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Orbits of Artificial Earth Satellites Used in the Intersputnik System with Optimum Position for Bulgaria

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This is an examination of the problems related to the determination of the optimum elliptic orbit for Bulgaria. Graphs have been given of geostationary and elliptic orbits with different longitudes of the apogee with respect to Sofia. The authors have analysed the conditions for communication of the other participants in the Intersputnik system when the satellite operates at an optimum orbit for our country. Quantitative evaluations have been given of the conditions for communication with an artificial earth satellite on elliptic and geostationary orbits.

Introduction

One of the forthcoming objectives of Bulgaria is the construction of an earth station (ES) for communications through artificial earth satellites (AES). In her capacity of participant in the Intersputnik international system for satellite communications, Bulgaria will operate with the satellites of that system and is interested in obtaining the optimum or near-optimum choice of the elliptic orbit to be used.

One basic variable parameter in the optimization of the conditions for operation with AES on an elliptic orbit is the position of the orbital plane in relation to Bulgaria. The distance between the meridian of the orbit apogee λ_A and the latitude λ_{ES} of the ES determines the proximity of the plane of the elliptic orbit.

The aim of our present work was to determine λ_A in such a manner as to obtain optimum conditions for communication between the AES and the ES of Bulgaria.

The optimum elliptic orbit is the one which ensures the following:

1. Maximum time for communication performance with AES;
2. Minimum in size biological zone of the ES;
3. Minimum by-pass angle in a horizontal direction.

This results in improvement of the electromagnetic compatibility with RRL operating or intended for operation in the band of joint operation with ES.

4. The noise temperature introduced through the aerial of the ES station from the atmosphere should be minimal.

Basic Dependences

The radius r_0 of the region of possible radio-communication between an ES and an AES travelling along an elliptic orbit of the Molniya-1 type is determined by the dependence (Fig. 1)

$$(1) \qquad r_0=\frac{\alpha_i}{180^0}\pi R,$$

where $2\alpha_i$ is an arc angle of the radiovisibility region from the satellite;

$i=1, 2, \ldots, n$ — points from the elliptic orbit; and R is the average Earth radius (6,370 km).

The angle γ characterizes the range of vision from an AES

$$(2) \qquad \gamma_i=\arcsin\frac{R\cos\beta_i}{R+H_{sat}}\,[\text{grad}],$$

$$(3) \qquad \gamma_i\leq\Theta^{[\circ]}_{0.5p},$$

where $2\,\gamma_i$ is the span of the radiovisibility apex angle from an AES upon its travel along an eliptic orbit.

$2\Theta^{[\circ]}_{0.5p}$ is the width of the diagram of AES antenna oriented for operation at a half-power level. According to [1], $2\Theta^{[\circ]}_{0.5p}=20^\circ$.

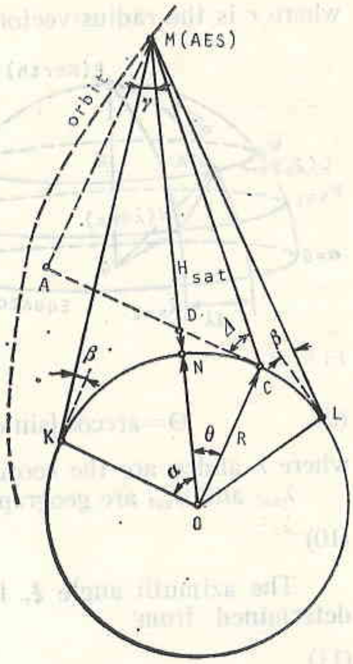


Fig. 1

$$(4) \qquad H_{sat}=r_i-R$$

is the height of the satellite above the Earth's surface; r_i — radius vector of an i point of the elliptic orbit where the satellite is to be found at the particular moment; and β_i is the minimum angle of operation of the aerial of the ES above the horizon.

In view of considerations for reducing the noise temperature of the aerial, as introduced from the Earth, $\beta_i\geqslant 5^\circ$.

The dependence between the above angles is determined from

$$(5) \qquad \alpha_i=90^\circ(\gamma_i+\beta_i)\,[\text{grad}]$$

and

$$(6) \qquad \beta_i=\arccos\frac{R+H^{sat}}{R}\sin\gamma\,[\text{grad}].$$

Determining the Optimum Elliptic Orbit for Bulgaria

The town of Sofia (geographic coordinates $\lambda=23^\circ$ e. l. and $\varphi=43^\circ$ n. l.) was selected as the observation point in determining the visibility of the satellite pass along a certain elliptic orbit. The position of the satellite in a vertical plane is determined by the angle above the horizon Δ°, while the direction toward the horizon is determined by the azimuth angle ξ.

The angle Δ° is determined by the dependence

(7) $$\Delta = \operatorname{arctg}\frac{AM}{CD+AD} = \operatorname{arctg}\frac{\cos\Theta - R/r}{\sin\Theta}\ [\text{grad}],$$

where r is the radius-vector of the point at which the AES is to be found, and Θ is the geocentric angle between the point of observation $C(\lambda, \varphi)$ and the projection of the satellite on the Earth's surface N (λ_{sat}, φ_{sat}). The angle Θ determines the distance between the points C and N by the dependence

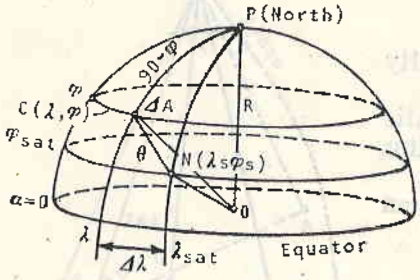


Fig. 2

(8) $$\varrho = \frac{\Theta}{180^\circ}\cdot \pi R.$$

The angle Θ is determined from the spherical triangle NCP (Fig. 2)

(9) $$\Theta = \arccos\left[\sin\varphi \cdot \sin\varphi_{sat} + \cos\varphi \cdot \cos\varphi_{sat} \cdot \cos\Delta\lambda\right]\ [\text{grad}],$$

where λ and φ are the coordinates of the observation point;

λ_{sat} and φ_{sat} are geographical coordinates of the satellite projection:

(10) $$\Delta\lambda = \lambda_{sat} - \lambda.$$

The azimuth angle ξ, taken in a North-East — South-West direction, is determined from

(11) $$\xi = \Delta A$$

when λ_{sat} is to the east of the meridian $\lambda = 23^\circ$ e. l. and from

(12) $$\xi = 360^\circ - \Delta A$$

when λ_{sat} is to the West of the meridian $\lambda = 23^\circ$ e. l., while ΔA is determined from the spherical triangle NCP

(13) $$\Delta A = \arccos\frac{\sin\varphi_{sat} - \sin\varphi \cdot \cos\Theta}{\sin\Theta \cdot \cos\varphi}\ [\text{grad}].$$

The geographic coordinates of the satellite λ_{sat}, φ_{sat} at any moment of its movement along the elliptic orbit are determined by the geocentric projection of the orbit on the Earth's surface. Figure 3 shows the geocentric projection of the odd elliptic trajectory, according to [2], due account being taken of the Earth's movement.

The projection of the even elliptic trajectory is a continuation of the odd one and has the position of the apogee λ''_A:

(14) $$\lambda''_A = \lambda'_A + 180^\circ.$$

Figure 4 shows graphically presented elliptic orbits with different longitude of the apogee λ'_A (λ''_A), as they are seen from the selected observation point. The position of the satellite is determined in relation to the moment of time in which the AES passes through the perigee point ($t_o = 00$ h).

Table 1 gives the basic quantities which are characteristic of the elliptic orbit, namely: the radius-vector r, V° (the angle between the direction to the perigee and r), the radiovisibility zone from the satellite (α, r_0) and the distance from the observation point to the projection of the satellite on the Earth's surface (Θ, ρ) for the selected elliptic orbits with different longitude of the apogee in function of absolute time.

For the purpose of determining the duration of the session for communication with the AES, we compare the visual zone of the AES from (1) and the distance to the undersatellite point from (8) (Table 1).

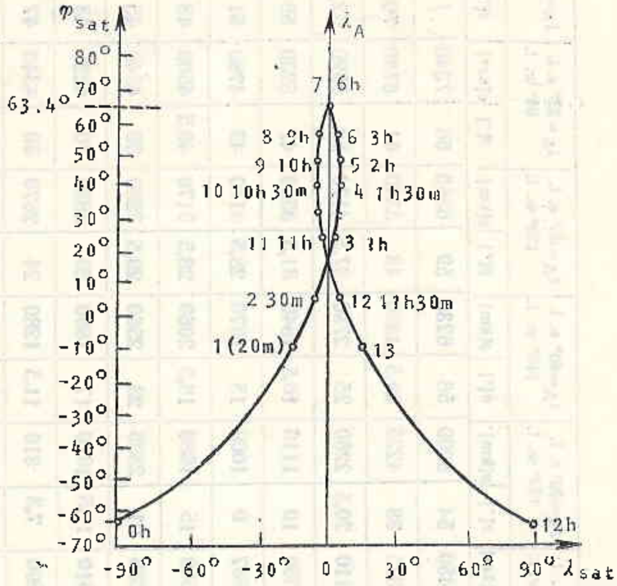


Fig. 3

1. At $\rho > r_0$ ($\Theta > \alpha$) the AES cannot "see" us with its aerials. Our visibility toward the satellite is determined by Δ from (7) and ξ from (11) or (12), and depends on the overlap angle to the horizon. When it is possible to ensure a minimum covering angle ($\beta_{min} = 5°$) for all orbits shown on Fig. 4, we can follow the movement of the satellite within an approximately 11-hour sector. In order to realize the communication session it is necessary to adjust the diagram of directed opetation of the satellite's aerial.

2. At $\rho \leqslant r_0$ ($\Theta \leqslant \alpha$) the AES satellite can be used to establish communication with member-country of the Intersputnik system. The boundary line $\rho = r_0$ at $\beta = 5°$ and $\gamma = 10°$, plotted by a broken line on Fig. 4, determines the duration of the communication session as shown in Table 2. The results obtained show that upon using one AES travelling along an elliptic orbit with different positions of the apogee, the total time of the communication session is a sum of two variable components.

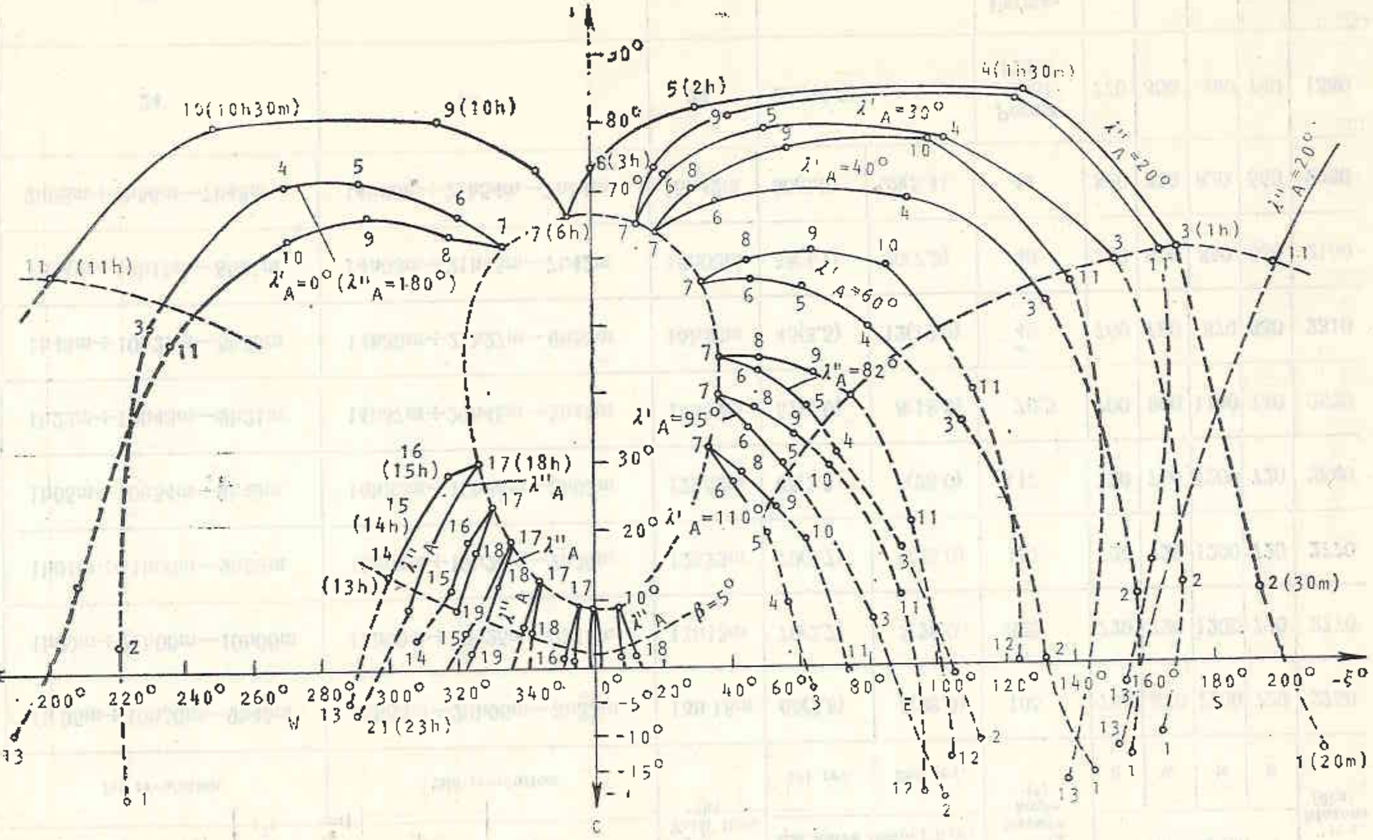
The dimensions of the biological zone of the ES for protection from the irradiation of the aerial within the microwave band for persons not professionally involved in radiation and for the population is determined, as regards intensity, at 1 μW/cm² [3].

The size of the biozone depends on the power of the operating transmitters and on the values of the operative angles in horizontal and vertical directions. The dimensions of the biozones for the selected orbits at transmitter power $P_{tr} = 10$ kW, as well as the bypass angles from the aerial in a horizontal direction, are given in Table 2.

The noise temperature of the aerial T_{na} (introduced from dry atmosphere) is significant to the quality of the signal received from the satellite, whose value is of the order of 10^{-14} W/m^2. It depends on the angle above the horizon $\Delta°$ at which the aerial is operating

Table 1

No.	Time after the perigee, [h; min]	$V°$, [°]	$\bar{r}$=R+H [km]	α [°]	$\bar{r}_0$ [km]	λ_A=0° e. l. 180° w. l.		λ_A=20° e. l. 160° w. l.		λ_A=30° e. l. 150° w. l.		λ_A=40° e. l. 140° w. l.		λ_A=60° e. l. 120° w. l.		λ_A=82° e. l. 98° w. l.		λ_A=95° e. l. 85° w. l.		λ_A=110° e. l. 70° w. l.	
						θ[°]	ϱ[km]	θ[°]	ϱ [km]	θ[°]	ϱ[km]	θ[°]	ϱ[km]	θ[°]	ϱ[km]	θ[°]	ϱ[km]	θ[°]	ϱ[km]	θ[°]	ϱ[km]
1	20 m	54,5	8376	3,2	350	63,1	7015	58	6450	54	6000	56	6230	59	6560	66	7340	/	/	/	/
2	30 m	76	9649	5,3	580	45,5	5058	39	4335	38	4225	39,5	4390	48	5340	61	6780	70	7780	/	/
3	1 h	117	18050	19,4	2153	26	2890	19	2110	20,5	2280	25	2780	37,5	4170	53	5890	62,5	6950	73	8115
4	1 h 30 m	138	26573	36,4	4038	14	1560	5	556	10	1110	16,5	1840	31,5	3500	47	5230	56	6230	67	7450
5	2 h	149,5	33140	59,5	6615	15	1670	6	667	9	1000	15	1670	28,5	3170	43	4780	51	5670	59,5	6615
6	3 h	160,5	39387	76	8460	20	2220	14	1560	15	1680	18,5	2060	28,5	3170	40,5	4500	48	5340	55	6115
7	6 h	180	45961	77	8560	25	2780	21	2335	21	2335	23	2560	29,5	3280	39	4340	45	5010	51	5670
8	9 h	200,2	39103	76	8460	21,5	2390	14,5	1610	14,5	1610	17	1890	26	2890	38	4225	43	4780	53	5890
9	10 h	210	33324	59,5	6615	15,5	1720	8	890	7,3	810	11,5	1280	24	2670	39	4340	47	5230	56	6225
10	10 h 30 m	221,5	26811	37	4100	21	2330	8	890	5	556	10	1110	24,5	2720	40	4450	49	5460	59	6560
11	11 h	241	18680	20,5	2280	28,5	3170	20	2220	19,7	2190	27	2450	35	3890	50	5560	60	6680	70	7780
12	11 h 30 m	280	10615	6,1	750	41,5	4610	38	4225	39,5	4390	43	4780	53	5900	68	7560	71	7910	/	/
13	14 h	149,5	33140	59,5	6615	/	/	/	/	/	/	/	/	/	/	74	6230	68	7560	59,5	6615
14	15 h	160,5	39387	76	8150	79	8780	80,5	8950	80,3	89,30	79,3	8320	73,3	8370	68	7560	63	7000	54	6000
15	18 h	180	45961	77	8560	73	8115	74	8230	73,5	8170	73	8115	70	7780	64	7115	59,5	6610	54	6000
16	21 h	200,2	39103	76	8460	78	8670	80,4	8940	80,5	8950	80	8390	76,3	8480	70	7780	64,5	7170	58	6450
17	22 h	210	33324	59,5	6615	/	/	/	/	/	/	/	/	/	/	77	8660	71	7910	63	7000



10(10h30m)
9(10h)
5(2h)
4(1h30m)
6(3h)
7(6h)
11(11h)
3(1h)
2(30m)
1(20m)
17(18h)
(15h)
(14h)
(13h)
21(23h)
90°
80°
70°
30°
20°
10°
0°
-5°
-10°
-15°
200°
220°
240°
260°
280°
300°
320°
340°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
W
S
E
-ξ°

Fig. 4

Table 2

No.	Longitude of the apogee [°]	Time of communication session: from -- to (h)		Total time (h)	Angle to the horizon and noise temp. [°]; [K]		Bypass angle [°]	Biozone [m]				Biozone (dca)
		1st revolution	2nd revolution		1st rev.	2nd rev.		E	W	N	S	
1	0° e. l. 180° w. l.	1h 05m÷10h50m—9h45m	16h33m÷20h06m—3h33m	13h 18m	65(2.8)	5(28.0)	105	760	670	1200	720	2750
2	20° e. l. 160° w. l.	1h00m÷11h00m—10h00m	17h00m÷19h25m—2h15m	12h15m	70(2.7)	5(28.0)	325	720	720	1200	720	2770
3	30° e. l. 150° w. l.	1h01m÷11h00m—9h59m	16h54m÷19h24m—2h30m	12h29m	70(2.7)	5(28.0)	151	720	720	1200	720	2770
4	40° e. l. 140° w. l.	1h05m÷10h54m—9h49m	16h32m÷19h36m—3h03m	12h52m	65(2.8)	5(28.0)	117	720	760	1200	720	2840
5	60° e. l. 120° w. l.	1h22m÷10h43m—9h21m	14h57m÷20h45m—5h48m	15h09m	57(3.0)	8(18.0)	70.5	700	800	1140	740	2820
6	82° e. l. 98° w. l.	1h48m÷10h27m—8h39m	14h30m÷21h27m—6h53m	15h32m	45(3.5)	12(12.0)	49	760	780	870	630	2310
7	96° e. l. 85° w. l.	1h54m÷10h15m—8h21m	14h03m÷21h45m—7h42m	16h03m	38(4.1)	20(7.3)	40	760	800	850	530	2150
8	110° e. l. 70° w. l.	2h08m÷9h56m—7h48m	14h00m÷21h54m—7h54m	15h42m	30(5.0)	28(5.4)	44	800	850	830	550	2280
9	68° e. l.	24	—	24	23.7(6.2)		Permanent 124.3°	770	350	490	740	1380
10	10° w. l.	24	—	24	30.1(5.0)		Permanent 223.6°	430	740	390	740	1320

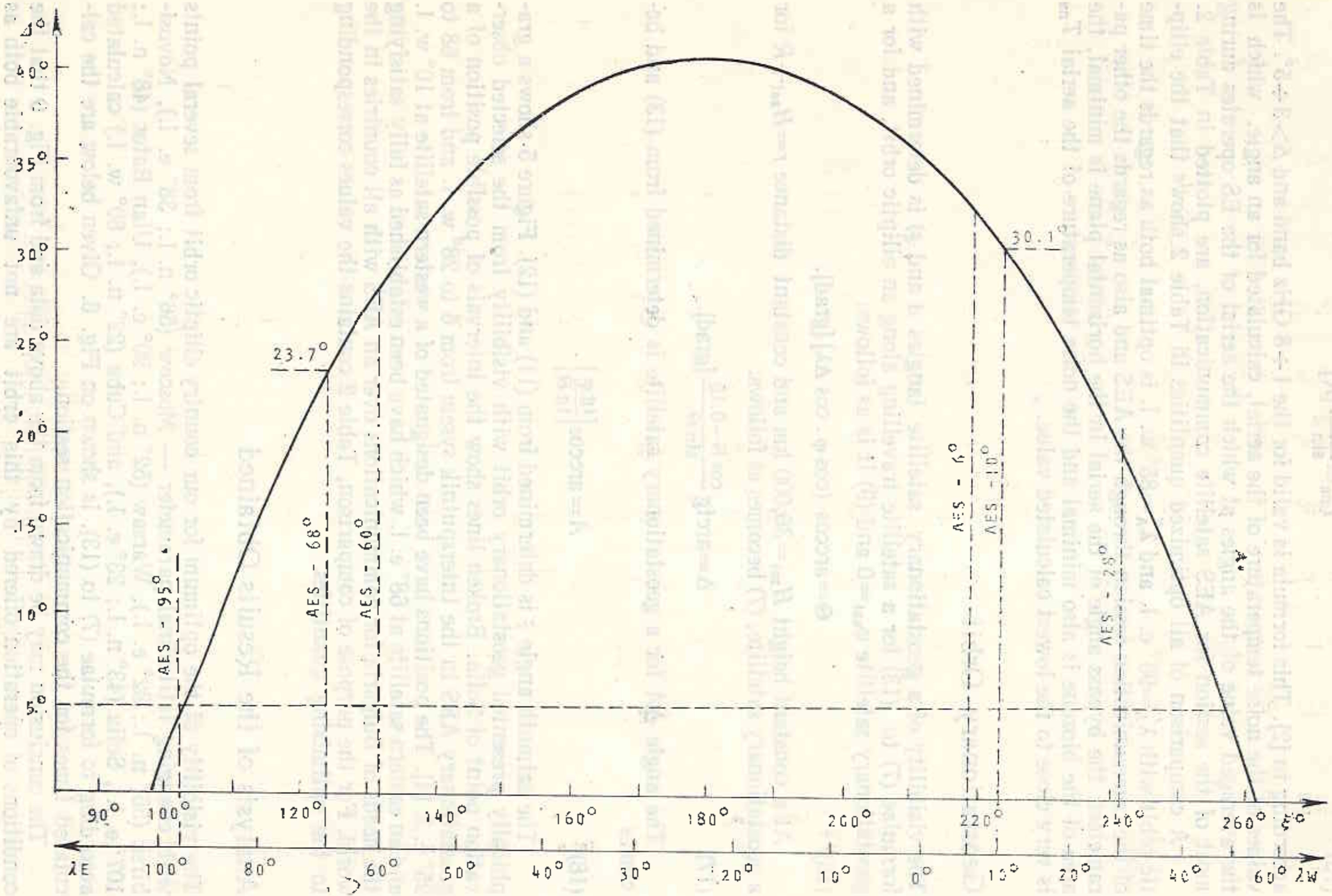


Fig. 5. Visibility of the geostationary orbit from Sofia ($\lambda = 23°$ e. l.; $\varphi = 43°$ n. l.)

(15) $$T_{na}=\frac{2.5}{\sin \Delta}\ [K]$$

according to [2]. This formula is valid for the 1÷8 GHz band and $\Delta > 3 \div 5°$. The values of the noise temperature of the aerial, calculated for an angle, which is the averaged value of the angles at which the aerial of the ES operates during most of the session for AES satellite communication, are plotted in Table 2.

A comparison of all optimized quantities in Table 2 shows that the elliptic orbit with $\lambda'_A=95°$ e. l. and $\lambda''_A=85°$ w. l. is optimal both as regards the time of the communication session through the AES and also as regards the other parameters: the bypass angle of the aerial in the horizontal plane is minimal, the area of the biozone is also minimal and the noise temperature of the aerial T_{na} is very close to the lowest calculated value.

Geostationary Orbit

The visibility of a geostationary satellite (angles Δ and ξ) is determined with formulae (7) to (13) for a satellite travelling along an elliptic orbit, and for a geostationary satellite $\varphi_{sat}=0$ and (9) it is as follows:

(16) $$\Theta=\arccos\ (\cos \varphi \,.\, \cos \Delta\lambda]\ [\text{grad}].$$

At a constant height $H_{sat}=36{,}000$ km and constant distance $r=H_{sat}+R$ for a geostationary satellite, (7) becomes as follows:

(17) $$\Delta=\text{arctg}\frac{\cos \Theta-0.15}{\sin \Theta}\ [\text{grad}].$$

The angle ΔA for a geostationary satellite is determined from (13) and becomes

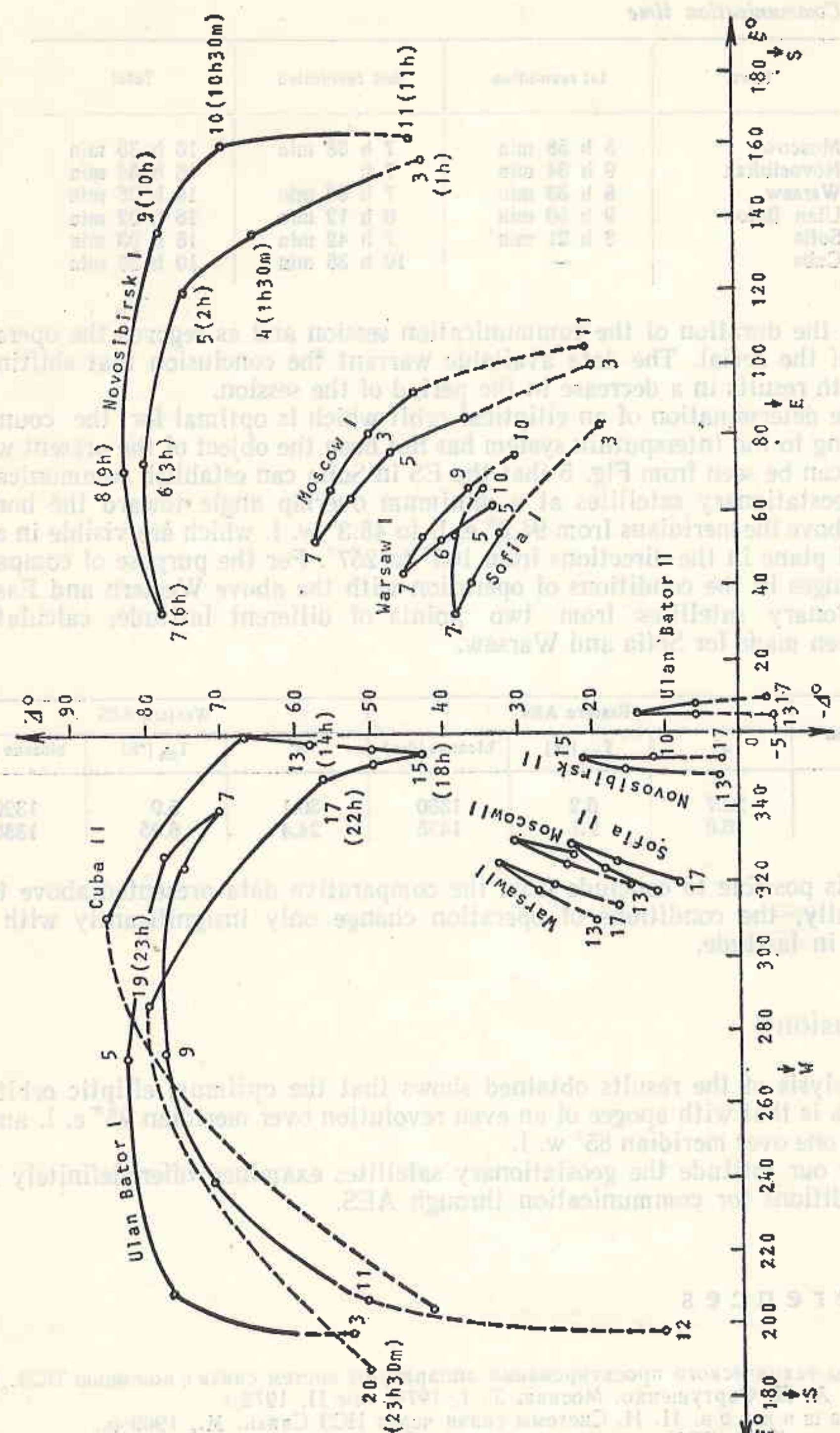
(18) $$A=\arccos\left[\frac{\text{tg}\,\varphi}{\text{tg}\,\Theta}\right].$$

The azimuth angle ξ is determined from (11) and (12). Figure 5 shows a graphically presented geostationary orbit with visibility from the selected observation point of Sofia. Broken lines show the intervals of possible position of a geostationary AES in the Intersputnik sysem from 6 to 28° w. l. and from 68 to 95° e. l. [4]. The positions have been designated of a western satellite at 10° w. l. and an eastern satellite at 68° e. l. which have been established as fully satisfying the needs of Bulgaria for communications over an AES with all countries in the world. For the purpose of comparison, Table 2 contains the values corresponding to the optimizing quantities.

Analysis of the Results Obtained

The visibility of the optimum for our country elliptic orbit from several points with changing latitudinal parameter — Moscow (56° n. l.; 38° e. l.), Novosibirsk (55° n. l.; 82° e. l.), Warsaw (52° n. l.; 20° e. l.), Ulan Bator (48° n. l.; 107° e. l.), Sofia (43° n. l.; 23° e. l.), and Cuba (22° n. l.; 80° w. l.) calculated according to formulae (7) to (13), is shown on Fig. 6. Given below are the calculated times for the communication session.

The conclusion may be drawn from the above data and from Fig. 6 that the conditions of operation offered by this orbit are not unfavourable both as



Novosibirsk I
Moscow I
Warsaw I
Sofia I
Ulan Bator I
Ulan Bator II
Cuba II
Novosibirsk II
Moscow II
Sofia II
Warsaw II
10(10h30m)
9(10h)
8(9h)
7(6h)
6(3h)
5(2h)
4(1h30m)
11(11h)
3(1h)
19(23h)
20(23h30m)
17(22h)
15(18h)
13(14h)
E°
Δ°

Fig. 6

Communication time

Town	1st revolution	2nd revolution	Total
Moscow	8 h 58 min	7 h 38 min	16 h 36 min
Novosibirsk	9 h 34 min	7 h	16 h 34 min
Warsaw	8 h 33 min	7 h 53 min	16 h 26 min
Ulan Bator	9 h 50 min	6 h 12 min	16 h 02 min
Sofia	8 h 21 min	7 h 42 min	16 h 03 min
Cuba	—	10 h 36 min	10 h 36 min

regards the duration of the communication session and as regards the operating angle of the aerial. The data available warrant the conclusion that shifting to the south results in a decrease in the period of the session.

The determination of an elliptical orbit which is optimal for the countries belonging to the Intersputnik system has not been the object of the present work.

It can be seen from Fig. 5 that the ES in Sofia can establish communication with geostationary satellites at a minimum overlap angle toward the horizon of 5°, above the meridians from 94.3° e. l. to 48.3° w. l. which are visible in a horizontal plane in the directions from 103° to 257°. For the purpose of comparing the changes in the conditions of operation with the above Western and Eastern geostationary satellites from two points of different latitude, calculations have been made for Sofia and Warsaw.

Location	Eastern AES			Western AES		
	$\Delta°$	T_{na} [°k]	biozone [dca]	$\Delta°$	T_{na} [°k]	biozone [dca]
Sofia	23.7	6.2	1380	30.1	5.0	1320
Warsaw	16.0	9.1	1425	24.4	6.05	1380

It is possible to conclude from the comparative data presented above that, practically, the conditions of operation change only insignificantly with the change in latitude.

Conclusion

The analysis of the results obtained shows that the optimum elliptic orbit for Bulgaria is that with apogee of an even revolution over meridian 95° e. l. and of the odd one over meridian 85° w. l.

For our latitude the geostationary satellites examined offer definitely better conditions for communication through AES.

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Оптимальные для НРБ орбиты ИСЗ, использованные в системе „Интерспутник“

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(Р е з ю м е)

Рассмотрены вопросы, связанные с определением оптимальной для НРБ эллиптической орбиты. Графически представлены геостационарная и эллиптические орбиты с изменением географической долготы и апогѐя по отношению к Софии. Анализированы условия связи с другими участниками в системе „Интерспутник“ в условиях работы со спутником на оптимальной для нашей страны орбите. Даны количественные оценки условий связи со спутниками на эллиптических и геостационарной орбитах.