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Radio-optic positioning systems based on mobile communication infrastructure in problems of ground objects

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Abstract
The article considers the problem of constructing an autonomous positioning system of objects using the infrastructure for mobile communications (repeater towers, cell phones) without the constant attraction of satellite navigation systems. It is shown that the use of dual-wavelength optical line for synchronization of spaced transmitters of towers gives error positioning of objects up to 10-20 mm. It is necessary to use additional control of moving of peaks towers and meteorological parameters both at the location of towers and at the location of controlled object. The paper is numerically investigated the difference between electrical and optical paths of propagation channels from humidity, pressure and temperature It is shown that if, along with the radio - frequency, repeater will emit a modulated optical signals, by measuring the difference between electrical and optical paths, the positioning of object can be measured with an accuracy of about 1 mm. Such systems may be useful in the case of deformation measurements in the unavailability of satellite positioning systems in the case of need for greater efficiency of data retrieval.

Keywords: positioning, repeater, laser, humidity, pressure, temperature, optical path, meteorological parameters, mobile communication.

1. Introduction

Currently, a cell phone offers a number of useful functionality, amongst which the most important one is to establish the connection between users and objects. However, its additional functionality, like clock time, digital video, photography, audio player, and various Internet services are very important. One of important functions is objects positioning by means of satellite systems. This function can furnish object location with an accuracy of up to one meter. Convention on terminological principles and standardizations for the object positioning systems by means of mobile network infrastructure are now undergoing the stage of formation and development (Azfar 2010; Wang 2008; Chu 2007).

Among various positioning methods, the most accurate is the method of trilateration. Trilateration determines relative position of an object with respect to two or more network nodes, e.g. bases. Thus, it uses known distances between a mobile device and each node. In turn, the distances between the mobile device and each node are obtained from the delay time measurement for the incoming signal with respect to a reference signal (Azfar 2010).

2. Result and discussion

In (Grigorievsky 2011) are proposed highly-accurate object positioning systems by means of infrastructure for mobile communications, and they are based on trilateration, in which satellites are substituted by ground based nodes with a system of time-synchronization.

One of these groups of nodes is shown in Figure 1. In this figure, two digital cameras work on the principle of triangulation and measure deviations from the calibrated position of the top of the tower in three dimensions: two horizontal and vertical. The cameras are located on a concrete floor, and they not may be displaced in the space of more than 1-2 mm. With the same precision, the digital cameras monitor for the displacements of a brilliant point on top of the tower. A brilliant point can specifically be made, in the form of a glowing laser.

As has been said, phase synchronization of repeaters transmitters, is either done by time signal or by means of radio or optical lines transmitting a synchronization signal from one tower to the others.

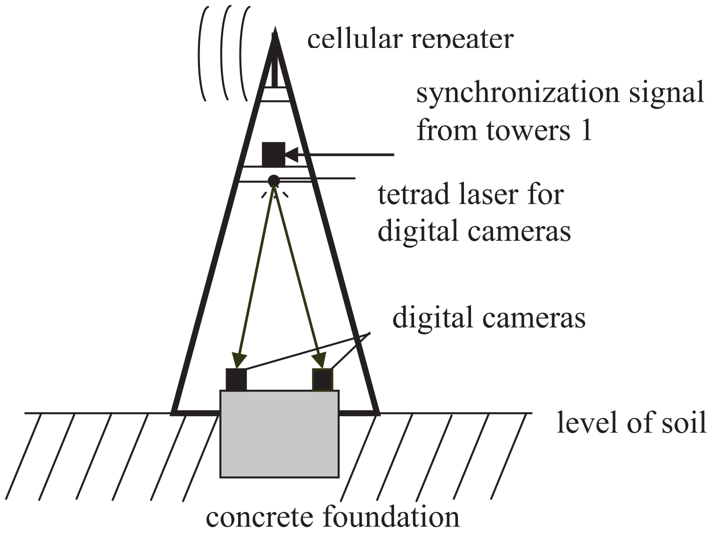

Figure 1. Monitoring system offset vertex of repeater tower

The accuracy of synchronization in the linear measure is less than 1 mm, if we recalculate it from the phase difference using the formula:

$$\delta D = \delta(\Delta\varphi) * \nu / 2\pi F, \qquad (1)$$

where $\delta(\Delta\varphi)-$ error of measurements of phase difference in radians, F-frequency of carrier in Hz, $\delta D-$ error of distance in meters , ν -velosity of light in air (~$3*10^8\ m/s$) .
It is shown that the usage of optical lines for synchronization of spaced synths (Armand 1991) allows us to determine the coordinates of objects with an accuracy of 10-20 mm. However, such accuracy is achievable only if exists a line of sight between the towers, when the optical lines, operating in the wavelength range of light ~ 0.4-0,6 mkm (region of maximum dispersion of the atmosphere) provides generator synchronization with an accuracy of 1 degree at 1 GHz, which in linear measure corresponds to a distance of ~ 1 mm. At other times, when there is no direct line of sight between towers, due to heavy fog for example, time synchronization may only take place over the radio and the accuracy of the phase synchronization is noticeably worse. However, the percentage of time when there is a line of sight at distances of ~ 10 km in the Europe region is ~ 80% in summer and ~ 50% in the winter, with an average 65% for the season (Baranov 1991). Thus, ~ 65% of the time accuracy of positioning 10-20 mm is realistic.
The aim of this work is the further development of the method for high accuracy positioning of objects using mobile communication infrastructure. It will be shown that it was realistic to position objects with an accuracy of 1-2 mm, even at the current level of optical and radio technologies.
At the base of improving the accuracy of positioning may be adding two optical carriers not only to the tower transmitter which carries out the synchronization of synths, but also to all the transmitters of all mobile communications towers. Accordingly, mobile receivers must have photo detectors for reception and processing of optical signals. This is schematically shown in Figure 2. Towers 1-5 in this figure along with the necessary radio frequencies emit optical frequencies in the spectral range of 0.4-0.6 mkm. Tower 1 emits signals not only for the object you want to position, but also synchronization signals for towers 2-5. Thus, the positioning system consists of (Grigorievsky2011) the system of repeater towers, the deviation vertices of which are fixed by cameras. The accuracy of tracking displacements of the vertices of the towers by cameras is better than ~ 1 mm in two horizontal coordinates and the displacements are transmitted in digital form by a radio frequency to the other towers and to the object. At the facility, along with a radio receiver, there must be receivers of optical radiation. Optical distances from the tower to the object can be written as follows:

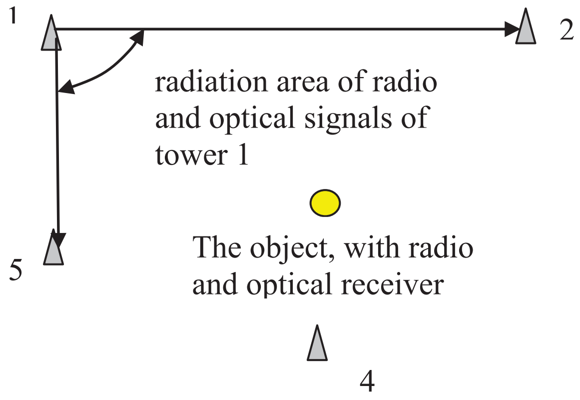

Figure 2. An example of the operation of one cell mobile communication with radio and optical channels, consisting of five towers (1,2,3,4,5) for positioning

$$L_1 = D * [1 + f(\lambda_1) P/T] \tag{2}$$

$$L_1 = D * [1 + f(\lambda_2) P/T] \tag{3}$$

where D-geometric distance to the object, f (λ)-function depends on the wavelength of light (Ouens 1974), P and T, respectively, the average air pressure and temperature. The exact expression for L1, for example, is written as follows (Kolosov1976).

$$L_1 = D \cdot \left[\frac{T_0}{P_0} \cdot \left(64.328 + \frac{29498.1}{146 - 1/\lambda_1^2} + \frac{255.4}{41 - 1/\lambda_1^2} \right) \cdot \frac{P}{T} \cdot 10^{-6} - 6 \cdot 10^{-6} \cdot \frac{e}{T} + 1 \right] \tag{4}$$

Here P_0 = 1013.25 mbar, T_0 = 288 K, e-humidity in mbar. At range $\lambda \sim$ 0.4-0.6 mkm formula (4) is as follows:

$$L_1 = D \cdot \left[80 \cdot \frac{P}{T} \cdot 10^{-6} - 6 \cdot 10^{-6} \cdot \frac{e}{T} + 1 \right] \tag{5}$$

It can be seen that the second term is much smaller than the first one because the pressure of water vapor e ~ 0-20 mbar. Hence, formulas (2) and (3) are legitimate. From the equations (2) and (3) we can determine the average value P/T along the distance as follows:

$$\frac{P}{T} = \frac{(L_1 - L_2)}{(f(\lambda_1) - f(\lambda_2))D} \tag{6}$$

Geometric distance is determined by (2), (3) and (6) as follows:

$$D = L_1 - \frac{f(\lambda_1)}{f(\lambda_1) - f(\lambda_2)} \cdot (L_1 - L_2) \tag{7}$$

and does not depend on atmospheric conditions. That is, if there is a the line of sight to facilitate reception of the optical signal, then the distance from the source to the object is independent of atmospheric conditions in the first approximation. The accuracy of the determination of the geometric distance D, as seen from (7) may be ~ 1-2 mm (measurements of L1, L2 must be better than ~ 0.1 - 0.05 mm), since the value of

$\frac{f(\lambda_1)}{f(\lambda_1)-f(\lambda_2)} \cong \frac{N(\lambda_1)}{N(\lambda_2)-N(\lambda_1)} \cong 20$ for wavelengths in the range of ~ (0.4-0.6) mkm

(Armand 1985, 1991). Here N - is refractivity of air. But the accuracy of the humidity measurements should be no worse than ~ 5-10 mbar because the weak dependence of the refractive index of air on humidity still remains, as can be seen from equation (5).

When the two optical channels are supplemented with a radio-channel, the accuracy of the distance D may be even better than ~ 1 mm. This follows from the following estimates. The phase shift of radio-wave from the tower to the object (or the electrical length) at a radio frequency can be written as follows (Kolosov 1976):

$$Le \cong D \cdot \left[1 + \frac{103.49}{T} \cdot 10^{-6} p + \frac{86.27}{T}(1 + 5748) \cdot e \cdot 10^{-6}\right] \qquad (8)$$

Here D - distance to the object, T - temperature in degrees Kelvin, P, e - the pressure and humidity of the atmosphere in mbar. We now define the difference between the electrical and optical path by subtracting (5) from (8),

$$Le - L_1 \cong D \cdot 10^{-6} \cdot \left[\frac{373256 \cdot e}{T^2} - \frac{2.4 \cdot P}{T} + \frac{6 \cdot e}{T}\right] \qquad (9)$$

It is weakly depends on e, almost independent of P and independent of T, as shown in Figure 3 for the D = 10 km. Therefore, knowing P and T by measuring meteorological data, humidity can be determined with an accuracy of ~ 0.1 mbar, when $Le - L_1$ is measured with an accuracy of 1 mm in distance (~ 1 deg in phase).

Ignoring in the right side of (9) all members except the first, the working formula for the estimation e can be written in the following form:

$$L_e - L_1 \cong 4 \cdot D \cdot e \cdot 10^{-6} \qquad (10)$$

In turn, the knowledge of e from measurements can improve the accuracy of the D, because the humidity for the refractive index in the optical range (5) can be accurately taken into account. Thus, if in addition to radio frequency, the repeater will emit modulated optical signals, (modulation can be performed on the same radio frequency or its subharmonics) one can determine the location of an object with an accuracy of 1 mm. If there is no line of sight between the towers and the object and the measurements are taken on only one radio frequency, the positioning accuracy is 10 ÷ 20 mm, if the average atmospheric parameters are determined with errors of the order: ~ 1mbar, 1degree, and these values should be transmitted from the towers to the object.

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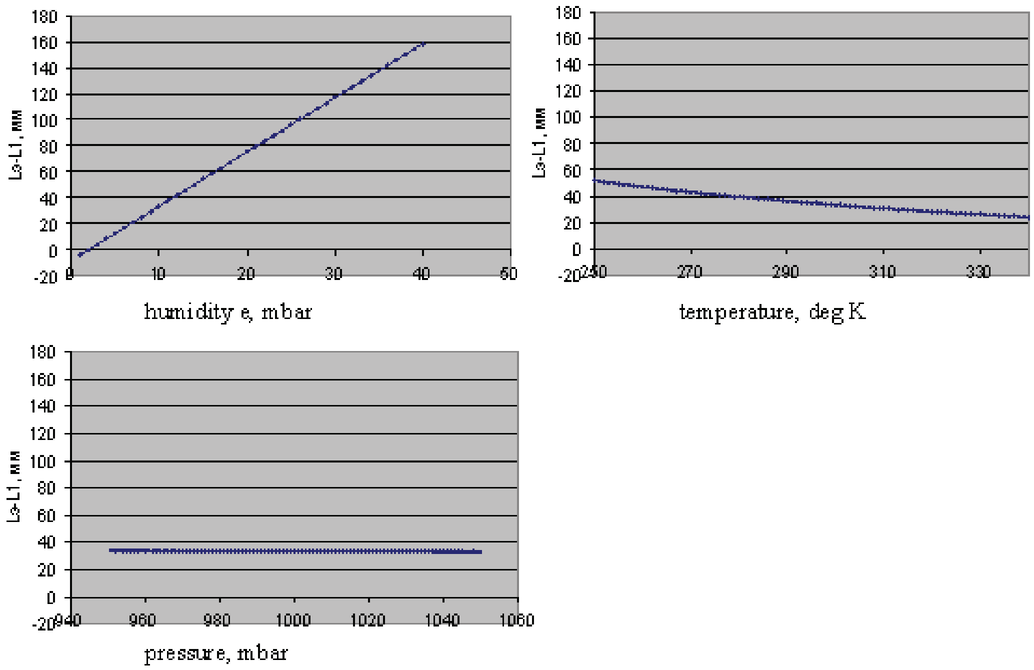

Figure 3. The dependence of the difference between electrical and optical lengths from meteorological parameters.

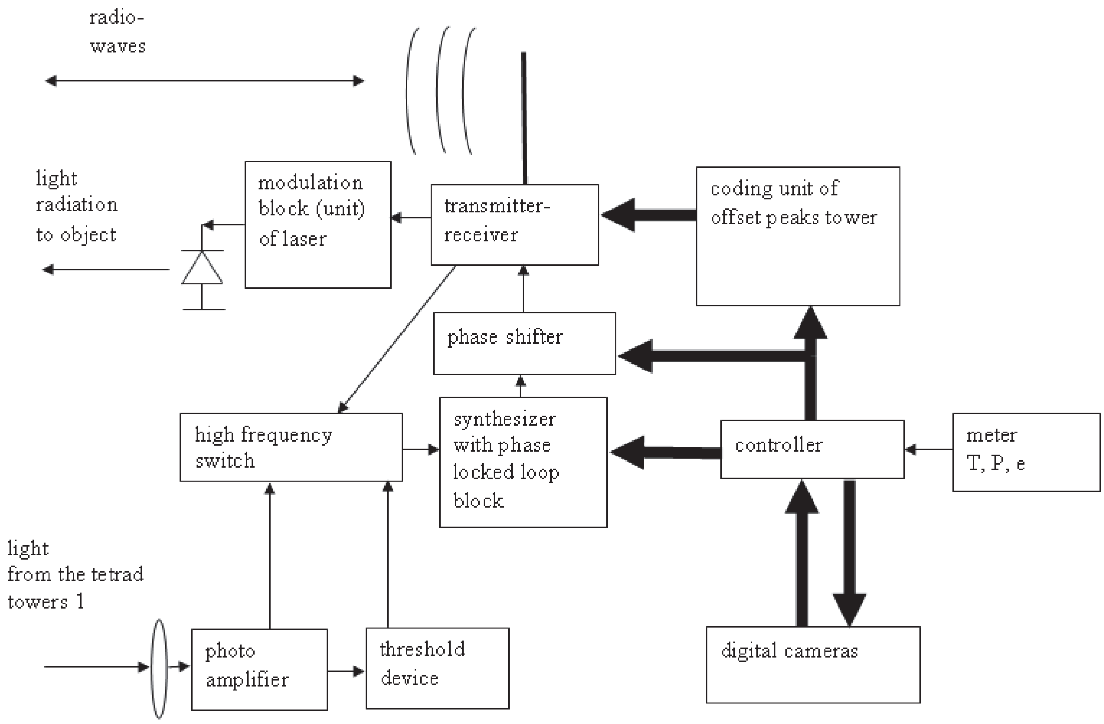

Figure 4. Block - scheme positioning system, located in one of the towers with radio and optical communication channels.

Finally, each tower must transmit radio frequency, optical signals, meteorological parameters and the coordinates of the offset tower to the object. In addition, a synthesizer synchronous with the synthesizer on the main tower 1 must be on each tower. This condition provides a radio-optic channel of synchronization. The block diagram of the position will appear as in Figure 4. Here, the synthesizer with phase-locking adjusts the phase of the signal to the reference signal from reference tower 1. For this purpose, a radio or optical channel from tower 1 is switched by means of the threshold device, a high-frequency switch and controller, when the optical signal is below the critical level. To compensate for the deviation of the tower, data from digital video goes to the controller (it can be your personal computer or a special processor), where it is processed, the error signal drives the phase shifter, which compensates for the tower's altitude change. Horizontal displacement of the tower by means of block coding is transmitted by means of radio and optical transmitters to the object being positioned.

Meteorological parameters T, P, e are also transmitted on the object by means block of coding , but this information is only necessary in the absence of an optical visibility. Optical transmitter, as mentioned above, is working on an optical wavelengths in the maximum dispersion of the atmosphere in the spectral range of 400 ÷ 600 nm (Grigorievsky 2009).

The receiver at the facility shall, in addition to standard cell phone functions, performs the following functions: receiving and decoding the deviations tops of towers, decoding the values of meteorological parameters on each tower, and contains an optical receiver that receives an optical signal in the case line of sight. Performance requirements of instrumentation, involved in the positioning system described in (Grigorievsky 2011). It should be noted that the stability positioning tops of towers and good time synchronization of their transmitters allow one the positioning of the object to within 1 mm, if time synchronization is done via an optical link. Summarizing calculations in relation to the improved positioning system, one can result the table 1.

Table 1 Positioning systems accuracy

Channels involved in the positioning	Visibility in the atmosphere	positioning accuracy	Synchronization between towers	The information transmitted to the object
Only radio channel	Strong fog, visibility is less than 10 km	10-20 mm	On a radio channel	temperature, pressure, humidity,
Only optical channel	visibility ~ 10 km	1- 2 mm	on the optical channel	deviation of towers
Radio channel and optical channel	visibility is more than 10 km	Less than 1 mm	on the optical and radio channel	deviation of towers and average moisture

The accuracy of the optical line for the synchronization of synths spaced apart by ~ 10 km at a frequency of ~ 1 GHz is ~1 mm.

We can estimate the energy characteristics of a laser transmitter, which provides sufficient power for reliable optical reception. The power of modern, compact lasers measures up to ~ 100 Watt (Pout) or more, so it is easy to calculate that if the diameter of the host optics 2r ~ 5 cm, signal power P at a distance R ~ 5 km will be:

$$P = Pout * \pi r^2 / 2\pi R^2 \sim 0.7 \text{ nanowatt} \qquad (11)$$

Here R ~ 5 km is the distance from the tower to the object. If we consider that the optical power of 0.1 nWatt is the maximum power, we can say that compact optics can provide the necessary signal levels for distances of ~ 5-10 km. Integral radiation power near the tower within a radius of 100 m is to the human eye a radius r = 1 mm and amounts to ~10 nWatt, which does not exceed health safety standards.The angular distribution of the optical emission and reception can be achieved by technical means such as wide-angle lenses, systems of scanning in space or their combinations.

3. Conclusion

It is proposed radio-optic positioning systems based on mobile communication infrastructure which gives error positioning of objects up to 10-20 mm. For this it is necessary to use additional control of moving of peaks towers and meteorological parameters both at the location of towers and at the location of controlled object. In the paper is investigated the difference between electrical and optical paths from humidity, pressure and temperature It is shown that if, along with the radio - frequency, repeater will emit a modulated optical signals, by measuring the difference between electrical and optical paths, the positioning of object can be measured with an accuracy of about 1 mm. Such systems may be useful in the measurements of deformation in the unavailability of satellite positioning systems in the case of need for greater efficiency of data retrieval.

In addition, one may say that, of course, there is no need for high-precision mobile receivers in everyday life. However, for the monitoring of high-rise buildings, structures, and operational forecasting of emergency situations when exceeding critical shear, such receivers may be in demand and pay off, especially when you consider that in dense, urban areas, GPS-navigation may not give the desired accuracy due to multipath wave propagation.

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