69	0,000 715	72,3	0,000 840	72,3	0,000 890	72,3
	7	100	0,000 665	92,3	0,000 765	92,3	0,000 890	92,3
	8	131	0,000 565	112,3	0,000 640	117,3	0,000 765	117,3
	9	160	0,000 440	132,3	0,000 540	137,3	0,000 640	142,3
	10	187	0,000 315	157,3	0,000 390	162,3	0,000 490	167,3
	11	216	0,000 165	182,3	0,000 265	197,3	0,000 390	197,3
	12	247	0,000 065	242,3	0,000 190	247,3	0,000 290	247,3
2022	1	280	0,000 165	342,3	0,000 215	312,3	0,000 340	297,3
	2	313	0,000 265	12,3	0,000 315	357,3	0,000 390	342,3
	3	341	0,000 390	27,3	0,000 515	22,3	0,000 540	12,3
	4	10	0,000 515	47,3	0,000 590	42,3	0,000 690	37,3
	5	38	0,000 565	62,3	0,000 665	62,3	0,000 765	57,3
	6	68	0,000 590	82,3	0,000 740	77,3	0,000 840	77,3
	7	99	0,000 615	97,3	0,000 715	97,3	0,000 840	97,3
	8	131	0,000 640	112,3	0,000 740	112,3	0,000 815	117,3
	9	160	0,000 590	132,3	0,000 715	132,3	0,000 765	142,3
	10	187	0,000 490	152,3	0,000 590	157,3	0,000 690	162,3
	11	216	0,000 365	182,3	0,000 490	192,3	0,000 590	197,3
	12	246	0,000 240	217,3	0,000 365	227,3	0,000 465	232,3
2023	1	279	0,000 165	272,3	0,000 290	272,3	0,000 390	277,3
	2	313	0,000 190	332,3	0,000 290	327,3	0,000 390	322,3
	3	341	0,000 265	7,3	0,000 390	2,3	0,000 490	2,3
	4	10	0,000 415	42,3	0,000 515	37,3	0,000 565	32,3
	5	37	0,000 540	67,3	0,000 640	62,3	0,000 740	57,3
	6	68	0,000 615	87,3	0,000 715	87,3	0,000 815	87,3
	7	99	0,000 590	107,3	0,000 715	107,3	0,000 865	102,3
	8	130	0,000 590	122,3	0,000 690	122,3	0,000 890	127,3
	9	159	0,000 540	147,3	0,000 640	147,3	0,000 740	147,3
	10	186	0,000 490	172,3	0,000 615	177,3	0,000 690	177,3
	11	215	0,000 490	202,3	0,000 590	207,3	0,000 690	207,3
	12	246	0,000 440	227,3	0,000 515	232,3	0,000 590	232,3

Table A.3 (continued)

Year	Month	L_S (°)	$C_R \times Alm = 0,04 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,05 \text{ m}^2/\text{kg}$		$C_R \times Alm = 0,06 \text{ m}^2/\text{kg}$	
			e	$\omega + \Omega$	e	$\omega + \Omega$	e	$\omega + \Omega$
2024	1	279	0,000 340	257,3	0,000 440	262,3	0,000 540	267,3
	2	312	0,000 240	307,3	0,000 340	307,3	0,000 465	302,3
	3	342	0,000 215	347,3	0,000 315	347,3	0,000 440	347,3
	4	10	0,000 290	32,3	0,000 390	27,3	0,000 490	22,3
	5	38	0,000 390	62,3	0,000 465	57,3	0,000 565	57,3
	6	69	0,000 440	92,3	0,000 515	87,3	0,000 665	87,3
	7	100	0,000 440	122,3	0,000 565	117,3	0,000 690	112,3
	8	131	0,000 465	152,3	0,000 565	147,3	0,000 665	142,3
	9	160	0,000 465	172,3	0,000 590	172,3	0,000 665	167,3
	10	187	0,000 490	192,3	0,000 615	192,3	0,000 715	192,3
	11	216	0,000 490	217,3	0,000 615	217,3	0,000 715	217,3
	12	247	0,000 440	237,3	0,000 540	242,3	0,000 640	242,3
2025	1	279	0,000 415	257,3	0,000 540	262,3	0,000 615	267,3
	2	312	0,000 390	282,3	0,000 490	287,3	0,000 590	292,3
	3	342	0,000 290	307,3	0,000 390	312,3	0,000 465	322,3
	4	10	0,000 240	342,3	0,000 315	347,3	0,000 415	357,3
	5	38	0,000 165	32,3	0,000 265	37,3	0,000 365	37,3
	6	69	0,000 215	77,3	0,000 315	77,3	0,000 440	77,3
	7	100	0,000 290	117,3	0,000 465	112,3	0,000 515	112,3
	8	131	0,000 390	147,3	0,000 490	147,3	0,000 590	147,3
	9	160	0,000 465	177,3	0,000 565	177,3	0,000 665	172,3
	10	187	0,000 540	202,3	0,000 615	202,3	0,000 740	197,3
	11	216	0,000 640	227,3	0,000 765	227,3	0,000 890	227,3
	12	247	0,000 640	247,3	0,000 740	247,3	0,000 840	247,3

Annex B (informative)

Optimal manoeuvre sequences

B.1 General

Two types of manoeuvre sequences are suggested depending on whether the orbit perigee is optimal near-sun-pointing at the end of the spacecraft's operational life. Actual planning should consider mission constraints and uncertainties in estimating propellant usage.

The two main criteria for the manoeuvre sequence planning are the following:

- a) ensuring sun-pointing or keeping final orbit eccentricity small (less than 0,005);
- b) ensuring all on-board energy sources are depleted or passivated at the end of manoeuvres.

Clauses B.2 to B.4 illustrate the two types of manoeuvre sequences for impulsive burns with chemical propulsion systems. Clause B.5 discusses the two types of manoeuvre sequences for spacecraft utilizing low-thrust propulsion systems.

B.2 Type A manoeuvre sequence

The initial perigee is already in the optimal direction, near-sun-pointing. Assuming there is an initial eccentricity of 0,000 5 and a target perigee of 300 km above GEO, the following actions should be taken:

- a) perform the first burn at apogee to raise the perigee to GEO plus 200 km ($\Delta V = 4,0$ m/s);
- b) perform a new orbit determination two orbits later;
- c) perform the second burn at the new apogee to raise the perigee to GEO plus 300 km ($\Delta V = 5,0$ m/s);
- d) perform a new orbit determination two orbits later;
- e) perform the third burn at the new apogee to raise the perigee to GEO plus 250 km ($\Delta V = 0,9$ m/s and $e = 0,000\ 589$);
- f) perform a new orbit determination two orbits later;
- g) perform the fourth burn at perigee to raise the apogee to GEO plus 350 km, if propellant is available ($\Delta V = 0,9$ m/s and $e = 0,001\ 18$);
- h) perform a new orbit determination 1,5 orbits later;
- i) perform the fifth burn at apogee to raise the perigee to GEO plus 300 km ($\Delta V = 0,9$ m/s and $e = 0,000\ 588$);
- j) perform a new orbit determination two orbits later;
- k) perform the sixth burn at apogee to raise the perigee to 325 km, if adequate propellant is available ($\Delta V = 0,45$ m/s and $e = 0,000\ 294$);

- l) continue to raise the perigee and apogee by about 25 km or less for each additional burn until propellant tanks are empty, and keep the perigee sun-pointing as shown for burns 7 and 8 in Table B.1; the last few burns should be small and well planned such that the final eccentricity vector is as close to the optimal vector as possible (see Annex C).

Table B.1 — Orbit conditions and ΔV consumed after each Type A burn

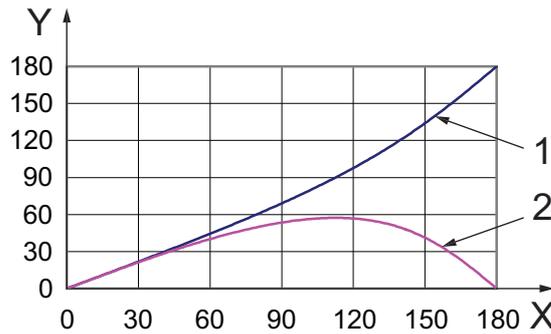
Burn	Perigee height above GEO km	Apogee height above GEO km	Accumulated longitude drift ° west	e	ΔV m/s	Accumulated ΔV m/s	Sun-pointing?
1	21	200	0	0,002 120	4,0	4,0	No
2	200	300	3,2	0,001 170	5,0	9,0	Yes
3	250	300	11,2	0,000 589	0,9	9,9	Yes
4	250	350	20,0	0,001 180	0,9	10,8	Yes
5 ^a	300	350	27,6	0,000 588	0,9	11,7	Yes
6	325	350	35,9	0,000 294	0,45	12,15	Yes
7	325	375	44,5	0,000 592	0,45	12,6	Yes
8	350	375	55,6	0,000 296	0,45	13,05	Yes

^a The minimum perigee increase, ΔH , computed by Equation (1), can usually be satisfied after the fifth burn. The remaining burns are used to increase altitude until the propellant is exhausted (the accumulated ΔV is 13,05 m/s, assumed total ΔV remaining for orbit disposal).

The actual manoeuvre sequence should consider the ground-station-viewing constraint as the satellite is gradually drifting westward as shown in the fourth column of Table B.1. It may be two to three months before the last two to three burns (burns 6 to 8) can be performed. The estimated propellant mass to achieve a minimum perigee increase of 280 km is about 8 kg for a 2 000 kg spacecraft with a chemical propulsion system ($I_{sp} = 300$ s).

B.3 Type B manoeuvre sequence

The initial perigee is not along the optimal direction for near-sun-pointing. When the initial perigee is not sun-pointing, the long-term eccentricity variation will be more pronounced and the minimum perigee altitude will be lower than the desired value of 300 km. The standard re-orbit strategy is to execute the first two to three burns away from perigee or apogee to change the argument of perigee or the eccentricity vector. The change can be achieved without additional propellant or burns. Figure B.1 gives an example of induced change in argument of perigee versus the burn location on the orbit.

**Key**

- X burn location (true anomaly), in degrees
 Y change in argument of perigee, in degrees
 1 exact solution
 2 Equations (B.1) and (B.2)

Figure B.1 — Induced change in argument of perigee versus burn location

The example assumes an initial eccentricity of 0,000 5 and the ΔV as 2,0 m/s. This burn will also raise the semi-major axis by the desired amount, approximately 110 km. The top curve is computed from equations based on closed-form orbit relations to be discussed in Annex C. The bottom curve is computed from simplified linear relations as follows:

$$\Delta e = \frac{\Delta a}{a} \times \cos v \quad (\text{B.1})$$

$$e\Delta\omega = \frac{\Delta a}{a} \times \sin v \quad (\text{B.2})$$

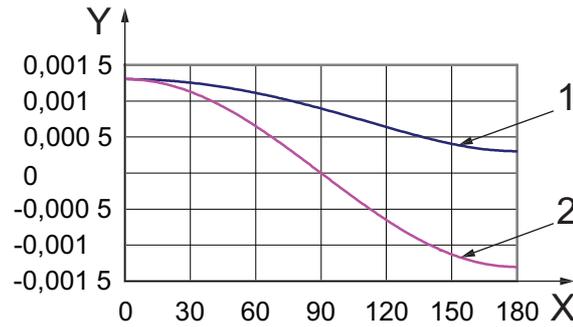
where

- Δe is the induced change in eccentricity;
 $\Delta\omega$ is the induced change in argument of perigee;
 Δa is the planned increase in mean orbit altitude or semi-major axis;
 v is the true anomaly where a single burn is executed.

The eccentricity in front of $\Delta\omega$ on the left-hand side of Equation (B.2) is the new eccentricity after the burn. Figure B.1 shows that the simplified relations for determining the induced change in argument of perigee give good approximations when the burn location (true anomaly or central angle from perigee) is less than 90°. Equations (B.1) and (B.2) are useful in the initial design of the Type B manoeuvre sequence for orbits whose perigees are not sun-pointing.

Figure B.2 shows the corresponding change in eccentricity. The approximate relation [Equation (B.1)] is good for eccentricity computation when the true anomaly is less than 40°.

When the perigee becomes sun-pointing after the first two or three burns, the remaining burn sequences should follow the Type A manoeuvre sequence.



Key

- X burn location (true anomaly), in degrees
- Y change in eccentricity
- 1 exact solution
- 2 Equation (B.1)

Figure B.2 — Induced change in eccentricity versus burn location ($e_0 = 0,0005$; $\Delta V = 2,0$ m/s)

B.4 Sample manoeuvre sequence

The following sample manoeuvre sequence assumes a 70° difference between the initial perigee and the sun vector (the sun is 70° east of the perigee vector):

- a) perform the first burn at 60° past perigee or when true anomaly equals 60° , with a ΔV of 2,0 m/s along the in-track direction to raise orbit altitude;
- b) perform an orbit determination one or two orbits later; the new orbit should be $a = 42\,220,86$ km, $e = 0,001\,613$, same inclination and RAAN, and argument of perigee advanced by $44,42^\circ$;
- c) perform the second burn at 56° past the new perigee, with a ΔV of 2,0 m/s along the in-track direction;
- d) perform an orbit determination one or two orbits later; the new orbit after the second burn should be sun-pointing with $a = 42\,275,96$ km, $e = 0,002\,584$, and argument of perigee advanced by another 25° ;
- e) perform the third burn at the new apogee to raise the perigee to GEO plus 250 km ($\Delta V = 4,52$ m/s and $e = 0,000\,362$);
- f) perform an orbit determination two orbits later;
- g) perform the fourth burn at the new apogee to raise the perigee to GEO plus 325 km ($\Delta V = 1,91$ m/s and $e = 0,000\,883\,3$);
- h) perform an orbit determination two orbits later;
- i) perform the fifth burn at the apogee to raise the perigee to GEO plus 300 km ($\Delta V = 0,9$ m/s and $e = 0,000\,294$);
- j) perform an orbit determination two orbits later;
- k) perform the sixth burn at the perigee to raise the apogee by 50 km if propellant is available ($\Delta V = 0,9$ m/s and $e = 0,000\,872$);
- l) repeat B.4 h) and B.4 i) to raise the perigee by 25 km ($\Delta V = 0,45$ m/s) after each additional burn, and continue until propellant tanks are empty as illustrated in Table B.2.

Table B.2 — Orbit conditions and ΔV consumed after each Type B burn

Burn	Perigee height above GEO km	Apogee height above GEO km	Accumulated longitude drift ° west	e	ΔV m/s	Accumulated ΔV m/s	Sun-pointing?
1	13	123	0	0,001 613	2,0	2,0	No
2	1	219	1,74	0,002 584	2,0	4,0	Yes
3	219	250	4,55	0,000 362	4,52	8,52	No
4	250	325	10,5	0,000 893	1,91	10,43	Yes
5	300	325	18,0	0,000 294	0,9	11,33	Yes
6	300	375	26,0	0,000 872	0,9	12,23	Yes
7	325	375	34,6	0,000 592	0,45	12,68	Yes
8	350	375	43,5	0,000 296	0,45	13,13	Yes

The actual manoeuvre sequence should consider the ground-station-viewing constraint as the satellite is gradually drifting westward as shown in the fourth column of Table B.1. It may be two to three months before the last two to three burns (burns 6 to 8) can be performed. The estimated propellant mass to achieve a minimum perigee increase of 280 km is about 8 kg for a 2 000 kg spacecraft with a chemical propulsion system ($I_{sp} = 300$ sec).

B.5 Manoeuvre sequence for low-thrust propulsion

For simplified illustration, we assume that a near-circular geostationary orbit is gradually pushed into the desired disposal orbit using a continuous and constant low-thrust propulsion along the velocity direction. The changes in semi-major axis and the eccentricity vector may be understood through the following set of Gaussian form of equations of motion.

$$\frac{da}{dt} = \frac{2aF}{V} \quad (\text{B.3})$$

$$\frac{dh}{dt} = \frac{2F \sin L}{V} \quad (\text{B.4})$$

$$\frac{dk}{dt} = \frac{2F \cos L}{V} \quad (\text{B.5})$$

$$\frac{dL}{dt} = n \quad (\text{B.6})$$

where

$$h = e \cos(\omega + \Omega);$$

$$k = e \sin(\omega + \Omega);$$

$$L = M + \omega + \Omega;$$

a is the semi-major axis;

F is the constant acceleration along the velocity direction;

V is the magnitude of the velocity;

n is the orbit mean motion;

M is the mean anomaly.

Equations (B.3) to (B.6) can be integrated by assuming constant a and V for a small increase in mean orbit altitude, e.g. $\Delta H = 280$ km, as follows:

$$\Delta a = \frac{2aF\Delta t}{V} \quad (\text{B.7})$$

$$\Delta h = \frac{2F(\cos L_0 - \cos L_1)}{Vn} \quad (\text{B.8})$$

$$\Delta k = \frac{2F(\sin L_1 - \sin L_0)}{Vn} \quad (\text{B.9})$$

$$L_1 = L_0 + n\Delta t \quad (\text{B.10})$$

The time required for the low-thrust propulsion to achieve the desired altitude increase can be determined from Equations (B.3) to (B.5), or from Equation (B.11):

$$\Delta t = \frac{\Delta HV}{2aF} \quad (\text{B.11})$$

For the Type A manoeuvre sequence, no change in eccentricity vector for retaining sun-pointing geometry is required. Therefore, $\Delta t > \frac{\Delta HV}{2aF}$ and $L_1 \approx L_0$.

For the Type B manoeuvre sequence, the time of action of the low-thrust propulsion should be such that the desired altitude increase is reached and the final eccentricity vector is sun-pointing. For example, a GEO spacecraft is equipped with the xenon ion propulsion system (XIPS) designed by the Boeing Company. The estimated thrust level is about 80 mN and the specific impulse (I_{sp}) is 3 400 s. Assuming the mass of the spacecraft at end-of-life is 2 000 kg, the estimated acceleration generated from the XIPS is approximately $(0,4 \times 10^{-4})$ m/sec². From Equation (B.11), the time required to reach 280 km above GEO is 2 956 days. In order to ensure sun-pointing, the propulsion should continue to act for an additional three days or three orbit revolutions to the point where L_1 is equal or close to L_0 . The required propellant mass for this transfer is about 0,7 kg (which is less than one-tenth of the mass using chemical propulsion).

In actual application, the low-thrust propulsion systems of a particular spacecraft can be rather complex with burn constraints. A detailed manoeuvre sequence should be outlined to achieve the required minimum perigee altitude increase and the desired sun-pointing geometry. A description should be included of the method to be used to monitor the remaining propellant and to estimate the effective thrust level.

Annex C (informative)

Example calculations

C.1 Closed-form equations for computing off-perigee burn locations

When a re-orbit burn is applied at a location away from perigee or apogee, changes in argument of perigee and eccentricity occur. The magnitude and direction of the changes depend on the burn vector and location of the burn.

In this application, the single-burn vector is assumed to be along the in-track direction or perpendicular to the radial direction and the burn is assumed to be impulsive. The computation starts with a given ΔV applied at a given location on the orbit or true anomaly v . The following Keplerian relations will lead to the induced eccentricity and argument of perigee.

If the total orbital velocity after the burn, V , is calculated from

$$V = V_0 + \Delta V \quad (\text{C.1})$$

where V_0 is the orbital velocity before the burn, then from the *vis-viva* integral, the new semi-major axis, a , is computed as shown in Equation (C.2) after the ΔV is applied at a given true anomaly v :

$$a = \frac{1}{2/r - V^2/\mu} \quad (\text{C.2})$$

where

r is the radius of the orbit at the time of burn;

μ is the gravitational constant for the Earth.

Assuming that the ΔV is along the in-track direction and the velocity component in the radial direction is not affected, one Keplerian relation gives Equations (C.3) and (C.4):

$$e \cos v = \frac{p}{r} - 1 = \frac{a(1-e^2)}{r} - 1 \quad (\text{C.3})$$

$$e \sin v = (\mu/p_0)^{1/2} \times (p/\mu)^{1/2} \times e_0 \sin v_0 = (p/p_0)^{1/2} e_0 \sin v_0 \quad (\text{C.4})$$

where

$$p = a(1-e^2) \quad (\text{C.5})$$

$$p_0 = a_0(1-e_0^2) \quad (\text{C.6})$$

and p_0 , a_0 and e_0 are the elements before the burn.

Equations (C.3) and (C.4) can then be used to calculate e and v by iteration, through Equations (C.7) and (C.8):

$$e^2 = (e \sin v)^2 + (e \cos v)^2 \tag{C.7}$$

and

$$v = \tan^{-1} \left(\frac{e \sin v}{e \cos v} \right) \tag{C.8}$$

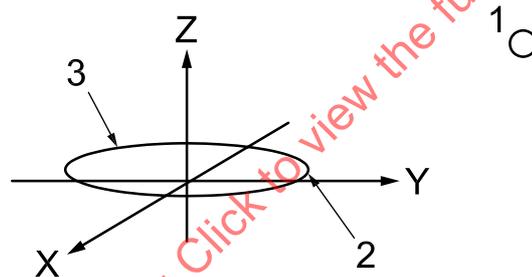
After knowing the true anomaly, v , the new value of argument of perigee is as calculated in Equation (C.9):

$$\omega = v_0 + \omega_0 - v \tag{C.9}$$

With Equations (C.1) to (C.9), the burn location, v_0 , can be determined by iteration.

C.2 Sample 100-year histories of sun-pointing disposal orbits

A sun-pointing geometry is selected by assuming an epoch of 2018-07-01. Figure C.1 illustrates the sun-pointing geometry of this example. A midnight-pointing perigee would be achieved for the same initial orbital elements by changing the epoch to 2018-01-01.



- Key**
- X, Y, Z Earth-centred Cartesian coordinates
 - 1 sun
 - 2 perigee of disposal orbit
 - 3 disposal orbit

Figure C.1 — Sun-pointing geometry with 2018-07-01 epoch

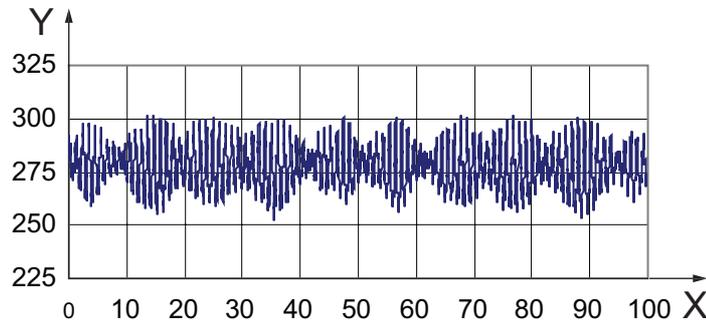
The sample orbital elements of a GEO disposal orbit for 100-year integration are determined from the assumed initial eccentricity of 0,000 5 with $A/m = 0,035 \text{ m}^2/\text{kg}$ and $C_R = 1,3$. The recommended altitude increase, ΔV , expressed in km, is

$$\Delta H = 235 + (1000 \times C_R \times A/m) = 235 + (1000 \times 1,3 \times 0,035) = 280,5 \text{ km} \tag{C.10}$$

The corresponding semi-major axis is 42 467,6 km, $e = 0,000 5$, $i = 0,1^\circ$, $\Omega = 90^\circ$, $\omega = 0^\circ$, and $M = 0^\circ$. A high-precision N-body numerical integration tool was employed to generate all the long-term orbit results presented in Figures C.2 to C.7. The perturbing forces included are Earth's gravitational harmonics (6 by 6 EGM96), lunisolar attractions and solar radiation pressure.

Figure C.2 shows the sun-pointing perigee height history of the 100-year integration. The perigee height history of such orbit is well behaved, with the perigee never below GEO plus 250 km. However, when the perigee is pointing to the local midnight, a much larger oscillation in perigee height is found in the 100-year

integration (see Figure C.3). The minimum perigee height above GEO is approaching 200 km. This finding suggests that the re-orbit insertion should be performed with perigee pointing to the sun. A long-period perigee height variation with a period of about 10,5 years, caused by sun/moon attractions, is apparent in these two cases (see Figures C.2 and C.3), as well as the other 100-year eccentricity histories.

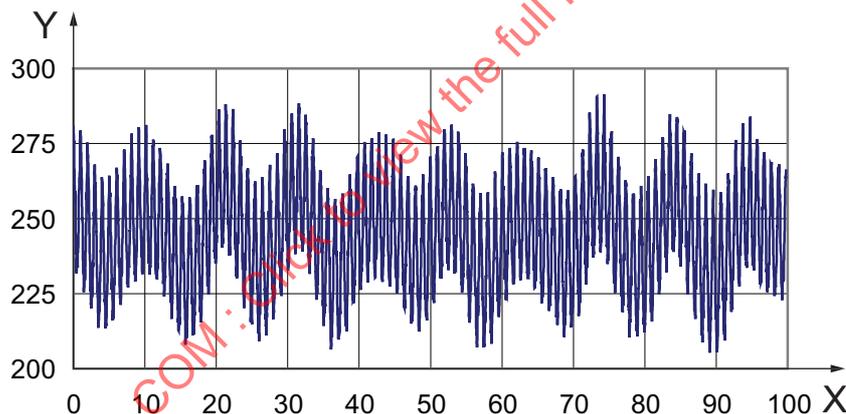


Key

X years after 2018

Y perigee above GEO, in km

Figure C.2 — 100-year perigee history (sun-pointing)



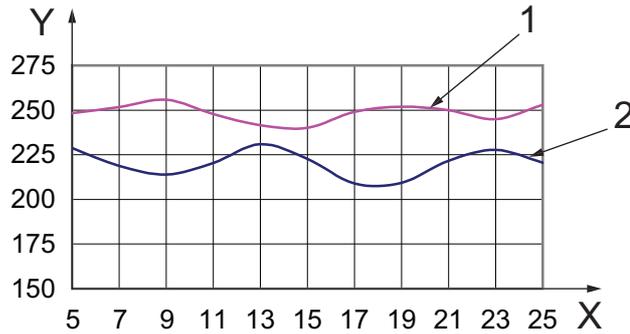
Key

X years after 2018

Y perigee above GEO, in km

Figure C.3 — 100-year perigee history (pointing to midnight)

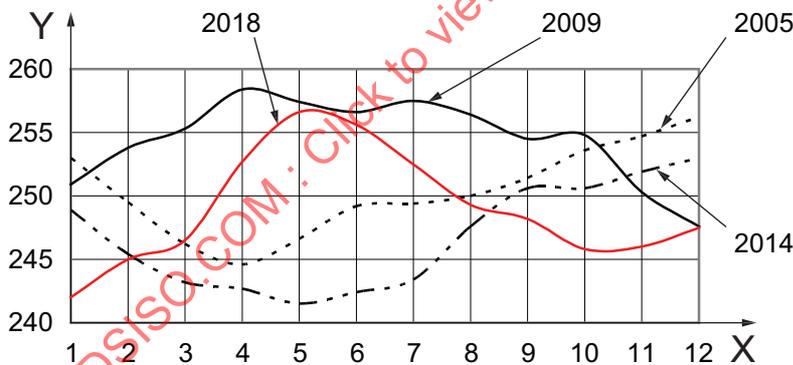
Several cases of 100-year integration were repeated to study the sensitivity of perigee height to epoch. The initial orbit elements are the same as before for each case at 07-01 or 01-01 of each epoch year. In each 100-year integration, only the minimum perigee height above GEO is recorded and plotted, as in Figure C.4. The upper curve represents the minimum perigee height for the 07-01 epoch (sun-pointing), and the lower curve represents the minimum perigee height for the 01-01 epoch (perigee pointing to midnight). The epoch is varied from 2005-01-01 to 2025-07-01. Figure C.4 shows the sensitivity of minimum perigee height to epoch.



- Key**
- X years after 2000
 - Y minimum perigee height above GEO, in km
 - 1 epoch on 07-01
 - 2 epoch on 01-01

Figure C.4 — Minimum perigee height versus epoch

To determine whether there is a seasonal variation, the 100-year integration only for the sun-pointing case (upper curve in Figure C.4) is repeated on the first day of each month for four selected years (2005, 2009, 2014 and 2018). Figure C.5 shows the seasonal variation of the minimum perigee heights. The four curves in Figure C.5 reveal another interesting fact: the peak of the seasonal variation changes to a valley about every 4 years, or one-quarter of the 18,6 year lunar cycle. The same trend can be seen in Figure C.4, where the peaks occur in summer (07-01) for 2009 and 2018.

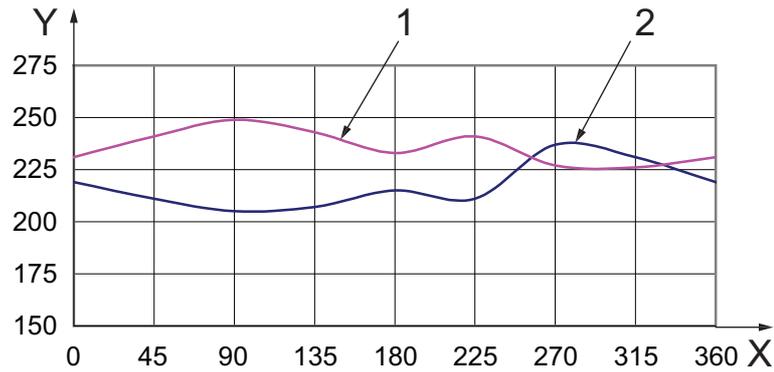


- Key**
- X month of the year
 - Y minimum perigee height above GEO, in km

Figure C.5 — Minimum perigee height versus month of the year

This finding reveals that the recommended altitude increase (280,5 km) yields a minimum perigee of 250 km or higher for 100 years if the orbit insertion is performed near the peak season (Figures C.4 and C.5) following sun-pointing geometry. For example, if a disposal orbit manoeuvre sequence is to be planned in 2009, the best time for the re-orbit is some time in April, as indicated in Figure C.5.

When the perigee is pointing away from the sun or toward midnight, the minimum perigee height from the 100-year integration changes in a different way. Figure C.6 shows the minimum perigee height as a function of the combined angle, $(\omega + \Omega)$, for two epochs. On 07-01, the sun-pointing geometry occurs when $(\omega + \Omega) = 90^\circ$. On 01-01, the sun-pointing geometry occurs when $(\omega + \Omega) = 270^\circ$. The results show that the highest value of minimum perigee height occurs when the perigee is sun-pointing.

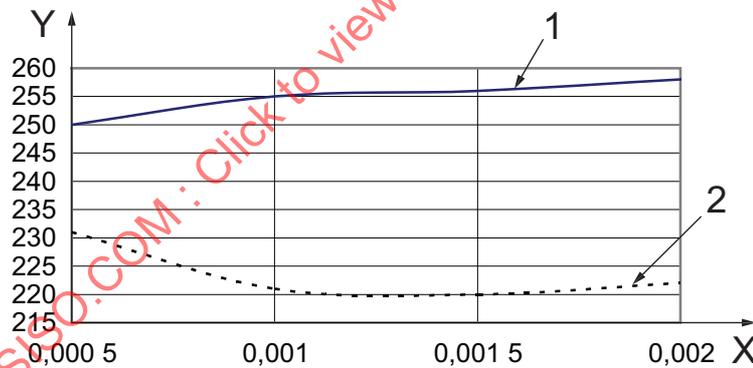


Key

- X angle of RAAN plus argument of perigee, in degrees
- Y minimum perigee height above GEO, in km
- 1 epoch on 07-01
- 2 epoch on 01-01

Figure C.6 — Minimum perigee height versus $(\omega + \Omega)$

Figure C.7 shows the minimum perigee height above GEO determined from 100-year integration versus the initial eccentricity of the disposal orbit. The same set of initial orbital elements is assumed with two epochs, 2018-07-01 and 2018-01-01. All the cases satisfy the initial perigee altitude increase, ΔH , determined by Equation (C.10) (280,5 km).

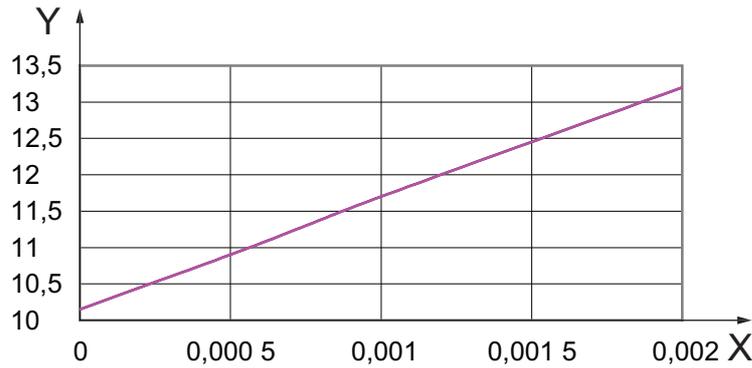


Key

- X initial eccentricity
- Y minimum perigee height above GEO, in km
- 1 sun-pointing
- 2 midnight-pointing

Figure C.7 — Minimum perigee height above GEO versus initial eccentricity

The results indicate that smaller eccentricity, at 0,000 5, tends to keep the minimum perigee higher, at 230 km, when the perigee is pointing to midnight (dashed curve in Figure C.7). The results also show that larger initial eccentricity actually increases the minimum perigee height if the sun-pointing geometry is followed (solid curve in Figure C.7). However, larger initial eccentricity with the same initial perigee altitude increase (280,5 km) requires more propellant, which is undesirable for mission operations. Figure C.8 gives an estimate of the ΔV requirement as a function of initial eccentricity of a GEO disposal orbit with an initial altitude increase of 280,5 km.



Key

- X initial eccentricity
- Y ΔV requirement, in m/sec

Figure C.8 — ΔV required for re-orbit versus eccentricity

As seen from the linear relation in Figure C.8, an initial eccentricity of 0,002 requires about 2,4 m/s or 22 % more ΔV than an eccentricity of 0,000 5 requires.

The uncertainties of the long-term prediction of perigee altitudes may be estimated from the uncertainties in predicting the semi-major axis and eccentricity. The major source of error in predicting the semi-major axis and eccentricity of a super-synchronous orbit comes from the uncertainty in modelling the solar radiation pressure that is proportional to the effective Alm of the spacecraft. Because of the uncertainty in the attitude of an inactive spacecraft, it is difficult to estimate accurately the effective Alm . In the 100-year predictions presented here, a constant effective Alm of 0,035 m²/kg with a C_R value of 1,3 is assumed for all cases. Numerical tests show that a 20 % decrease in Alm will increase the minimum perigee height by about 5 km.

To summarize, the sample plots shown in Figures C.1 to C.7 illustrate that long-term eccentricity or perigee stability of GEO disposal orbits can be significantly improved by the following:

- a) having the initial perigee pointing to the sun;
- b) performing the re-orbit in the most favourable season of the year.