Satellite communication system design using locally-stationary orbits

Y. N. Razoumny, D. O. Shkolnikov, V. Y. Razoumny

Abstract

The geostationary circular orbit (GSO) (at the height of approximately 36,000 km with zero inclination) proposed by Arthur C. Clark in the middle of the 20-th century has become very popular for creation of different satellite systems for communication, TV broadcasting and some other purposes. Insertion one or more satellites to geostationary orbits is the best way to provide coverage of big equatorial parts of the globe. In spite of obvious GSO advantages it is clear now that GSO implementation has some difficulties connected with existing limitation for insertion of GSO satellites as well as impossibility to cover the non-equatorial regions of the globe.

The elliptical orbits of Molniya type firstly used for Russian communication satellites of the same name do not have the GSO disadvantages mentioned above. But this type of orbits (with 63,4 deg inclination and perigee and apogee of nearly 500 km and 40,000 km accordingly) can not pretend for universal use.

The locally geostationary orbits (LGO) invented by first author of the present paper in 1987 give the possibility for design of the satellite constellations in more general situations connected with the Earth local coverage. Mathematical description of the LGO includes GSO and Molniya orbits as the particular cases (herewith the GSO is the only circular orbit in the locally geostationary, generally elliptical, class of orbits).

Taking into account that implementation of LGO based on emulation of geostationary observation of the Earth using elliptical orbits is becoming nowadays very popular, the paper contains some new aspects of LGO parameters calculation for different implementations.

It is impossible to envisage contemporary society without satellite telecommunication means being of major and with years steadily growing significance. The most important component of any telecommunication system is its orbital part – satellite system that is a set of satellites solving jointly an entire goal-oriented problem to provide communication (as a rule, a wide range of telecommunication services) in the Earth preset areas. Ballistic design of modern satellite systems is a complicated scientific and engineering problem connected with the necessity to take into account purposefully not only the satellite system purely ballistic parameters but a whole series of its objective (system) features being either expressly or by implication dependent on specified ballistic parameters, as well as reflecting the operation efficiency of some or other satellite group used to achieve the preset goal.

The systems supporting continuous round-the-clock communication of the users in the Earth preset area take a really important place among satellite systems. Presently, geostationary orbits proposed first more than 50 years ago by well-known fantasist Arthur Clark, became the widest application. A number of specific merits make these orbits extra attractive for providing communication to remote users on the Earth surface. Distinctive features of the orbits are their large acquisition range, real invariability to Earth over a whole period of the satellite active operation, stability of the satellite attitude that simplifies the use of on-board multi-beam antennas forming the beams and contour directional patterns, stability and high quality of radio communication, negligible Doppler translation, absence of necessity to transit from one satellite to another in the course of communication session, simplifying or full exclusion of the antenna system servo drives at ground terminals.

Thus, it is assignable that many domestic and foreign satellite systems are built just for geostationary orbits. Therewith, on the other hand, it exerts poisonous influence upon the outlooks of the geostationary satellite communication systems application broadening. Actually, just such orbits are presently so “populous” that new satellites can be hardly placed on them, and often it is even impossible owing to arisen inferences. So, more than 300 artificial Earth satellites (EAS) belonging to different countries are situated now on a geostationary orbit. “Points of location” on a geostationary orbit are widely discussed in politics, up to the complaints of some countries (often having no deal with space activity) situated in near-equatorial areas to possess such points above their territory. Taking also into account that not all “points of location” on a geostationary orbit are convenient for placing satellites under the aspect of servicing the specific Earth areas, it becomes obvious that a geostationary orbit is too “crowded”, and in actual fact the geostationary orbit “saturation” limit is already reached.

Along with mentioned general considerations, there are specific engineering restrictions for the geostationary orbits application. One is the most significant restrictions is the intricacy (sometimes impossibility) to provide communication for the areas situated in the Earth upper latitudes far from equator, for example, on the territory of Russia. In this case, the known elliptic orbits of “Molniya”-type proposed in due time (USSR period) become very efficient. In general, satellite systems placed in middle and high elliptic orbits allow the users on the better part of the Russian territory (Russian middle and northern latitudes) to work at significantly bigger elevations (as compared to geostationary orbits). It is especially important for promising communication systems of millimeter range, as well as for mobile communication. Less energy is required to ascent satellites in such orbits than for orbital injection of geostationary satellites.

A certain shortage of satellite communication system constructed on elliptic orbit is a significant value of its Doppler translation. However, the engineering solutions (equipping the ground stations with special devices compensating Doppler translation) have long been obtained during the exploitation of home-produced satellite systems on elliptic orbits. These technological solutions allow if not to eliminate, then at least to minimize this factor’s influence to a degree sufficient for practice.

The above is evidence of actuality and technical realizability of the elliptic orbit wide application in order to solve the communication problems; if so, the development of general methodical approach to ballistic design of satellite communication systems on elliptic orbits is of interest. The essentials of such approach based on the use of the notion of so called local-stationary orbits (LSO) first reasoned in [1, 2], are set forth in present paper. It should be noted that since the LSO presentation in abovementioned publications by one of this paper’s authors, many references to the LSO have been made by other authors right up to the present days. It gives rise to pleasure due to the obtained result came to be in great demand, but at the same time to sadness because the authors do not often correctly refer to these orbits’ inventor.

The LSO class is interesting because it includes as particular cases both geostationary orbit (an exclusive circular orbit in this orbit class) and also known elliptic orbit of satellite communication systems of “Molniya” type. This orbit class contains at the same time an infinite set of other elliptic orbits having the properties alike those of two said orbits being most widely used for designing the satellite communication systems.

The LSO attribute is zero-value of the rate of subsatellite point instantaneous displacement relatively to the Earth, at the orbit apogee placed above the observation area. The LSO existence is possible on straight orbits (i<90°) at the alignment of their apogees with apex or vertex points (argument of the latitude perigee ω = ± 90°).

The LSO perigee radius rP is determined for given values of apogee radius rA and inclination i from the equality of the satellite orbital velocity VA in apogee and velocity of the end point of geocentric radius-vector of length rA placed at angle i<90° to the equatorial plane, rigidly bound to the Earth and rotating with it with angular velocity ωE:

$$V_A = \omega_E \cdot r_A \cdot \cos i \,. \tag{1}$$

It is also known [3] that velocity VA of the satellite in apogee is equal to:

$$V_A = \sqrt{\frac{2\mu \cdot r_P}{r_A \cdot (r_A + r_P)}}\,, \tag{2}$$

where μ is the Earth gravitation constant. After equating right parts of (1) and (2) and solving relatively to rP the expression for LSO perigee radius can be obtained in the form:

$$r_P = \frac{\omega_E^2 \cdot r_A^4 \cdot \cos^2 i}{2\mu - \omega_E^2 \cdot r_A^3 \cdot \cos^2 i}\,. \tag{3}$$

Herefrom, semi-major axis a and LSO eccentricity e are defined by formulas:

$$a = \frac{r_A + r_P}{2} = \frac{\mu \cdot r_A}{2\mu - \omega_E^2 \cdot r_A^3 \cdot \cos^2 i}\,,$$
$$e = \frac{r_A - r_P}{r_A + r_P} = 1 - \frac{\omega_E^2 \cdot r_A^3 \cdot \cos^2 i}{\mu}\,. \tag{4}$$

The LSO existence can be illustrated in Fig. 1 presenting the following relationships:

- $V_{cir}(H_{cir})$: dependence of velocity V_{cir} of the EAS on a circular orbit, on the orbit altitude H_{cir};
- $V_A(H_A/H_P)$: dependence of velocity V_A in elliptic orbit apogee on altitude H_A at fixed values of perigee altitude H_P = 500, 5500, 18000 km;
- $V_i(H/i)$: dependence of velocity V_i of the end point of geocentric radius-vector rotating with the Earth, on altitude H of this point above the Earth surface at fixed angles $i=\{0°;\ 63.4°\}$ of radius-vector inclination to equatorial plane.

In this figure, the intersection point of straight line H=HA with plotted function Vi(H/i) is to be found on given HA and i, then relationship of VA(HA/HP) type is drawn through this point till its intersection with graph Vcir(Hcir), and thus the LSO perigee can be obtained (as the last intersection point's abscissa) corresponding to chosen HA and i.

In general case, the use of LSO allows to realize coverage of the Earth area in question on one or several consecutive satellite circuits. Thereupon, the LSO being simultaneously geosynchronous are of practical interest. One satellite in such an orbit provides during the period of satellite path repetition (n effective days) m communication sessions with the users in the preset Earth areas. Communication continuity in the area can be provided by that satellite system by "disposing" a necessary number of additional satellites along such single satellite path. It can be said herein that in order to build the satellite communication system, the maximum of the session time duration is provided by the LSO form choice, as well as minimal number of said additional satellites.

It is known that while moving along geosynchronous orbits the satellite path closes within a finite time span – period Ttr of the path repetition:

$$T_{tr} = m \cdot T_{dr} = n \cdot T_{ef}, \qquad (5)$$

where T_{dr} is EAS draconic orbital period; T_{ef} – efficient period of the Earth revolution with regard for the EAS orbit precession, i.e. time span between two sequential passages of the fixed equator point through the satellite orbit ascending node; m, n – coprime integers equal to the number of EAS circuits and the number of effective days within the T_{tr} period.

Geostationary orbits and elliptic orbits of the “Molniya”-type satellites are special cases of local-stationary geosynchronous orbits realized at m=n=1 и m=2, n=1, respectively. It should also be noted that apparently it is not accidentally that the orbits of two other known satellite communication systems (“SuperTundra”, “Loopus”) realized on elliptic orbits are in some or other measure similar to local-stationary geosynchronous orbits in their parameters (see Fig. 1).

Moving along high elliptic LSO the satellite provides communication during a long period of time due to its high apogee. So, for instance, the session of communication with orbital satellite “Molniya” (apogee about 40 000 km, perigee 460 km) lasts approximately 8-10 hours, and the system consisting of three such satellites supports global round-the-clock communication. In recent years, the interest to elliptic orbits in middle altitudes (with lower apogee and perigee) has grown. Satellite systems built on elliptic orbits of middle altitudes are usually destined to provide communication for relatively small Earth regions. At losing in comparison with high elliptic orbits in duration of coverage sessions, the systems on elliptic orbits of middle altitudes are energy-wise notably ahead. Application of the LSO permits to carry out optimization within a wide range of possible realizations of elliptic orbits while optimizing also energetic parameters demanded for orbital injection of satellites.

To design local-stationary geosynchronous orbits, the following expressions for draconic period Tdr of the satellite revolution, effective period Tef of the Earth revolution, and angular displacement δΩ of the satellite orbit ascending node, can be obtained [3] per one revolution:

$$T_{dr} = 2\pi\sqrt{\frac{a^3}{\mu}} \cdot \left\{1 - \frac{1}{a^2} \cdot \frac{\varepsilon}{\mu} \cdot \left[3 - \frac{5}{2} \cdot \sin^2 i - e \cdot \cos\omega \cdot \left(1 - 5 \cdot \sin^2 i\right)\right]\right\},$$

$$T_{ef} = \frac{2\pi + \frac{m}{n} \cdot \delta\Omega}{\omega_E}, \qquad (6)$$

$$\delta\Omega = -\frac{2\pi}{a^2\left(1-e^2\right)^2} \cdot \frac{\varepsilon}{\mu} \cdot \cos i,$$

where ε – constant value making allowance for the Earth compression.

Let us substitute (5) and (6) into (1). In view of that for the LSO ω=± 90°, it can be obtained:

$$\frac{\omega_E \cdot T_{dr} - \delta\Omega}{2\pi} = \frac{n}{m}. \qquad (7)$$

Equality (7) is equation for unknown value of the LSO apogee radius rA (apogee altitude HA) at given inclination i, number m of the satellite circuits, and number n of days in the satellite path repetition period.

It is marked that formulas (4) above allow to design unambiguously the LSO orbit shape (semi-major axis and eccentricity) for given values of apogee altitude and orbit inclination. When geosynchronous local-stationary orbits are used to find the apogee altitude, it is needed to solve equation (7) at known inclination and repetition factor of geosynchronous orbit. The elliptic orbit inclination is always chosen unambiguously as 63.4° providing stability of the line of apsides, but the choice of apogee altitude (geosynchronous orbit repetition factor) in abovementioned cases is not so evident and has to be done in view of other considerations connected with the peculiarities of the satellite communication system technical realization and with the known characteristics of the communication system transmitting-receiving duct.

Complementing the above by evaluation of the orbit apogee altitude as a function of demanded level of the goal-oriented use of satellite communication systems at preset parameters of their realization (those of transmitting-receiving devices), the efficient method can be developed providing the ballistic design method of satellite communication systems according to preset efficiency level of their goal-oriented application.

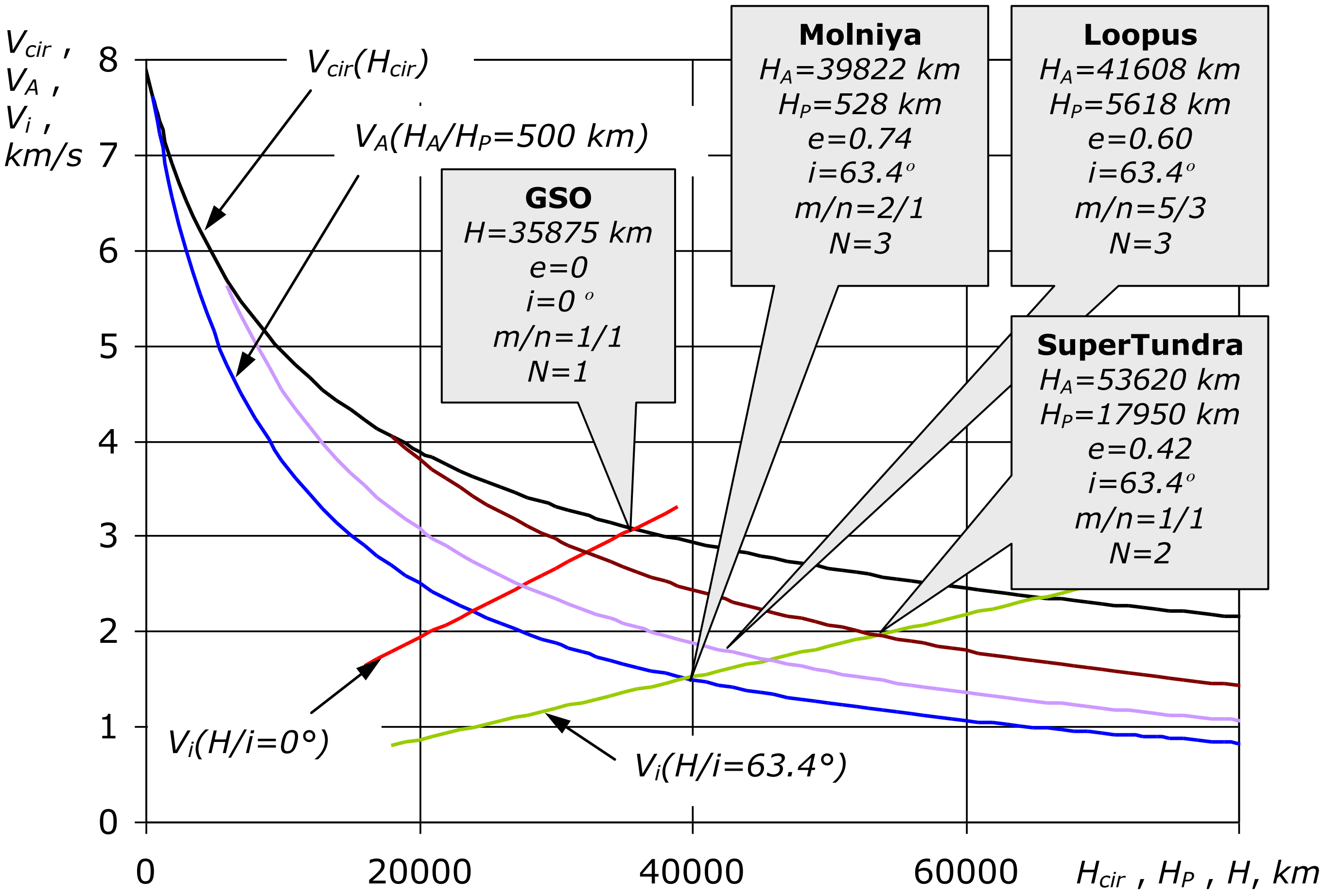

Fig.1. To defining the local-stationary orbits

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Authors

Y. N. Razoumny,

Moscow State Technical University, 5, 2nd Baumanskaya Str., Moscow, 107005, Russia.

Contacts: yr@viaspace.ru

D. O. Shkolnikov,

Moscow State Technical University, 5, 2nd Baumanskaya Str., Moscow, 107005, Russia.

Contacts: dmitry@shkolnikov.net

V. Y. Razoumny,

Moscow State Technical University, 5, 2nd Baumanskaya Str., Moscow, 107005, Russia.

Contacts: vr@viaspace.ru