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Satellite Infocommunications Protection against Unauthorized Use

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Abstract
One of the important elements of the modern infocommunication infrastructure is satellite communications, the main advantage of which is the provision of information and communication services on a very large area. This circumstance led to the unpunished pirate capture of the onboard transponder resources and is a problem of the international community since a pirate can be located in the territory of any state within the coverage area of space communications. The coordinates of a space vehicle, on the board of which a transponder is installed, and its characteristics are well known, what simplifies the task of capturing a frequency resource. The pirate activity leads to a violation of the legitimate user rights, who pays for the leased frequency band, but cannot use it due to the pirate capture, and of the rights of an onboard transponder owner, to whom the pirate does not pay for the utilized resource. This requires the development of methods, software, and hardware to ensure an adequate protection of the information interests of the legitimate users of the satellite communications by positioning an unknown ground station (UGS). The article describes the methods and characteristics of the UGS positioning based on the measurements of Doppler shift and/or phase delay of signals proportional to the time of the radio signal propagation. It is shown that the proposed methods allow for the accuracy of the UGS positioning to a tenth of a degree.

Keywords: Information Systems, Satellite Communications, Positioning, Doppler Shift Of The Carrier Frequency, Phase Measurements, Antenna Array, Virtual Antenna Array.

Introduction
Mass distribution of infocommunication technologies has led to the need for protecting the transported information against malicious interventions [1, 2]. The satellite communications has been widely used for the data transmission, Internet access, television, voice messages in the phone mode, etc. As one of the communication technologies forms, the satellite communications is also exposed to the possibility of malicious intervention [3, 4].

One scenario for this intervention is as follows. The most widely used satellites are those placed in a geostationary orbit (GEO). The area illuminated by such satellite is approximately 1/3 of the Earth's surface. Therefore, an unknown ground station (UGS) can be placed at arbitrary points within a rather vast territory [5, 6]. An onboard satellite transponder is not protected against the unauthorized access, which gives rise to the problem of ensuring information security of this type of telecommunications since an illegal use of the transponder's frequency resource is possible. According to reports at the Scientific Conference in Dubna (Russia) in 1999, the number of registered events of the pirate captures of the satellite's frequency resource reached 200 cases [7]. By now, the statistics of captures is not published in the open press, but the experience shows that such a practice takes place. It characterizes the urgency of the problem of satellite infocommunication protection against an unauthorized use.

There are knows several proposals dedicated to the solution of this problem. In particular, it is possible to install an intentional interference for a malicious user as suggested in [8] with the aim of ousting the attacker from the operating frequency band. This technique has a limited perspective.

Much more promising is the positioning of the pirated UGS location followed by the implementation of legal measures including those of the international level.

One of the first attempts to solve this problem dates from the early 1990-ies [3]. It was proposed to use two satellites in a geostationary orbit with a small but well-known distance between them. The UGS signals to be received by each satellite and transmitted to a Measuring Earth Station (MES). The UGS coordinates are determined by the difference between the signal's time of arrival to MES and a Doppler frequency shift. The experimental testing showed that antennas with a diameter of about 20 m are required for receiving weak signals. An error value of 150–200 km and sometimes 600 km was reached. This method was further discussed in [9 ... 13], but has no future as the demand for receiving signal by two or more satellites extremely complicates the technical implementation. In [14], the authors propose a method for radio source positioning when receiving radio signals of one radio source using non-linear (including circular) antenna systems of arbitrary shape [15] consisting of weakly directional and directional elements (vibrators). The UGS location is possible through the use of a multi-beam antenna on a satellite [15], but this solution has not moved beyond the purely theoretical framework because the complexity of an onboard antenna and the low positioning accuracy, which is determined by the each beam width, require further significant development. In [16] it is proposed to pre-select the signals from an illegitimate user according to

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the discrepancy criterion of the complex frequency spectrum and the spectrum of wavelet transformation with respect to the signals from legitimate users and only then to evaluate the coordinates.

Positioning based on the Doppler frequency shift measurements.

Fig. 1 schematically shows the layout of a geostationary satellite in the geocentric coordinate system at point A. The Z axis is directed to the north (N). Satellite coordinates: latitude λ_s and longitude φ_s. UGS is located on the Earth's surface at point B. R1 is the distance from the center of the Earth to the satellite, and R2 is the distance to point B (Earth's radius).

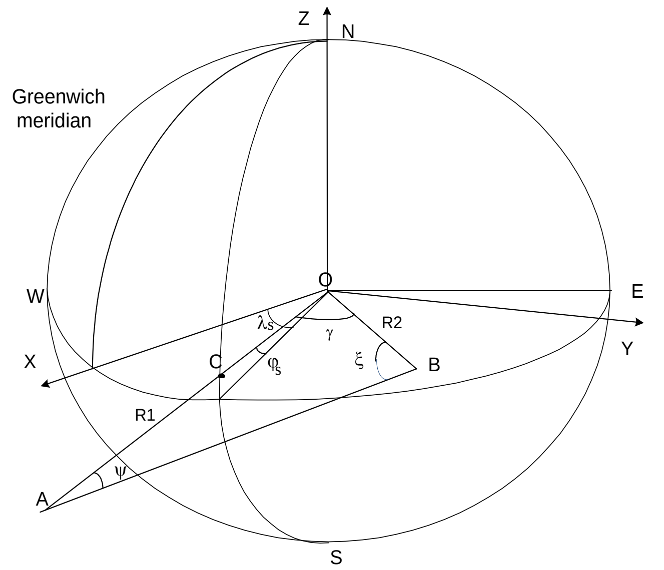

Figure 1: A schematic layout of a geostationary satellite

The projection to the Earth's surface of the trajectory of a geostationary satellite slow motion during the day resembles a figure 8 (Bernoulli's lemniscate). This satellite motion causes a Doppler frequency shift. If a satellite-transponder moves relative to a fixed pirated radio source (the coordinates of which can be determined) with the velocity V and at an angle ψ to the direction of a communication line, then the resulting Doppler shift F_D of the frequency f_0 is given according to [5]:

$$F_D = f_o \frac{V}{C} \cos(\psi) \qquad (1)$$

Here, C is the velocity of light in free space.

We will further consider the use of only one satellite for UGS positioning with the help of Doppler techniques. Using the known coordinates of the satellite and the measured Doppler frequency value F_D, we can determine the UGS coordinates. At a fixed satellite position, the line of the F_D constant value on the Earth's surface is a closed second-order curve formed by the intersection of cone (at the top of which a satellite is located) and the Earth's surface. The shape of this curve depends on the angle α between the satellite's velocity vector and the radius-vector, which is understood as an imaginary line connecting the center of the satellite mass and the center of the Earth. At $\alpha \approx 0/\pi$, this curve is an ellipse. When the angle α deviates from the set value, then the curve of the constant values f_0 degenerates into a hyperbole. The procedure of UGS positioning when the angle α is in the neighborhood of points 0 or π. Thus, when the satellite moves away from the Earth at a sufficiently long period of time ($\alpha \approx \pi$) or approaches the Earth ($\alpha \approx \pi$), then the other components of the daily satellite movement can be neglected. The daily ephemerides of the geostationary satellites allow allocating areas with $\alpha \approx 0$ or $\alpha \approx \pi$. Therefore, we will continue to consider only $\alpha = 0, \pi$.

A subsatellite point is located in the center of the ellipse (point C in Fig. 1). It should be noted that Fig. 1 schematically shows a satellite with a shift to the north of the geostationary orbit. For the above stated reasons, the satellite movement leads to a change in the coordinates of the station point and the F_D value, which corresponds to a different ellipse. The UGS coordinates are to be determined at the point of at least three ellipses intersection with the known coordinates of the centers. The UGS coordinates can be obtained as follows. Angle ψ is determined from (1):

$$\psi = \arccos\left(\frac{(F_D - F_{DGS})}{f_o v} C \right), \qquad (2)$$

where F_{DGS} – a Doppler frequency shift on the line satellite – measuring earth station path. This option can be easily taken into account by a special test signal passing along the line MES – satellite – MES of the feedback loops and allows for the accurate measurement of F_{DGS}. Angle γ is determined from (1):

$$\gamma = 180 - (\psi + \xi) = 180 - \{\psi + \arcsin[(R1/R2)\sin\psi]\} \qquad (3)$$

where R1 is the satellite's radius-vector, R2 is the distance between the center of the Earth and the point B. The coordinates of the ellipse center: x_0, y_0, z_0

$$\left.\begin{aligned} x_o &= R_2 \cos(\gamma)\cos(\varphi_s)\cos(\lambda_s) \\ y_o &= R_2 \cos(\gamma)\cos(\varphi_s)\sin(\lambda_s) \\ z_o &= R_2 \cos(\gamma)\sin(\varphi_s) \end{aligned}\right\} \qquad (4)$$

Here, λ_s is the satellite's longitude.

As noted above, an UGS is located at the intersection of at least three ellipses formed at three different positions of the satellite. However, it is easier to search for the intersection point of three planes, in which the ellipses are located. Moreover, this approach allows determining the coordinates of UGS located, for example, on an airplane. The canonical form, which defines a plane in the space E, in which the ellipses are located, is determined by the following expression:

$$E = A(x - x_0) + B(y - y_0 + C(z - z_0) = 0 \ ,$$

where x_0, y_0, and z_0 are the coordinates of a point in a given plane, i. e. the ellipse center coordinates. It should be noted that these are the coordinates of the satellite's station point projection to the plane E. A, B, and C are the coordinates of the normal vector (A, B, C) to this plane, where $A=(x_0-x)$, $B=(y_0-y)$ and $c=(z_0-z)$. In this case, the beginning of the normal vector coincides with the center of the geocentric coordinate system, i. e. x=y=z=0. Thus, the plane, in which the ellipse is located, and which intersects with the Earth's surface, is given

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by the following equation:

$$x_o x + y_o y + z_o z = x_o^2 + y_o^2 + z_o^2 \qquad (5)$$

The solution of the system of three equations for the Doppler frequency shift FD at three points of the satellite's daily movement trajectories allows obtaining the target coordinates x, y, and z. The transformation of x, y, z into the geographical latitude and longitude of UGS is carried out by solving the following equation:

$$\varphi = \text{arctg}\,(z/\sqrt{x^2 + y^2}),\ \lambda = \text{arctg}\ y/x$$

The positioning errors are caused by the inaccurate knowledge of satellite coordinates and the Doppler frequency measurement error. It can be shown that the error in determining the latitude and longitude at FD = const is respectively equal to:

$$\Delta\lambda = \frac{1}{1+(y/x)^2}\left(\frac{1}{x}\delta y - \frac{y}{x^2}\delta x\right),$$

$$\Delta\varphi = \frac{1}{1+z^2/(x^2+y^2)}\left[\frac{\delta z}{\sqrt{x^2+y^2}} - \frac{x\delta x + y\delta y}{x^2+y^2}\right] \qquad (6)$$

The calculation results are shown in Fig. 2, 3. Here, x, y, z are the indirect measurement errors obtained by a Taylor series expansion with neglecting the terms of order higher than the first one [17]. The calculation results according to (6) are shown in Fig. 2, 3.

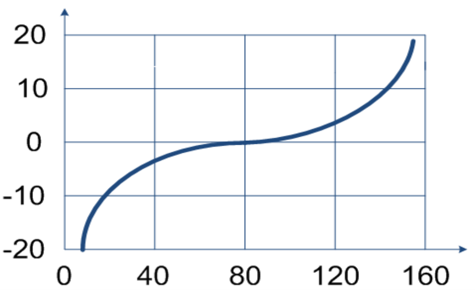

Figure 2: The dependence $\Delta\lambda(\lambda_{UGS})$

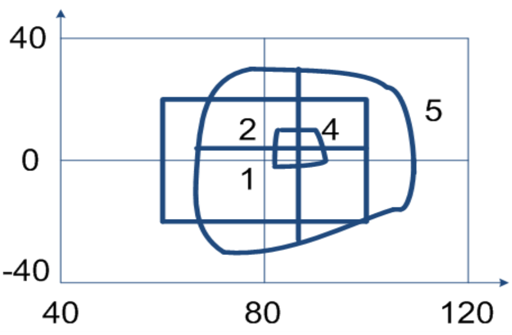

Figure 3: The boundaries of working areas.

Fig. 2 shows the dependence of the $\Delta\lambda$ error as a function of longitude λ_{UGS}. As can be seen, the error increases at the edges of the radio coverage zone. The dependence $\Delta\varphi(\varphi_{UGS})$ has the same complex variable nature. Based on the estimated dependences $\Delta\lambda(\lambda_{UGS})$ and $\Delta\varphi(\varphi_{UGS})$, the working areas were presented graphically (fig. 3). The figure 1 is the "station" point, the curve 2 is $\Delta\lambda(\lambda_{UGS})=0$, the curve 3 corresponds to $\Delta\varphi(\varphi_{UGS})=0$. The figure 4 marks the boundary of the working area, within which the error does not exceed 0.1^0, and in Fig. 5 – 1^0.

During the satellite movement along the daily trajectory, there are sections where $|V_1| = |-V_2|$, the antipodal path sections are conditionally designated by the indices 1, 2. In the vicinity of these points, the positioning error $|\ \Delta\lambda_1\ | \approx |\ -\Delta\lambda_2\ |$ and, respectively, $|\ \Delta\varphi_1\ | \approx |\ -\Delta\varphi_2\ |$. It is obvious that $\lambda_1 = \lambda_{TRUE} + \Delta\lambda_1$, $\lambda_2 = \lambda_{TRUE} - \Delta\lambda_2$, where λ_1 and λ_2 are the estimated values of longitude at the first and the second points, respectively, λ_{TRUE} – is the true value of the UGS longitude. The following equation is true:

$$\lambda_{PR} = \lambda_{TRUE} + \frac{|\ \Delta\lambda_1\ | - |\ \Delta\lambda_2\ |}{2}\ . \qquad (7)$$

In the area between the figures 3 and 4 in Fig. 3, the errors are calculated by (7), and the values for latitude do not exceed 0.29^0. All calculations are made for the relative measurement error of the Doppler frequency shift $F_D \approx 10^{-3}$. If for some reason the use of Doppler method is impossible, then for the measurements it is necessary to use the UGS coordinates based on the phase measurements (see below).

iii. Positioning based on the phase measurements.

Let the antenna array consisting of two pairs of receiving antennas be mounted on a satellite fixed in GEO in point A (Fig. 1). One pair is oriented in the equatorial plane and another one – orthogonally in the meridian plane. Using a Krasovsky ellipsoid [6] for describing the Earth's surface, it is possible to get an expression for calculating the target UGS latitude and longitude in the geocentric coordinate system:

$$\varphi = \arcsin(\sin\gamma \sin\alpha),\ \lambda = \lambda_s + \arcsin\frac{tg\varphi}{tg\alpha},$$

where φ and λ are the UGS latitude and longitude, respectively; λ_s is the satellite latitude in a station point; $\gamma = 180 - (\arcsin\frac{d\sin\beta}{R} + \beta)$ is an angle between *R* and *L*, *R* is the Earth's radius; *L* is the distance from the Earth's center to the geometric center of the antenna array; $\alpha = arctg\frac{\Delta\varphi_{1-2}}{\Delta\varphi_{3-4}}$, $\beta = \arcsin\left[\frac{\upsilon}{2\pi d}\sqrt{\Delta\varphi_{1-2}^2 + \Delta\varphi_{3-4}^2}\right]$ are the angles determining the direction of arrival of a radio wave emitted by the UGS transponder; *d* is the antenna array base; υ is the wavelength of the received signal; $\Delta\varphi_{1-2}, \Delta\varphi_{3-4}$ are the phase shifts between the signals received by the receiving antenna array elements.

Thus, by measuring the phase shifts of the signals received by an antenna array, it is possible to determine the direction to UGS relative to the geostationary satellite.

The UGS latitude and longitude determination errors depend on as follows:

- The measurement errors of phase differences $\Delta\psi_{1-2}^*$ and $\Delta\psi_{3-4}^*$.
- The inaccuracy of the satellite delivery to the stationary point.
- The per diem evolutions of the satellite position (see above).

- The error of orienting a satellite array relative to meridians and parallels.

The UGS latitude and longitude determination errors due to indirect measurements are calculated according to the formulas (6). In the calculations, it is assumed that UGS is located in the right top quarter of a spheroid with $0^\circ \le \alpha \le 90^\circ$. The spheroid quarters are formed by the intersection of the equatorial plane and the meridional plane corresponding to the satellite's station point. The angle β is determined by the UGS position in one quarter of a spheroid. The maximum value of the angle is determined by the boundary of the illuminating UGS contour due to the nonspherical shape of the Earth. For the case $\alpha = 90^\circ$ (UGS is located on the meridian of the satellite's station point), angle α can take on values from 0^0 to 8.65°. For $\alpha = 0^\circ$ (UGS is at the equator), angle $\beta = 0^\circ \ldots 8.67^\circ$.

Fig. 4 presents the curves of equal errors on the Earth's surface for three error values $\Delta\varphi$ (solid lines) and $\Delta\lambda$ (dashed lines). Within each curve, the errors are within the allowable limits. The curve built with $\Delta\varphi = \Delta\lambda = 0.1^0$ is the boundary of the radio coverage zone, and the point with the coordinates $\varphi = \lambda = 0^0$ is named as a subsatellite point on the earth's surface. The errors that lie within the curves are characteristic of satellites with an illuminated spot on the Earth's surface of any shapes and sizes.

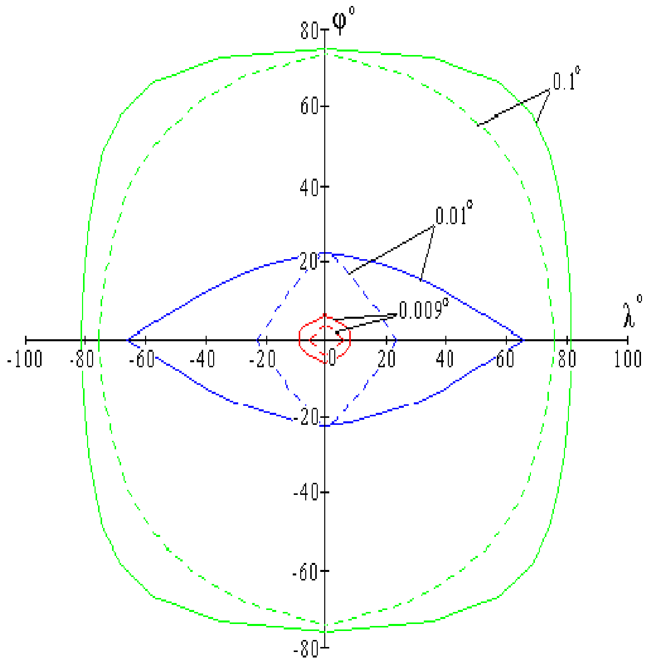

Figure 4: The calculation results for the phase method with an antenna array on the satellite.

Fig. 5 shows a block diagram of an apparatus embodying the phase method for positioning [18].

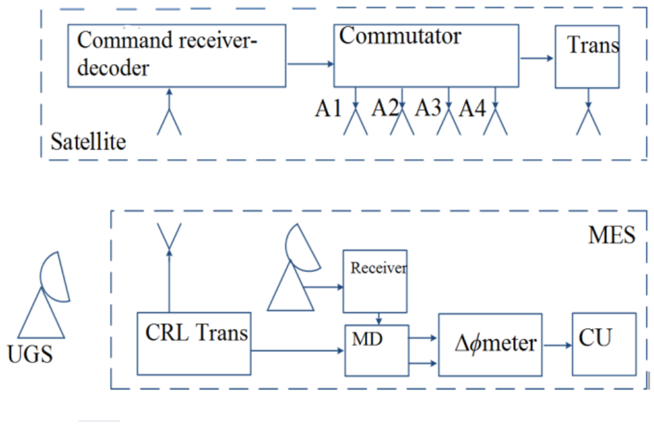

Figure 5: A block diagram of an apparatus for UGS positioning.

Onboard an Artificial Earth Satellite, the apparatus has an antenna array consisting of at least four antennas A1, A2, A3, and A4. The signals received from the antenna array elements are successively transmitted to MES using a commutator and the transponder's transmitter *Trans*. One axis of the antenna array lies in the meridian plane, and the other – in the Earth's equatorial plane. The commands to connect antenna array elements A1…A4 are generated in the command radio link transmitter *CRL Trans*. Using the same commands, a memory device *MD* stores the signals received in MES from the antenna array elements. After reading the signals from all the elements A1…A4, the measurement of phase shifts Δφ starts, and further – the calculation of coordinates in the computing unit *CU* according to the following formulas:

$\varphi = \arcsin(\sin\gamma \sin\alpha)$,

$\lambda = \lambda_c + \arcsin\frac{tg\varphi}{tgd}$.

Here, φ and λ are the UGS latitude and longitude, respectively. $\gamma = 180 - (\arcsin\frac{L\sin\beta}{R} + \beta)$ is an angle between R and L; R is the Earth's radius; L is the distance between the Earth's center and the geometric center of the antenna array. $\alpha = arctg\,\frac{\Delta\varphi_{1-2}}{\Delta\varphi_{3-4}}$, d is the antenna array base. λ_c is the longitude of the satellite station point; $\Delta\varphi_{1-2}$ and $\Delta\varphi_{3-4}$ are the phase shifts between the signals received by the antenna array elements.

iv. A phase method for the detection finding using a virtual antenna array

The slow satellite movement along the per diem trajectory allows for generating a virtual antenna array (VAA) on a basis of several in-time successive positions of the satellite [19]. By measuring the phase difference between the UGS signals, in these positions of the known (or measured with high accuracy from the ground control complex) satellite coordinates, it is possible to conduct UGS positioning.

At a fixed satellite position, the line of constant values of the difference between phases $\Delta\psi_{1-2}$ on the Earth is a closed curve produced by the intersection of a cone, the apex of which is at the point belonging to the VAA base, and the Earth's surface. The shape of this curve depends on the angle between the VAA base and vector connecting the earth's center of mass with the point A at one of the VAA bases. When α = 0, the curve is insignificantly different from the circle since the globe is a spheroid. When angle α deviates from the normal, the curve of the constant value of the difference between phases $\Delta\psi_{1-2}$ becomes an ellipse, and further degenerates into a hyperbole. The further consideration would be limited to α= 0.

The VAA projection on the Earth's surface is in the center of the area limited by the curve of constant values of the difference between phases $\Delta\psi_{1-2}$. The deviation of the satellite orbit from the geostationary one for the reasons stated above leads to the change in the point C with the coordinates and values $\Delta\psi_{1-2}$, which corresponds to another closed curve.

The UGS is located at the juncture of at least three closed curves, the center coordinates of which are known and varied.

In order to conduct measurements, an array of clusters is generated, each consisting of 3+N elements; the first, the second, and the third elements of each cluster are the current satellite coordinates, respectively: the distance, the angle of site, and azimuth. The rest cluster elements are the values of the UGS signal phase at the moment of satellite positioning, and the other elements of each cluster present the signal phases of the legitimate Earth's transmitters, the coordinates of which are also known at the moment of satellite positioning. Then at least four best clusters are selected, which are grouped into pairs for generating at least two virtual bases, respectively, for calculating the UGS coordinates. A selection criterion for a pair of clusters is the proximity of the angle therebetween to 90^0. By using the known coordinates of the legitimate transmitters and the results of their calculations of the coordinates, it is possible to calculate the measurement errors that are taken into account when calculating the UGS coordinates.

The results of the coordinate error calculations based on the phase method are shown in Fig. 6. Based on the estimated values $\Delta\lambda(\lambda_{UGS})$ and $\Delta\varphi(\varphi_{UGS})$, the working zones are presented at $\Delta\lambda_s = \Delta\varphi_s = 0.04^0$, $\Delta R_1 = 1$ km, and $\Delta\psi_{1-2} = 1^0$. The subsatellite point is at the origin of the coordinates. Within each error, the specified limits are not exceeded.

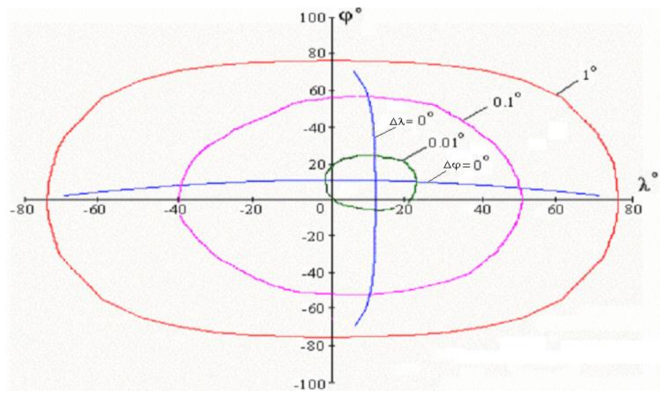

Fig. 6. The calculation results for the phase method with VAA

A common disadvantage of the above methods is the low UGS positioning accuracy due to the systematic error, which grows with the increasing distance between the UGS and the subsatellite point, and to the errors associated with the per diem, seasonal, and other changes in the electromagnetic characteristics of the signal propagation. The resolution of phase ambiguity has been deeply investigated in theory and in practice [20].

v. The ways for enhancing the accuracy of the UGS positioning

The positioning accuracy enhancement can be shown as follows by an example of just one geographical coordinate of an unknown transmitter. Fig. 7 demonstrates an estimated dependence of the determination error of one of the coordinates (conditionally designated Y) ΔY^0 on the value of the Y^0 coordinate itself.

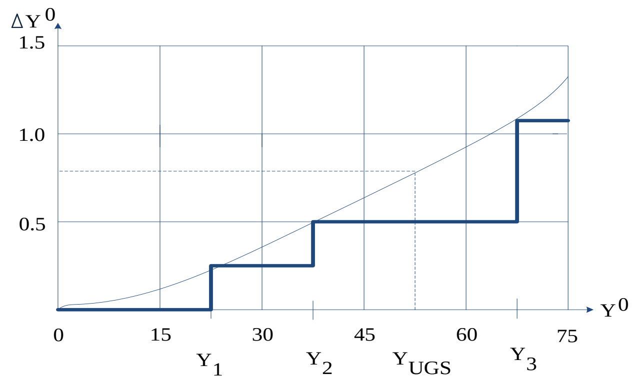

Figure 7: Dependence $\Delta Y^0(Y^0)$ and its approximation.

The value Y^0=0 corresponds to the subsatellite point when the distance between the satellite and the Earth's surface is minimal. If the UGS is located at the subsatellite point then the systematic error equals to zero. The error caused by the condition of the signal propagation path is unknown and can be considerable for any UGS location. Let also the legitimate transmitters be located in the positions Y_1, Y_2, Y_3. Since the coordinates of the legitimate transmitters are known, then using the measurement results, it is easy to calculate the errors ΔY_1, ΔY_2, ΔY_3. It is most easy to use stepwise approximations of a real error curve (bold line in Fig. 7), and calculate the target coordinate according to the rules specified in Table 1.

Table 1: A rule for recalculating the coordinate measurement results

The measured value Y_{UGS} Belongs to the interval	The target value Y_{UGS}
$0<Y_{UGS}<Y_1$	$Y_{UGS}=Y_{meas}$
$Y_1<Y_{UGS}<Y_2$	$Y_{UGS}=Y_{meas}-Y_1+Y_{1meas}$
$Y_2<Y_{UGS}<Y_3$	$Y_{UGS}=Y_{meas}-Y_2+Y_{2meas}$

Here, Y_{1meas}, Y_{2meas} are the measured coordinate values of the legitimate transmitters ` 1 and 2. Let the UGS be located in the position Y_{UGS}. Then, as seen in Fig. 7, the error is 0.75°.

The error of the coordinate determination by the described technique does not exceed 0.25°. The application of other approximation methods, for example, a linear method or a spline function, with nodes at the location points of legitimate transmitters will further enhance the effectiveness of the suggested method.

The second direction for enhancing the coordinate measurements accuracy is the account of the measured parameter impermanence (phase delay) during the time of measurement. The satellite movement causes the changes in the measured parameter during the time of measurement, which was noted as early as in 1973 [21]. The measured parameter comprises a time-dependent component. Therefore, the measurement time may not exceed a few milliseconds per smallness of this component during the time of measurement. This leads to the need for a substantial increase in the signal/noise ratio. Assuming that the satellite moves along the linear section of the orbit, we can eliminate a variable part considering the two adjacent measuring cycles: $\varphi_x=2\Psi 1-\Psi 2$, where $\Psi 1$ and $\Psi 2$, respectively, are the measurement results in the first and second cycles. The measurement time of an informative component φ_x can be increased in order to reduce the requirements for the signal/noise ratio.

In order to enhance the UGS positioning accuracy, it is necessary to take into account the conditions of the signal propagation within all path segments, and use the special algorithms of processing [22].

Conclusions

The methods for determining the UGS coordinates based on the Doppler or phase measurements provide for the accuracy to a tenth of a degree within a large territory. As the territory sizes decline, a more accurate determination of the UGS coordinates is ensured. The VAA positioning is inferior to the technique using an antenna array onboard the satellite in the size of the territory, within which the positioning errors do not exceed the specified values. However, this technique is technically more preferable because it requires no additional satellite hardware debugging and can be used with the modern family of running communication satellites.

Applying the differential techniques based on the use of certain sections of trajectories and/or the techniques taking into account the error corrections with respect to the known UGS coordinates will significantly expand the size of the served territory while maintaining an acceptable level of accuracy of the UGS positioning, and, as a consequence, the protection of satellite infocommunication against an unauthorized use.

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