The analysis of the lateral refraction influence during the active radar sensing

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Abstract. The article provides the lateral refraction influence factors analysis during the active radar sensing. With the passage of radio waves, a change in the refractive index in the atmosphere affects the radar image geometry due to the radio waves refraction and an increase in the time of their propagation. These factors shift the image in the direction of increasing distance. The solution to the problems of determining the corrections due to the refraction influence in trigonometric leveling is considered. The simulations of the quantities involved in the process obtained by the joint geodetic and meteorological measurements are used. The practical examples show the features of the corrections’ calculation. The formulas for determining the change in the distance ΔRδ due to the curvature of the trajectory of radio waves are given. The analysis of the data presented in the article is based on the data from the studies conducted using different brands of devices. The given indicators are generalized.

Introduction

Trigonometric leveling is currently the most common type of work to determine the excess and elevations. Civil engineers use different devices, but despite the brand, when conducting trigonometric leveling, the refraction of light waves passing through the layers of the different densities’ atmosphere should be taken into account. The curvature of the light waves’ propagation path distorts the angular measurements data. The main component of the spatial refraction curve is its projection onto a vertical plane, which is called vertical refraction [1].

When using the radar survey, it is possible to obtain the information about the terrain and other objects in any weather conditions, at any time of the day.

During the radio waves passage, a change in the refractive index in the atmosphere affects the radar image geometry due to the radio waves refraction and an increase in their propagation time (signal delay, decrease in the speed of radio waves). These factors shift the image in the direction of the distance increasing.

When determining the refractive error, two main components are distinguished - short-period and regular. Short-period - is a consequence of the turbulent air movement, which is a random process. When sighting, the error is manifested by a decrease in the accuracy of the measurement itself, since the image fluctuates as declining. The regular component of the refraction does not affect the image quality and is a consequence of the stationary slowly changing processes leading to atmospheric stratification [4].
Results

In work [2] the approximate formulas are given to determine the change in $\Delta R_s$ distance due to curvature of the radio wave trajectory

$$\Delta R_s = \frac{1}{24} \frac{R_s^3}{\delta^2},$$  \hspace{1cm} (1)

where $\delta$ – is the radius of the circular arc, for which the trajectory of radio waves is taken, $R_s$ – is the radio wave path length; at $z_g = 80^\circ$, $H \approx 100$ km $R_s = 477$ km, $\delta = 7R_s = 44600$ km, $\Delta R_s = 2.3$ m; to determine the distance due to the radio waves’ increased propagation time

$$\Delta S' = \Delta R_s = -R_{meas}(n_{meas} - 1) = -R_{meas} n_{meas} \cdot 10^{-6}$$  \hspace{1cm} (2)

where $n_{meas}$ – mean troposphere refractive index on the path of radio waves, $R_{meas}$ – measured distance.

It is noted that “the radio waves trajectory curvature influence on the accuracy of determining the coordinates of terrain points can be neglected, since even when shooting from the space, the errors are expressed in units of meters. At the same time, the errors caused by the increase in the radio waves’ propagation time reach a significant value. For example, when shooting from a height of 20 km at a distance of 100 km, the error $\Delta Y_{ref}$ will make 40 m. Therefore, when the photogrammetric processing of the radar images obtained from the high altitudes, it is necessary to introduce the corrections into the measured ranges for changing the refractive index of the troposphere at altitude [2].

The formulas (1) and (2) obtained in [2] are approximate. When deriving the formula (1), the radio waves’ trajectory is taken as an arc of a circle, which is not correct. In formula (2), a linear change in the refractive index with height is assumed, while this change is more complex and does not correspond to a linear law. Therefore, it is advisable to obtain more rigorous formulas that take into account the phenomena under consideration.

In [3, 4] to determine the correction to the distance measured using the radio waves, the formula

$$\Delta S = -22.282 \frac{P_{ref} - P_{atm}}{QG_g s} \sec z_g - 64,700 \cdot 10^{-6} \int_0^H \frac{e}{T} \left(1 + \frac{5748}{T}\right) \sec z dH,$$  \hspace{1cm} (3)

where $\sec z_g = \sec\left[z_g - K(z_g - z_g)\right]$, $K = 0.5 - 0.008409H_a - 0.0485\sin4.5^0H_a$.

for the heights over 40 km

$$\Delta S = -22.282 \frac{P_{ref} - P_{atm}}{QG_g s} \sec z_g - 22.333 \frac{P_{atm}}{G_g s} \sec z_g - 64,700 \cdot 10^{-6} \int_0^H \frac{e}{T} \left(1 + \frac{5748}{T}\right) \sec z dH,$$  \hspace{1cm} (4)

where $P_{atm}$, $z_{atm}$ – define the pressure and anti-aircraft distance at an altitude of 40 km.

The zenith distance of the radio wave path at a height $H$ for a spherical model of the atmosphere is determined by the well-known formula:

$$\sin z = \frac{(a + H_g) n_g \sin z_g}{(a + H)n},$$  \hspace{1cm} (5)

where $H_g$, $n_g$; $H$, $n$ - denote the point height and the refractive index $G$ (at the device) and at the current point.
In the formulas (3), (4), (5) \( z_g, p_c, g_s \) - are the zenith distance, pressure and acceleration of gravity at a point \( G \) (at the appliance); \( z, T, e \) are the zenith distance, absolute temperature and water vapor elasticity at the current point of the EMW trajectory. The coefficient \( Q \) is given in the works [4], [5].

To determine the accuracy of the correction \( \Delta S \) according to the formulas (2) - (5) in Table 1, taken from [4], for various heights \( H \) are given the values \( T, p, e, p=p_c+e, N, N_e \).

**Table 1. Values \( T, p, e, p=p_c+e, N, N_e \) for different heights \( H \)**

| \( H, \) km | \( T, \) \( ^\circ\text{K} \) | \( p_c, \) hPa | \( e, \) hPa | \( p=p_c+e, \) hPa | \( N \) | \( N_e \) |
|-----------|----------------|------------|----------|----------------|---|---|
| 0         | 297.95         | 981.95     | 31.30    | 1013.25        | 393.74 | 137.92 |
| 1         | 292.75         | 874.70     | 22.80    | 897.50         | 335.91 | 103.98 |
| 2         | 287.35         | 777.55     | 16.20    | 793.75         | 286.58 | 76.61  |
| 3         | 281.65         | 689.63     | 11.10    | 700.73         | 244.65 | 54.59  |
| 4         | 274.95         | 610.05     | 6.55     | 616.60         | 205.99 | 33.76  |
| 5         | 266.95         | 537.87     | 3.40     | 541.27         | 174.97 | 18.57  |
| 6         | 256.15         | 472.12     | 1.85     | 473.97         | 154.02 | 10.95  |
| 7         | 241.35         | 411.63     | 1.00     | 412.63         | 139.04 | 6.65   |
| 8         | 228.85         | 356.07     | 0.50     | 356.57         | 124.47 | 3.69   |
| 9         | 221.15         | 306.03     | 0.15     | 306.18         | 108.60 | 1.18   |
| 10        | 218.75         | 262.12     | 0.04     | 262.16         | 93.34  | 0.32   |
| 11        | 216.65         | 191.72     | 0.00     | 191.72         | 68.69  | 0.00   |
| 12        | 216.65         | 140.04     |          | 140.04         | 50.18  |       |
| 13        | 216.65         | 102.31     |          | 102.31         | 36.66  |       |
| 14        | 216.65         | 74.76      |          | 74.76          | 26.79  |       |
| 15        | 216.65         | 54.64      |          | 54.64          | 19.58  |       |
| 16        | 219.57         | 40.03      |          | 40.03          | 14.15  |       |
| 17        | 220.56         | 29.41      |          | 29.41          | 10.35  |       |
| 18        | 222.54         | 21.66      |          | 21.66          | 7.55   |       |
| 19        | 224.53         | 16.00      |          | 16.00          | 5.53   |       |
| 20        | 226.51         | 11.85      |          | 11.85          | 4.06   |       |
| 21        | 236.51         | 5.71       |          | 5.71           | 1.87   |       |
| 22        | 250.35         | 2.85       |          | 2.85           | 0.88   |       |
| 23        | 270.65         | 0.78       |          | 0.78           | 0.22   |       |
| 24        | 247.02         | 0.21       |          | 0.21           | 0.07   |       |
| 25        | 219.58         | 0.05       |          | 0.05           | 0.02   |       |
| 26        | 196.60         | 0.00       |          | 0.00           | 0.00   |       |

In the Table. 2 for the values given in Table 1, the values \( \Delta S_6 \) calculated by the numerical integration using the Simpson formula for \( z_g = 0^\circ \); \( \Delta S \) defined by the formulas (3) – (5); \( \Delta S' \), obtained by the formula (2), and the differences of these quantities are determined.

**Table 2. DSI Values calculated by numerical integration using the Simpson formula for \( z_g = 0^\circ \), \( \Delta S \), \( \Delta S' \) and the difference between these values**

| \( H, \) km | \( \Delta S_6, \) mm | \( \Delta S, \) mm | \( \Delta S', \) mm | 3-2, mm | 4-2, mm |
|------------|---------------------|-------------------|-------------------|--------|--------|
| 1          |                    |                   |                   |        |        |
| 2          | -674.6             | -674.7            | -680.3            | -0.1   | -5.7   |
| 3          | -1165.0            | -1165.2           | -1199.5           | -0.2   | -34.5  |
| 4          | -1518.4            | -1518.8           | -1643.3           | -0.4   | -124.9 |
| 5          | -1796.6            | -1795.8           | -2072.8           | 0.8    | -276.2 |
| 6          | -2014.0            | -2012.7           | -2435.4           | 1.3    | -421.4 |
| 7          | -2292.8            | -2291.4           | -3107.4           | 1.4    | -814.6 |
The table 2 shows that the formulas (3) - (5) make it possible to determine the correction to distances with an error of less than 2 mm, while the error in the calculations by the formula (2) gives a value of -5.7 mm at \( H \leq 2 \) km till -17.07 m at \( H = 100 \) km. i.e. the formula (2) at large heights gives the corrections that are 6.5 times higher than their actual values.

To determine the corrections \( \Delta S \) to the inclined distances by the formula (2), it is necessary to know the measured distance \( R_{meas} \). To determine it by the cosine theorem, we have

\[
R_{meas}^2 = a_g^2 + a_a^2 - 2a_g a_a \cos \phi ,
\]

where \( a_g = a + H_a \), \( a_a = a + H_a \).

To determine the angle \( \phi_a \), the formula known for the model of a spherical atmosphere is used

\[
\sin \phi_a = \frac{n_g a_g \sin \phi_g}{n_a a_a} .
\]

Table 3 shows the calculation results \( R_{meas} \) for a spherical model of the atmosphere at \( \phi_a = 60 \) and 80°.

**Table 3.** Results of calculations of the RMA for the spherical model of the atmosphere at \( \phi_a = 60 \) and 80°

| \( H, \) km | \( \phi_a \) | \( r_c \) | \( \epsilon \) | \( R_{meas}, \) km | \( \phi_a \) | \( r_c \) | \( \epsilon \) | \( R_{meas}, \) km |
|----------|-----------|--------|--------|-----------------|-----------|--------|--------|-----------------|
| 0        | 60.0000°  | 80.0000° | 0.00492° | 0.02543° | 3.464 | 79.9330 | 0.01605° | 0.08302° | 9.447 |
| 2        | 59.9795   | 0.00913 | 0.05658 | 7.457 | 79.8581 | 0.02969 | 0.17163 | 19.505 |
| 4        | 59.9526   | 0.1271 | 0.08225 | 10.942 | 79.7746 | 0.04118 | 0.26659 | 30.259 |
| 6        | 59.9281   | 0.1573 | 0.11336 | 14.936 | 79.6848 | 0.05080 | 0.36603 | 41.505 |
| 8        | 59.8745   | 0.1824 | 0.14376 | 18.867 | 79.5693 | 0.05876 | 0.46247 | 52.428 |
| 10       | 59.8169   | 0.2240 | 0.20547 | 26.818 | 79.4158 | 0.07177 | 0.65597 | 74.353 |
| 12       | 59.7576   | 0.2478 | 0.26716 | 34.772 | 79.2326 | 0.07908 | 0.84651 | 95.966 |
| 14       | 59.6974   | 0.2605 | 0.32863 | 42.708 | 79.0494 | 0.08291 | 1.03355 | 117.209 |
| 16       | 59.6365   | 0.2652 | 0.39018 | 50.627 | 78.8677 | 0.08496 | 1.21728 | 138.103 |
| 18       | 59.5761   | 0.2707 | 0.45097 | 58.537 | 78.6828 | 0.08690 | 1.39782 | 158.659 |
| 20       | 59.4264   | 0.2739 | 0.60282 | 78.240 | 78.2507 | 0.08692 | 1.83624 | 208.688 |
| 22       | 59.3117   | 0.2748 | 1.49037 | 114.667 | 75.9233 | 0.08716 | 4.16382 | 477.125 |

The complete refraction angle \( r_c \) is taken from [6] for the standard atmosphere conditions GOST 4401-81.

In the Table 4 for the different heights of \( H \) and the zenith distances \( z \) are given the values \( \Delta S_r \), calculated by the numerical integration using the Simpson formula; \( \Delta S \), defined by the formulas (3) – (5); \( \Delta S' \), obtained by the formula (2), and their differences.

**Table 4.** DSI Values for different heights \( H \) and Zenith distances \( z \)
The Table 4 data confirm the conclusion that, at high altitudes, the corrections $\Delta S'$, calculated by the formula (2) exceed the actual value of the correction of 6.4 (for $H = 100$ km, $z = 600$) and at 5.4 times - for $H = 100$ km, $z = 800$ [3].

Therefore, the corrections in the distances during the radar survey (remote sensing) must be determined by the formulas (3) - (5), allowing to find their values with an error of less than 5 mm.

**Summary**

The methods for determining the radar refraction indicators are divided into instrumental and calculated. The instrumental methods, in turn, are divided into dispersion and compensation. The calculation methods are based on the refraction dependence on meteorological quantities [4]. Unfortunately, these methods are complex and not always accurate in measurements.

The meteorological method for determining the refractive index is based on measuring the ambient temperature by means of the sensors located at different heights above the Earth [3].

The main external factors affecting the refraction amount include [5]:
- structure and type of underlying surface;
- geographic location;
- time of year and day;
- wind direction and speed;
- overcast;
- precipitation or humidity;
- astronomical events, such as, for example, the conjunction of Venus and Jupiter, or the eastern elongation of Mercury;
- Atmosphere pressure;
- turbulent characteristics of the atmospheric surface layer.

The refraction amount directly depends on the height of the target beam above the underlying surface, as well as on its length [3]. According to geodetic studies, the following conclusions can be drawn:
- fluctuation of the refractive index during the day can reach large values (from +3.0 to −4.4). For most of the day, the coefficient is negative, and within 1-2 hours after sunrise and before sunset, it is positive. In case of negative refraction, the line of the sight is deflected to the left and the measured angles, like the difference of two directions, are not distorted, or are slightly distorted;
- negative refraction appears with increasing air humidity with height, and most often in autumn or spring during morning surface mists;
- the errors in measuring excess due to refraction are greater in clear and calm weather, and in cloudy weather they decrease only by 10–20% [2]. According to the research of E. K. Nikolsky [1], the accuracy of determining excess in cloudy weather is 2 times higher than in clear or cloudy. The amplitude of the
refractive origin errors per day can reach 60". Refractive errors are the subject to sharp changes during the day. In addition, fluctuations occur day by day due to different weather conditions. [2]:

- with bilateral leveling and leveling from the middle, the refraction influence is compensated. The errors caused by residual influence are random;
- leveling can be performed throughout the day, excluding hours, when the image of the reticle is highly fluctuating and vague, as well as within 1-1.5 hours after sunrise and before sunset [4];
- increasing the height of the device can significantly reduce errors.

It can be seen from the observations that asymmetry appears at a negative temperature. Errors in leveling can be performed throughout the day, excluding hours, when the image of the reticle is highly fluctuating and vague, as well as within 1-1.5 hours after sunrise and before sunset. In order to avoid errors, it is necessary:

1) to make the height of the target beam as large as possible by increasing the height of the instrument;
2) to consider the periods with distinct images as favorable measurement time during the day, excluding 2 hours after sunrise and before sunset;
3) to consider the periods of overcast, cloudy weather, and light winds as favorable conditions for observations;
4) in conditions of measurements at negative temperatures to shorten the distance of measurements (25-50 m.)
5) to make sure that the level has accepted the ambient temperature before performing the measurements.

This article presents the conclusions based on the studies’ results by the authors using various measurement methods.

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