UDC 629.7.016.3
Doi: 10.31772/2587-6066-2019-20-4-465-476

For citation: Kolovsky I. K., Shmakov D. N. Spacecraft motion in a low circular orbit in establishing intersatellite link. *Siberian Journal of Science and Technology.* 2019, Vol. 20, No. 4, P. 465–476. Doi: 10.31772/2587-6066-2019-20-4-465-476

Для цитирования: Коловский И. К., Шмаков Д. Н. Исследование движения космических аппаратов на низкой около круговой орбите при создании межспутниковой линии связи // Сибирский журнал науки и технологий. 2019. Т. 20, № 4. С. 465–476. Doi: 10.31772/2587-6066-2019-20-4-465-476

SPACECRAFT MOTION IN A LOW CIRCULAR ORBIT IN ESTABLISHING INTERSATELLITE LINK

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The article investigates the problem of inter-satellite linking in the constellation of spacecraft in a low circular orbit. A specific problem of establishing intersatellite link (IL) in that orbit – cross-pointing of the antennae – is also studied. To support cross-tracking, it is important to place spacecraft (SC) in the orbital plane so that they are constantly in the zone of mutual visibility. The line-of-sight range is analyzed both in one orbital plane and between adjacent planes. IL is treated in terms of the orbital constellation (OC) ballistic formation. Several typical modes of motion of SC with IL in adjacent planes are determined – parallel, orthogonal, oncoming. The parameter values of IL antenna pointing are also assessed. The obtained results of OC formation and antenna pointing parameters' calculations may be relevant for establishing a modified system.

Keywords: ballistics, range, low circular orbit, orbital constellation, intersatellite link.

ИССЛЕДОВАНИЕ ДВИЖЕНИЯ КОСМИЧЕСКИХ АППАРАТОВ НА НИЗКОЙ ОКОЛО КРУГОВОЙ ОРБИТЕ ПРИ СОЗДАНИИ МЕЖСПУТНИКОВОЙ ЛИНИИ СВЯЗИ

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В работе исследуется задача организации межспутниковой линии связи (МЛС) в космической системе, которая строится на основе орбитальной группировки (ОГ) космических аппаратов (КА) на низкой около круговой орбите. Рассматривается одна из проблем при создании МЛС на такой орбите – наведение антенны КА друг на друга. Для возможности отслеживания друг друга важно размещать КА в орбитальной плоскости так, чтобы они были постоянно в зоне взаимной видимости. Анализируется дальность прямой видимости как внутри одной орбитальной плоскости, так и в соседних плоскостях. Создание МЛС рассматривается с точки зрения баллистического построения ОГ. При организации МЛС определены несколько типов характерного движения КА в соседних плоскостях: параллельного, ортогонального, встречного. Приводятся значения параметров наведения антенны МЛС. Полученные результаты построения ОГ и вычисления параметров наведения антенны могут быть актуальны для создания модифицированной системы.

Ключевые слова: баллистика, дальность, низкая круговая орбита, орбитальная группировка, межспутниковая линия связи.

Introduction. Intersatellite links can increase the efficiency in achieving the principle objective of satellite systems – providing communications for subscribers distributed globally. Besides, operating IL helps to solve the problems of parallel control of all spacecraft in the constellation without numerous ground tracking stations [1].

There are several satellite systems which provide monitoring and data transmission, such as "Globalstar", "Iridium". Development of such intersatellite systems is also essential for solving various problems of data transmission, monitoring and locating moving objects. Technical solutions of these systems provide the basis of monitoring facilities development [2; 3].

The aim of IL is to provide radio exchange of subscribers not in the line of sight of the same spacecraft - that requires information exchange both between SC in the same plane and between ones in different planes. The use of IL significantly increases the efficiency of radio links [4]:

– the service area is increased by interconnection of all radio visibility zones (RVZ) of SC into an integrated RVZ of the orbital constellation;

– the load on the satellite links is reduced due to instant information exchange;

– the reliability and stability of satellite links is increased.

Establishing IL in OC of SC. For the experiment we assume that there is an OC of 24 SC in a near-circular orbit of 1500 km altitude, and from the point of view of the OC ballistic formation and SC motion, we review the ways of plotting the IL for the given satellite system, both in one plane and between adjacent planes. A similar IL configuration is already introduced in "Iridium" satellite system [5]. "Iridium" is a low-orbit system operating in circular orbits. The orbit altitude is about 700 km; the standard OC includes 66 interlinked SC [6].

When an IL are made in a circular orbit of 1500 km altitude, the optimal mutual visibility of SC in the orbital plane is achieved when the number of SC in the plane is more than or equals 6 [7].

It must be noted that for IL correct operation in one plane, orbit correction must be carried out to keep the orbital position of all SC stable, otherwise the distance between the SC can alter too much and cause operational failure.

We can determine the station-keeping zone and positioning of SC in the orbital plane for IL operation in reference to 5, 6, 7 SC. It is necessary to view the orbit configuration of SC 1 and SC 2 in more detail (fig. 1).

The symbols in fig.1 are: a – Earth radius; b – half-distance between SC 1 and SC 2; c – major semi-axis of SC orbit; $\angle\beta$ – half of the center angle between SC 1 and SC 2.

We take the basic relation of a right-angled triangle [8] to calculate $2\cdot\angle\beta$ – the limit angle of keeping SC in the line of sight

a = 6378.16 km – Earth radius [9];

c = 1500 + 6378.16 = 7878,16 km – major semi-axis of SC orbit;

$$\sin\alpha = a/c;$$

$$\angle\alpha = 54.056°;$$

$$\angle\beta = 35.944°;$$

$$2\cdot\angle\beta = 71.888°. \quad (1)$$

According to the formula (1), for a number of SC composition variants in the orbital plane, we obtain the values of the angle between the nearest SC and of the station-keeping zone (tab. 1).

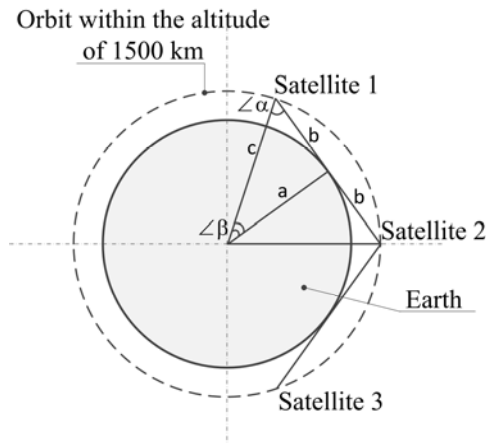


Fig. 1. IL within an orbital plane

Рис. 1. МЛС внутри орбитальной плоскости

The results in tab. 1 show that for IL at 1500 km altitude with five SC in the plane, to provide mutual visibility it is necessary to keep the SC in orbit with an accuracy of 0.5° by latitude argument, which is quite demanding technically.

Therefore, an architecture of 6 SC in the plane with ± 5° station-keeping zone relative to the SC orbital position can be applicable. In this case, the distance between two adjacent SC with an IL will depend on the accuracy of keeping the SC in the orbital positions with respect to the latitude argument. Half-distance value between adjacent SC with IL (parameter b in fig. 1) when there are 6 SC in the orbital plane will make

$$b = c\cdot\sin\beta. \quad (2)$$

In case 6 SC are evenly positioned in the plane, (the center angle between these SC is 60 °) and the station-keeping accuracy is ± 5º, the expression (2) gives the 7878 km distance in the nominal position. The distance calculations for the center angle of 50° and 70° are listed in tab. 2.

We form the chosen for the experiment standard OC architecture of 24 SC for modeling and studying the ballistic parameters of IL as follows: four orbital planes of 6 SC each (tab. 3).

Absolute longitude divergence of the ascending nodes of adjacent orbital planes is 46°. The SC phase distribution is taken for the moment of SC 11 passing the ascending node of the orbit.

Fig. 2 represents 24 SC in four orbital planes and the track of every SC in flight period of a few minutes.

Table 1

Station-keeping zone for a SC with 1.500 km orbit altitude operating IL

SC number in the orbital plane	SC positioning in the plane with respect to the argument of latitude, °	Station-keeping zone, °
5	71.9	±0.5
6	60.0	±5.0
7	51.4	±9.3

Table 2

Values of distance and center angle between SC in the plane

	Distance between SC, $2 \cdot b$, km	Center angle between SC, $2 \cdot \angle\beta$, °
Minimal	6658	50
Nominal	7878	60
Maximal	9037	70

Table 3

Distribution for OC of 24 SC

Plane number	SC number	Ascending node longitude, °	Argument of latitude, °	Plane number	SC number	Ascending node longitude, °	Argument of latitude, °
1	11	0	0	3	31	92	50
	12	0	60		32	92	110
	13	0	120		33	92	170
	14	0	180		34	92	230
	15	0	240		35	92	290
	16	0	300		36	92	350
2	21	46	25	4	41	138	75
	22	46	85		42	138	135
	23	46	145		43	138	195
	24	46	205		44	138	255
	25	46	265		45	138	315
	26	46	325		46	138	15

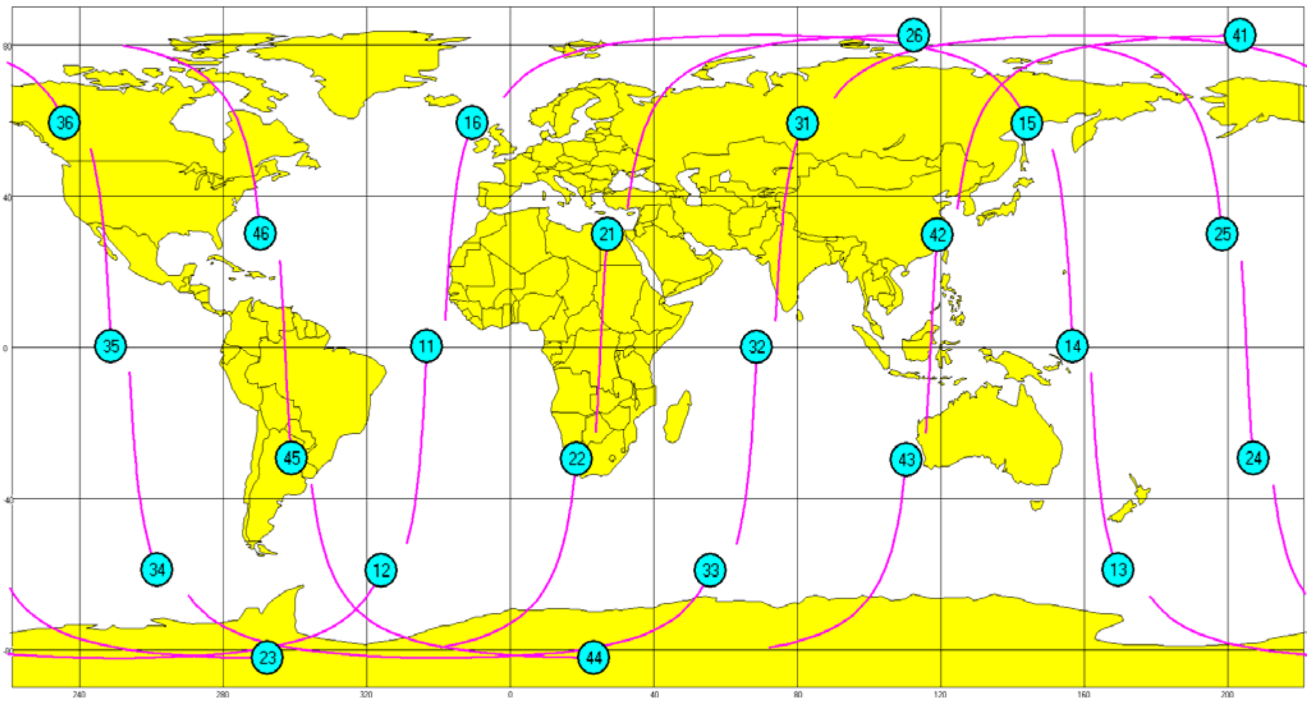


Fig. 2. Routes of 24 SC in the OC

Рис. 2. Трассы ОГ из 24-х КА

IL is a unique element of "Iridium" communication system, every SC of which is interconnected with 4 adjacent ones, 2 of them in front and in aft position in the same orbital plane, and 2 on the left and on the right in adjacent orbital planes [10].

For the experimental OC architecture of 24 SC we can outline the following IL configurations:

– Configuration 1 – IL between the SC in one orbital plane;

– Configuration 2 – IL between SC of adjacent planes № 1 and 2, № 2 and 3, № 3 and 4 (parallel motion);

– Configuration 3 – IL between SC in planes № 1 and 3, № 2 and 4 (orthogonal motion in the moment of mutual visibility);

– Configuration 4 – IL between SC in planes № 1 and 4 (cross-movement in the moment of mutual visibility).

Operating IL dictates the need of continuous communication during the SC flight. The analysis of this aspect is presented in [11] for "CubeSat" system.

Below, there is an analysis of some specified SC from every orbital plane in the experimental OC of 24 SC, as well as of ballistic parameters variation for each of the IL configurations, including the periods of SC mutual visibility.

Here is an analysis of the following ballistic parameters:

– the SC positioning range and the rate of its changing;

– declination and the rate of its changing;

– elevation and the rate of its changing;

– period of mutual visibility in an orbit pass.

These parameters allow to determine SC antenna control characteristics in IL communication, as well as the mutual visibility periods of SC within IL zone.

Configuration 1 – IL between the SC in one orbital plane. Fig. 3 presents an IL variant in one plane, when all RVZ of six SC (at an elevation angle of 10 °) are networked into a common RVZ of the orbital plane. Common RVZ will significantly increase the coverage zone.

Further we review the requirements for IL-providing equipment on the example of two most closely positioned SC of the first orbital plane SC № 11 and SC № 12. Fig. 4 presents the SC, their subsatellite points and flight route.

Tab. 4 presents the initial data – SC №11 and SC № 12 reference. MDT – Moscow decree time in the ascending node, the SC coordinates and velocities are in the Greenwich rotating coordinate system (GRCS).

Let us review the information transfer for SC № 11 to SC № 12 in the nominal position during one orbit pass (115 min).

In fig. 5–7 are shown ballistic parameter variations (where subitem a) parameter, b) parameter change rate):

– Range – line-of-sight distance between SC [12]. Range change rate;

– Declination – antenna direction angle from one SC to another measured from the direction to the Earth's center. Declination change rate;

– Elevation – antenna direction angle from one SC to another measured from velocity vector in the clockwise direction. Elevation change rate.

We can put the calculations of SC antenna pointing ballistic parameters together. The range of parameter changing for IL in an orbit pass between SC № 11 and SC № 12 is listed in tab. 5.

We must point out that in the orbit pass SC № 11 and SC № 12 are constantly in the zone of mutual visibility – that is confirmed by the parameter of 100 %.

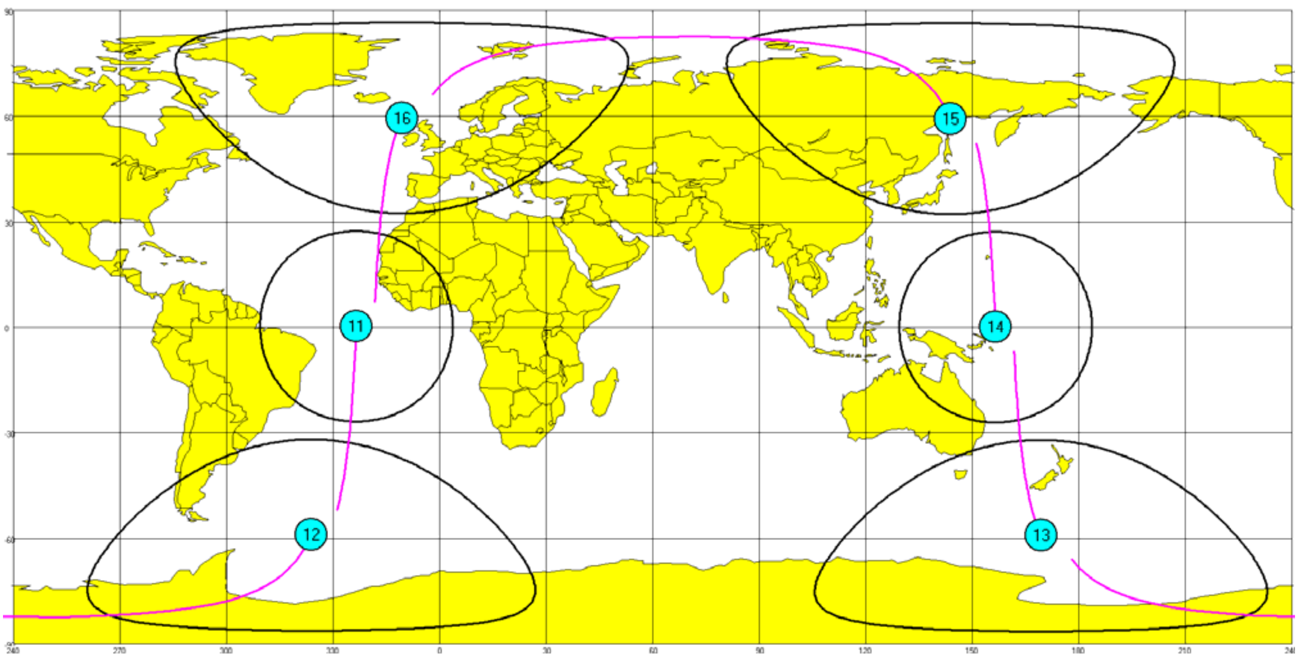


Fig. 3. Common RVZ in one orbital plane with IL within that plane

Рис. 3. Общая ЗРВ одной орбитальной плоскости при МЛС внутри плоскости

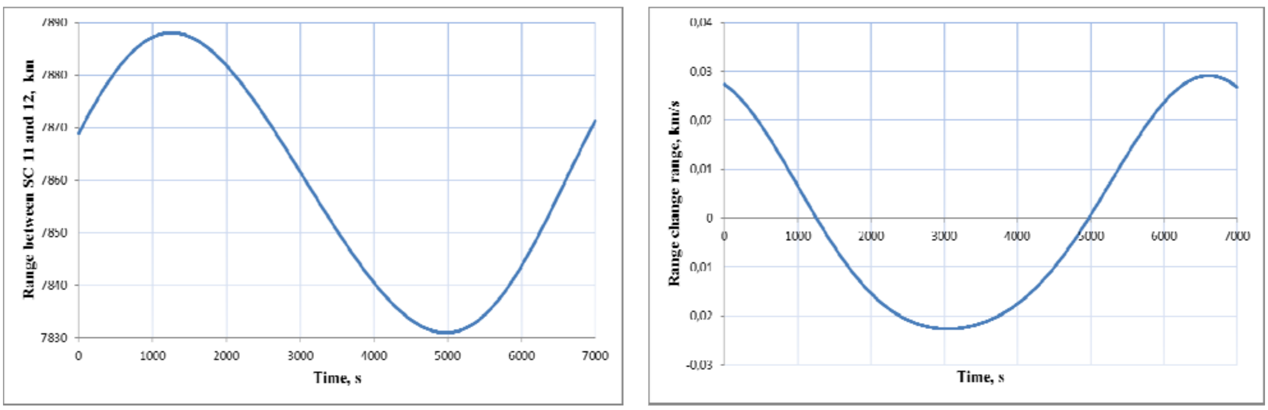
Fig. 4. The motion of two close-positioned SC № 11 and SC № 12
in the first orbital plane

Рис. 4. Движение двух ближайших КА № 11 и КА № 12
первой орбитальной плоскости

Table 4

SC № 11 and SC № 12 reference

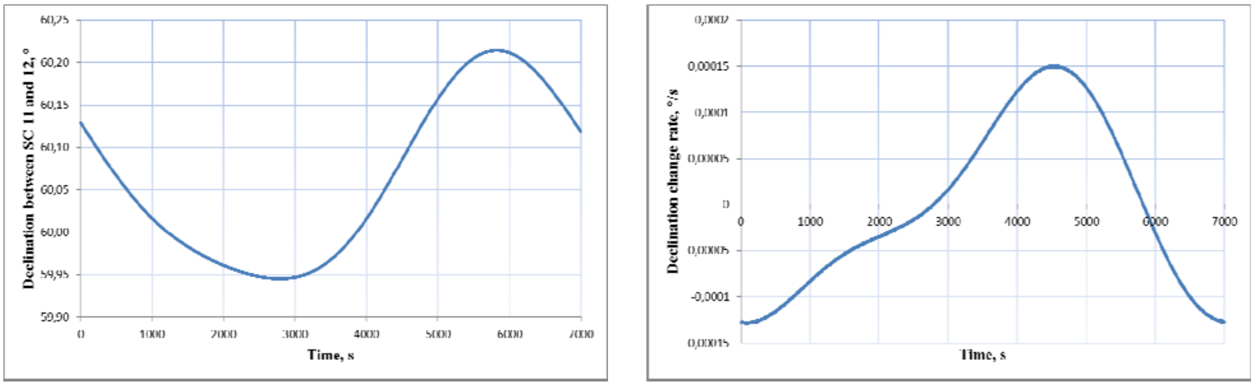
Parameter	SC № 11	SC № 12
Date	31.05.2019	31.05.2019
MDT	11:59:57	12:19:14
Coordinate X, km	7232.954011	6936.407866
Coordinate Y, km	–3120.071909	–3714.968713
Coordinate Z, км	0,0	0.0
Velocity Vx, km/s	0.140334	0.171858
Velocity Vy, km/s	0.325291	0.310911
Velocity Vz, km/s	7.052965	7.060811



a *b*

Fig. 5. Ballistic parameter range:
a – range changing between SC 11 and 12; *в* – range change range

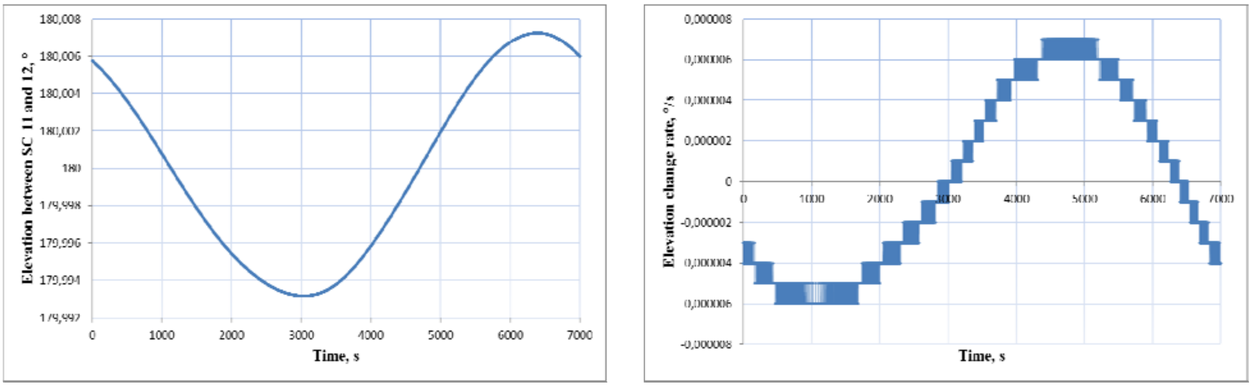
Рис. 5. Баллистический параметр «дальность»:
а – изменение дальности между КА 11 и 12;
б – скорость изменения дальности



a *b*

Fig. 6. Ballistic parameter declination:
a – declination changing between SC 11 and 12; *в* – declination change rate

Рис. 6. Баллистический параметр «склонение»:
а – изменение склонения между КА 11 и 12; *б* – скорость изменения склонения



a *b*

Fig. 7. Ballistic parameter elevation:
a – elevation change between SC 11 and 12; *в* – elevation change rate

Рис. 7. Баллистический параметр «восхождение»:
а – изменение восхождения между КА 11 и 12; *б* – скорость изменения восхождения

Table 5

Changing of IL ballistic parameters between SC within the orbital plane

Parameter	Range of parameter changing
Range, km	from 6658 to 9037
Range change rate, km/s	from –0.03 to 0,03
Declination, °	from 54.37 to 65.36
Declination change rate, °/s	from –0.001 to 0.001
Elevation, °	from 179.99 to 180.01
Elevation change rate, °/c	from –0.00006 to 0.00006
SC mutual visibility period in an orbit pass, min	115.9 (100 %)

Fig. 5–7 and tab. 5 data analysis demonstrates in the first place the stability of the basic parameters. Elevation is close to 0° in signal transmission from SC № 12 to SC № 11, and close to 180° in transmission from SC № 11 to SC № 12. The greatest variations are demonstrated by the SC antenna declination parameter.

Configuration 2 – IL between SC of adjacent planes № 1 and 2, № 2 and 3, № 3 and 4. Here is an analysis of IL configuration for SC moving in adjacent planes № 1 and 2, on example of SC № 12, 22, 23.

Tab. 6 presents the reference of SC № 22 and SC № 23, SC № 12 – in tab. 4.

Fig. 8 shows the OC fragment, consisting of SC № 12 from the first orbital plane and SC № 22, SC № 23 from the second orbital plane, for the moment of their positioning in the equator and pole areas. During the full orbit pass SC № 12 motion is mostly parallel to SC № 22, SC № 23 is also parallel; SC routes get crossed only in the pole areas.

We can put together the calculations of SC antenna pointing parameters for planes № 1 and 2. The range of IL parameter changing is listed in tab. 7.

We must point out that the sampled SC № 12, SC № 22 and SC № 23 continuously remain in the mutual visibility zone.

The IL in tab. 7 compared to the IL of one orbital plane (tab. 5) shows the increasing dynamics of declination and elevation angles changing. Here the declination change rate increased by 50 times (0.001 and 0.05), and the elevation change rate increased from 0.00006 °/s to 0.15°/s.

We have the best conditions for information transmission in the equator area. There the information can be transmitted in chain order to all 4 planes of the system.

It should be noted that for the sampled OC of 24 SC at 1500 km altitude, the common IL including configurations 1 and 2 is self-supporting (provides general linking of all SC in the OC).

Configuration 3 – IL between SC in planes № 1 and 3, № 2 and 4. Let us review the IL configuration, in which SC move almost transversely, at the example of orbital planes № 1 and 3.

Tab. 8, in addition to Tab. 4, presents SC № 31, 32, 33 reference.

Here the mutual visibility of SC in different planes occurs at high latitudes.

Each SC of one orbital plane can see from two to three SC of another orbital plane. We can point out that the time of simultaneous visibility of three SC is not long. We analyze the example of IL for SC № 11 of the first orbital plane, and SC № 31, 32 and 33 of the third orbital plane (fig. 9).

IL parameter changes between SC № 11 and SC № 31, 32, 33 are listed in tab. 9.

In motion of SC № 11 relative to SC № 31, 32 and 33, mutual visibility period or IL operational time of the SC is rather long, mainly close to revolution half-period.

Comparison of this IL parameters (tab. 9) with IL in one orbital plane (tab. 5) and IL in adjacent orbital planes (tab. 7) demonstrates still more growing dynamics when the declination and elevation angles get changed. Now the declination change rate comes up to 0.17 °/s, and elevation change rate – to 0.55 °/s.

Configuration 4 – IL between SC in planes № 1 and 4. Here is an analysis of IL configuration in planes № 1 and 4. Its main feature is the SC oncoming motion.

During the revolution half-period a SC of one orbital plane runs across all other SC of another orbital plane.

The dynamics of the SC route intersection depends on the Earth's surface latitude, over which the SC route intersection takes place. In this case, there may be three variants: equator zone, middle latitudes and high latitudes.

Let us review the IL on the example of SC № 11 of the first orbital plane and all six SC of the fourth orbital plane.

Tab. 10 shows the reference of SC № 41-46, SC № 11 – in tab. 4.

SC of one orbital plane can see from one to three SC of another orbital plane at the same time. Fig. 10 shows SC positioning in equator and pole areas.

Table 6

SC № 22 and № 23 reference

Parameter	SC № 22	SC № 23
Date	31.05.2019	31.05.2019
MDT	12:09:37	12:28:54
Coordinate X, km	7386,336533	7591.458385
Coordinate Y, km	2724.447324	2091.536252
Coordinate Z, km	0.0	0.0
Velocity Vx, km/s	–0.127584	–0.086993
Velocity Vy, km/s	0.341148	0.352760
Velocity Vz, km/s	7.055772	7.054474

Table 7

Changing of IL ballistic parameters between SC in adjacent planes № 1 и 2

Parameter	Range of parameter changing
Range, km	from 3800 to 7200
Range change rate, km/s	from –3 to 3
Declination, °	from 63 to 77
Declination change rate, °/c	from –0.05 to 0.05
Elevation, °	from –60 to 60; from 120 to 240
Elevation change rate, °/c	from –0.4 to 0.15; from –0.15 to 0.15
SC mutual visibility period in an orbit pass, min	115.9 (100 %)

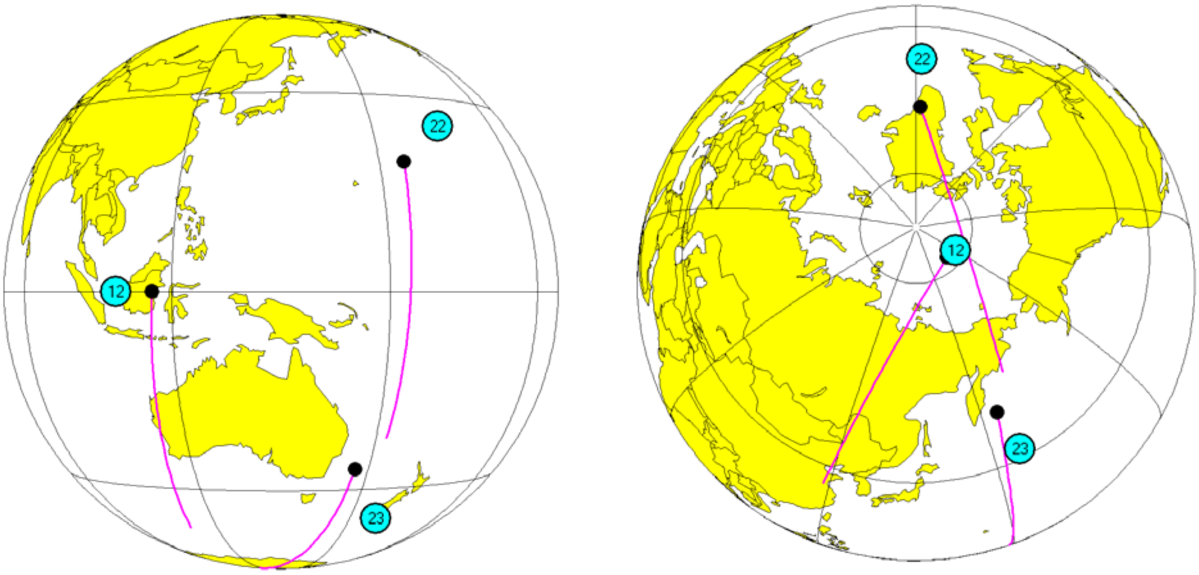


Fig. 8. SC motion in adjacent planes № 1 and 2

Рис. 8. Движение КА в соседних плоскостях № 1 и 2

Table 8

SC № 31, 32 and 33 reference

Parameter	SC № 31	SC № 32	SC № 33
Date	31.05.2019	31.05.2019	31.05.2019
MDT	11:40:43	12:00:00	12:19:17
Coordinate X, km	2233.447140	2864,993939	3469.973938
Coordinate Y, km	7544.938345	7337.622768	7062.144241
Coordinate Z, km	0.0	0.0	0,0
Velocity Vx, km/s	–0.354350	–0.342044	–0.328272
Velocity Vy, km/s	0.099865	0.133551	0.166529
Velocity Vz, km/s	7.059052	7.051298	7.059063

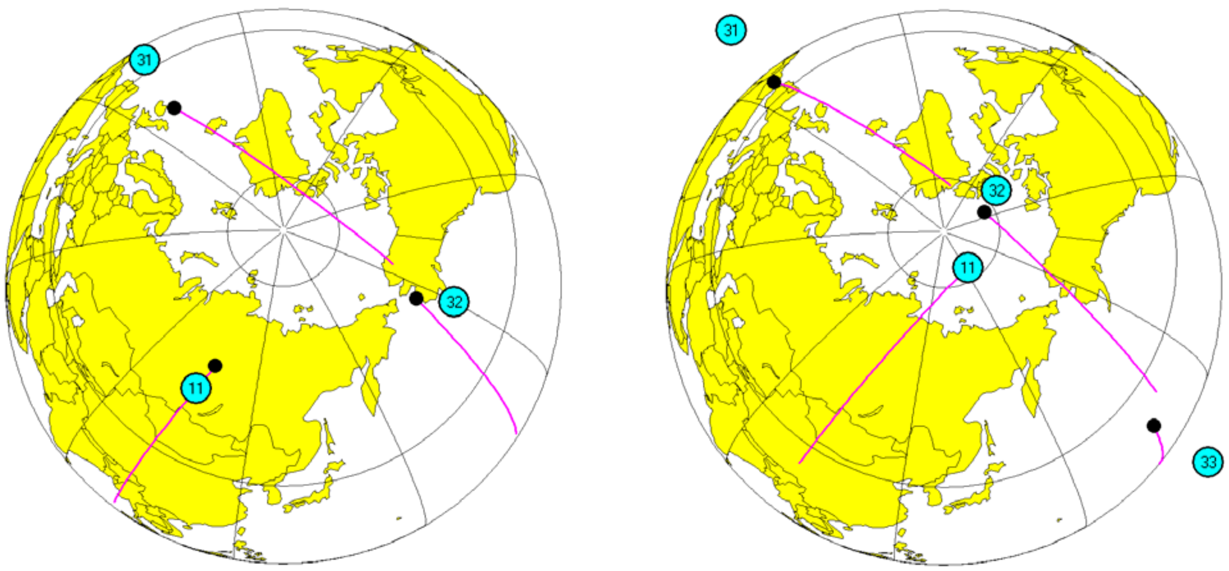


Fig. 9. SC orthogonal motion in planes № 1 and 3

Рис. 9. Ортогональное движение КА в плоскостях № 1 и 3

Table 9

Changing of IL ballistic parameters between SC in planes № 1 and 3

Parameter	Range of parameter changing		
	SC № 11 and 31	SC № 11 and 32	SC № 11 and 33
Range, km	from 6000 to 9200	from 500 to 9200	from 5000 to 9200
Range change rate, km/s	from –6 to 6	from –9 до +9	from –6.3 to +6.3
Declination, °	from 54 to 68	from 54 to 88	from 54 to 71
Declination change rate, °/c	from –0.14 to 0.14	from –0.17 to 0.17	from –0.15 to 0.15
Elevation, °	from 7 to –93; from 170 to 267	from 60 to –120; from 140 to 310	from 82 to 190; from –20 to 100
Elevation change rate, °/c	from –0.5 to 0.05	from –0.18 to 0.06	from –0.05 to 0.55
SC mutual visibility period in an orbit pass, min	50.1 (43.2 %)	71.1 (61.3 %)	56.0 (48.3 %)

Table 10

Reference of SC № 41–46 in the OC

Parameter	SC № 41	SC № 42	SC № 43	SC № 44	SC № 45	SC № 46
Date	31.05.2019	31.05.2019	31.05.2019	31.05.2019	31.05.2019	31.05.2019
MDT	11:31:05	11:50:22	12:09:40	12:28:57	12:48:20	13:07:37
Coordinate X, km	–4165.747	–3585.969	–2981.510	–2356.174	–1709.746	–1055.799
Coordinate Y, km	6682.119	7008.555	7286.171	7513.579	7688.098	7804.910
Coordinate Z, km	0.0	0.0	0.0	0.0	0.0	0.0
Velocity Vx, km/s	–0.302	–0.324	–0.335	–0.348	–0.353	–0.359
Velocity Vy, km/s	–0.199	–0.164	–0.139	–0.099	–0.080	–0.047
Velocity Vz, km/s	7.054	7.055	7.056	7.054	7.053	7.052

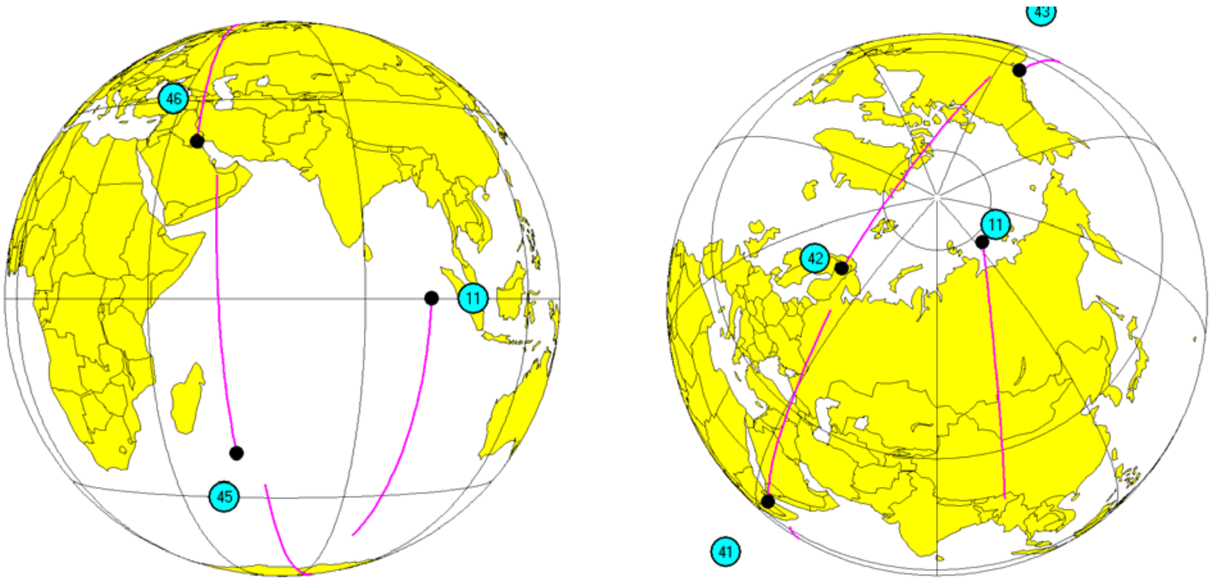


Fig. 10. Oncoming motion of SC from planes № 1 and 4

Рис. 10. Встречное движение КА плоскостей № 1 и 4

IL parameter changing range between SC № 11 and all SC of the fourth orbital plane, SC № 41–46, is listed in tab. 11.

Mutual visibility period of SC № 11 and SC in the fourth orbital plane is less than in the other previously reviewed IL configurations.

This IL (tab. 11) compared to the other previously reviewed IL (tab. 5, 7, 9) shows That the type of IL presented here demands the most dynamic SC antenna pointing by declination angle and elevation angle change. Here the declination change rate comes up to 0.24 °/s, and elevation change rate – to 0,75 °/c.

Conclusion. The analysis of the main ballistic parameter changing taken into account for antenna pointing in transmission of data via IL either in one orbital plane or in adjacent planes shows that the changing is quite varied. Table 12 presents generalized ranges of main ballistic parameter changing for the IL configuration within OC of 24 SC (4 orbital planes, 6 SC each) at the orbit of 1500 km.

We can conclude that for an orbital constellation IL antenna pointing and proper operation, the destabilizing factors analyzed in this article must be taken into account:

– limited time intervals for information exchange of SC in the line of sight;

– mutual change of position at SC high motion velocity.

IL operating optical or radio communication channels of a satellite system has a number of special characteristics – limited power supply of IL equipment; that should be taken into account in hardware design [13] .

Comparing the reviewed IL types for the sampled OC of 24 SC, we can find that the simplest IL to be put into practice is the inter-satellite line within one plane. With this type, the ballistic parameters change in the least, and the neighboring SC stay in the line of sight all the time.

For the IL configuration in OC adjacent orbital planes, special apparatus and antennae for dynamic tracking of one SC by another are required, since the target indications used for antenna pointing get dynamically and considerably changed.

In this case, favorable conditions for IL operation – the lowest parameter changing rates for IL antenna pointing – develop in SC parallel motion in adjacent orbital planes (between orbital planes № 1 and 2, № 2 and 3, № 3 and 4).

It should be noted that to improve the OC of 24 SC consumer characteristics from the point of view of its usability, it is enough to make use of the first two IL types reviewed above: inside any single plane and in adjacent planes № 1 and 2, № 2 and 3, № 3 and 4.

After successful IL configuration for OC of SC in a low circular orbit, further development of SC between the SC positioned in various orbits can be considered. This type of IL was outlined in [14; 15], describing a combined satellite communication system, comprising a relay satellite operating in a highly elliptical orbit and providing information exchange with SC in its line of sight moving in low earth orbits.

The use of the results obtained in design of updated SC, in OC ballistic configuration and establishing IL in the OC of 24 SC, may help to produce a highly-efficient monitoring and data transmission satellite system.

Table 11

Changing of IL ballistic parameters between SC in planes № 1 and 4

Parameter	Parameter change rate between SC № 11 and SC № 41-46					
	SC № 46	SC № 41	SC № 42	SC № 43	SC № 44	SC № 45
Range, km	from 6000 to 9200	from 5000 to 9200	from 2640 to 9200	from 500 to 9200	from 3300 to 9200	from 5340 to 9200
Range change rate, km/s	from –9.0 to 9.0	from –9.3 to 9.3	from –10.3 to 10.3	from –12,3 to 12.4	from –10.1 to 10.1	from –9.1 to 9.1
Declination, °	from 54 to 68	from 54 to 72	from 54 to 80	from 54 to 88	from 54 to 78	from 54 to 70
Declination change rate, °/c	from –0.2 to 0.2	from –0.22 to 0.22	from –0.23 to 0.23	from –0.24 to 0.24	from –0.24 to 0.24	from –0.2 to 0.2
Elevation, °	from 220 to 320	from 230 to 340	from 220 to 360	from 30 to 200	from 45 to 180	from 47 to 155
Elevation change rate, °/c	from –0.65 to 0.20	from –0.75 to –0.15	from –1.4 to 0	from –0.1 to 0.1	from 0,55 to 1.15	from 0.18 to 0.71
SC mutual visibility period in an orbit pass, min	37.9 (32.7 %)	41.5 (35.8 %)	48.0 (41.4 %)	50.5 (43.5 %)	46.6 (40.2 %)	40.6 (35.0 %)

Table 12

Changing of IL ballistic parameters for OC of 24 SC

Parameter	IL configuration type			
	Within a plane	Between 1 and 2, 2 and 3, 3 and 4 planes	Between 1 and 3, 2 and 4 planes	Between 1 and 4 planes
Range, km	from 6658 to 9037	from 4000 to 7200	from 5000 to 9000 from 500 to 9000	from 500 to 9000 from 3500 to 9000 from 5500 to 9000
Range change rate, km/s	from –0.03 to 0.03	from 0 to 3	from –10 to 10	from –12 to 12
Declination, °	from 54.37 to 65.36	from 63 to 75	from 55 to 90	from 54 to 90
Declination change rate, °/c	from –0.001 to 0.001	from 0 to 0.01	from –0.035 to 0.035	from –0.05 to 0.05
Elevation, °	from –0.01 to 0.01; from 179.99 to 180.01	from 10 to 60; from 330 to 360	from 300 to 360; from 0 to 120	from 340 to 360
Elevation change rate, °/c	from –0.000006 to 0.000006	from 0.03 to 0.07	from –0.05 to 0.05	from 0 to 0.9
SC mutual visibility period in an orbit pass, min	115.9 (100 %)	115.9 (100 %)	from 50.1 to 71.1 (from 43.2 to 61.3 %)	from 37.9 to 50.5 (from 32.7 to 43.5 %)

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