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THE NUMERICAL SIMULATION OF THE ATMOSPHERE DELAYS IMPACT ON RADAR MEASUREMENT IN AVIATION

The article presents numerical simulations with regard to determining the impact of the ionospheric and tropospheric delays on a radar-aircraft slant distance measurement. During the first experimental test, numerical calculations were made, showing the relationship between the ionosphere correction and the zenith angle in order to determine the measurement error of a radar-aircraft slant distance. During the second experimental test, numerical calculations were made demonstrating a relationship between the tropospheric correction and zenith angle in order to determine a measurement error of a radar-aircraft slant distance. The experimental test was conducted for the primary surveillance radar AVIA-W located on the grounds of the military aerodrome EPDE in Deblin. Based on the conducted research tests, it was found that the impact of the ionosphere delay can cause an error in a radar measurement above 4 m. Moreover, influence of the troposphere delay can cause an error of a radar measurement by approximately 0.2 m. The numerical simulation made in this research study may be used in the radiolocation of moving objects, as well as the GNSS satellite navigation in aviation.

Keywords: *radar, troposphere delay, ionosphere delay, aircraft*

1 Introduction

Radar as an air traffic control system is one of the most important navigation devices. It provides a safe, orderly and expeditious flow of air traffic. For this purpose, two types of radars are used: primary surveillance radar (PSR) and secondary surveillance radar (SSR). The primary surveillance radar provides a graphic representation of the aircraft location, displaying the azimuth and distance of the aircraft in relation to the radar antenna to be used by the air traffic controller. Additionally, through use of the secondary surveillance radar, the following information can be displayed: flight altitude, identification, speed of the aircraft, and many other data. The primary surveillance radar can operate as the Air Traffic Control (ATC) Radar or as the en-route radar. The Air Traffic Control Radar is designed as a short range radar (operating within 120 km), working in the vicinity of one or more aerodromes. It is used to provide an efficient performance of air traffic services in the terminal manoeuvring area (TMA). The en-route radar can also aid an instrumental approach to landing (ILS, NDB, TACAN, VOR). In the case of exploiting an en-route radar to control an area, the radar‘s range must be much larger (above 200 km). The en-route radar provides information about the position of the aircraft and the progress of its flight from a large area. An increase in the size of surveillance is at the cost of impaired accuracy [1].

The main role of a radar operation is to determine the position of an aircraft as a function of a slant distance and azimuth. The measurement of slant distance to the aircraft is heavily affected by the atmosphere factor in the form of the ionospheric and tropospheric delay. Ionosphere is a dispersive medium [2], which translates into the relationship between the speed of a carrier wave and a radar frequency operation. For this reason, the ionospheric delay shortens the radar-aircraft slant distance [3]. Moreover, the ionosphere delay exerts a direct impact on determination of the aircraft coordinates in the horizontal plane. On the other hand, troposphere is a neutral medium [4], so the speed of a carrier wave does not depend upon the frequency of the radar operation. The parameter of the tropospheric delay causes scaling (also reducing) [5] of a radar-aircraft slant distance. An atmospheric disturbance is therefore an extremely important aspect in radar measurements.

The aim of this article is to present a relationship, as well as conducting simulation tests, with regard to impact of the atmospheric delays for designation of a radar-aircraft slant distance. The paper proposes a numerical solution to determine the effect of the atmosphere upon a radar measurement, taking into account the ionosphere and troposphere corrections. The proposed algorithms for the conducted computer simulations facilitate a better understanding of impact of the atmosphere upon the operation of the primary surveillance radar within the microwave band. The article is divided into five parts. At the end, it is supplemented with a list of scientific references.

2 Mathematical model

The study uses two basic models determining the relationship between the atmospheric delay and the

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Figure 1 *Location of the AVIA-W radar at Deblin aerodrome [8]*

accuracy of the designation of a radar measurement. In the first place, the relationship between the ionospheric delay and the radar-aircraft slant distance is shown. The mathematical relationship has been presented in Equation (1), as below [6]:

$$\frac{dl}{L} = \frac{Cx}{2} \cdot \frac{VTEC}{R \cdot \cos z} \cdot \frac{1}{f^2}, \tag{1}$$

where:

dl - absolute error of a slant distance radar-aircraft for ionosphere delay,

L - slant distance radar-aircraft,

$$\frac{Cx}{2} = 40.3 \cdot 10^{16} \ \frac{m}{TECU \cdot s^2},$$

VTEC - Vertical TEC,

R - Earth radius, $R = 6371\ km$,

z - maximum of zenith angle,

f - frequency of radar microwave,

f = 1300-1400 *MHz*.

Influence of the ionospheric delay to designate the radar aircraft slant distance is determined as a function of VTEC ionospheric delay, Earth radius, zenith angle, and the radar frequency carrier wave.

In the second place, the authors designated the effect of the tropospheric delay to determine the radar aircraft slant distance. The mathematical relationship is presented in Equation (2), as below [6]:

$$\frac{db}{L} = \frac{dTrop}{R} \cdot \frac{1}{\cos z}, \tag{2}$$

where:

db - absolute error of slant distance radar-aircraft for the troposphere delay,

dTrop - absolute error of the troposphere delay.

Influence of the tropospheric delay to designate the radar aircraft slant distance is determined as a function of *dTrop* absolute error of troposphere delay, Earth radius, and zenith angle.

Equations (1) and (2) are used in computer simulations and calculations to estimate the impact of the atmospheric delay on the determination of the radar-aircraft slant distance.

3 Research test

In the framework of the experimental test, a number of computer simulations were made with regard to impact of atmospheric delays on radar measurements. The numerical calculations were performed for the localization of the primary surveillance radar AVIA-W [7], mounted on the grounds of the military aerodrome EPDE in Deblin (see Figure 1) [8]. The basic technical specifications of the AVIA-W radar, localized at the military aerodrome EPDE in Deblin, are presented below [7, 9]:

- Radar maximum range 100 km,
- Maximum height range capability: 10 km,
- Accuracy of distance measurement: does not exceed 350 m,
- Accuracy of azimuth measurement: does not exceed 1°,
- Coverage for elevation angle: not more than 45°,
- Azimuth bandwidth: 1.3°,

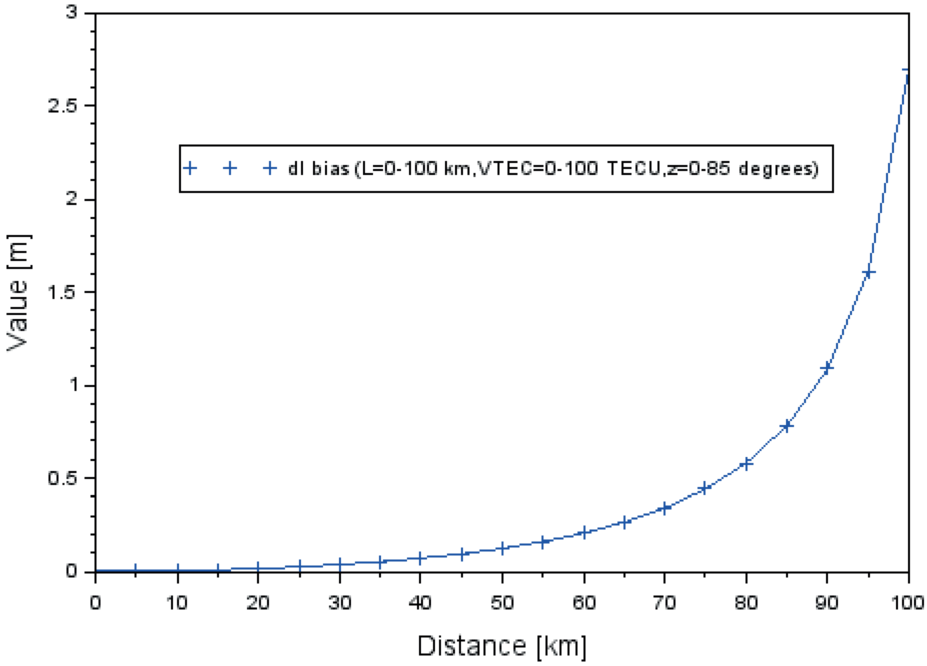

Figure 2 *Impact of the ionospheric delay in a radar measurement (case 1: L=0÷100km, VTEC=0÷100 TECU, z=0÷85⁰)*

- Radar's operating frequency band: L,
- Operating frequency of primary surveillance radar receivers: 1310 ± 5 MHz (channel A), 1347 ± 5 MHz (channel B),
- Wavelength: 23 cm,
- Average repetition rate: 939 pps,
- Number of pulses per one revolution of antenna: 6,432 pulses/revolution,
- UWB high peak power pulse: 0.45 MW (channel A), 0.5 MW (channel B),
- UWB pulse width: 1.25 µs (channel A), 1.35 µs (channel B),
- Coefficient of noises of main waveguide system: 5.5 dB,
- Coefficient of noises of auxiliary waveguide system: 8 dB,
- Correct system operation at wind speeds of up to 30 m/s,
- Strength of antenna system at wind speeds of up to 50 m/s,
- Dimensions of antenna reflector: 12 x 4 m,
- Antenna rotation speed: 10 or 15 rev/min ± 10% (depending on the operating mode),
- Power consumption: 65 kW.

The AVIA-W in Deblin is equipped with the two transmit-receive channels, ensuring a high degree of reliability, contrary to one channel operation. It is also possible to use a frequency-diversity receiver. The system also has the adjustable polarity, thus it is capable of suppressing harmful reflections from the storm clouds and clear air turbulence (referred to as angels). Moreover, AVIA-W facilitates a remote control of the equipment, thus the transmit-receive part of its operation is possible without the necessity to keep a constant watch at the place of its installation. The radar is equipped by a digital compensation system of passive interference (constant echo suppression). In the past, the signals originally developed by the station were displayed on analogue indicators. Currently, the AVIA-W in Deblin was equipped by a device TU-20L of imaging and data processing, which made the imaging displayed on digital indicators [7, 9].

The basic technical parameters of AVIA-W radar were applied in numerical simulation in research test. In addition, the value of parameter such as a radar maximum range, operating frequency of primary surveillance radar receivers and maximum height range capability were included in computations. Based on this, the numerical simulation was executed in a specialist software. The numerical simulation was done in the software Scilab v6.0.0 [10], being part of Windows 64. In the course of the conducted numerical tests for the determination of the impact of the ionospheric delay in radar measurements, the following initial values of the parameters from equation (1) were adopted:

- the value L changes from 0 km to 100 km,
- the value $VTEC$ changes from 0 TECU to 100 TECU,
- Earth radius is equal to $R = 6371\ km$,
- the frequency f equals 1310 MHz,
- the maximum zenith angle changes from 0^0 to 85^0,
- zenith angle is calculated as follow [11]:

$$z = 90^{\circ} - el\,, \tag{3}$$

where:
el - elevation angle, $el = \arctan\left(\frac{h}{L}\right)$,
h - radar height range, h=10 km.

In the course of the conducted numerical tests for determination of the impact of the tropospheric delay

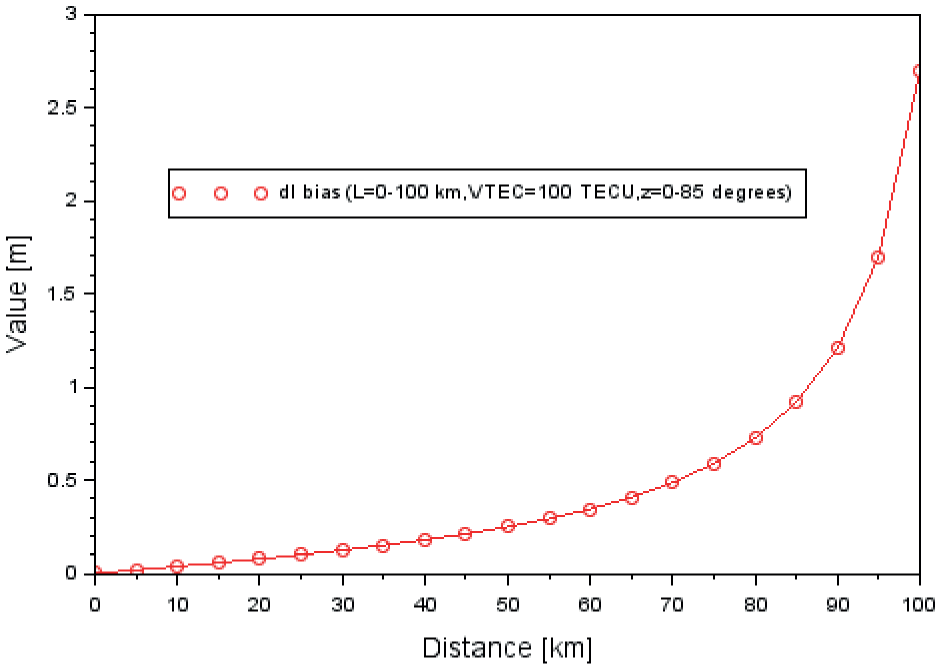

Figure 3 *Impact of the ionospheric delay in a radar measurement (case 2: L=0÷100 km, VTEC=100 TECU, z=0÷85⁰)*

in radar measurements, the following initial values of parameters from equation (2) were adopted:

- the value L changes from 0 km to 100 km,
- the value *dTrop* changes from 0 m to 1 m,
- Earth radius is equal to R = 6371 *km*,
- the maximum zenith angle changes from 0^0 to 85^0.

4 Results and discussion

Within the conducted research, a number of computer simulations on the impact of atmospheric delays were made. The simulations were related to determining the radar-aircraft slant distance. Regarding the impact of the ionospheric delay in radar measurements, three numerical simulations were made, assuming the following initial conditions:

- Case 1: all parameters (*L,VTEC,z*) change,
- Case 2: the parameters (*L,z*) change, parameter *VTEC* is constant,
- Case 3: the parameters (*L,VTEC*) change, parameter *z* is constant.
- Regarding the impact of the troposphere delay in radar measurements, three numerical simulations were made, assuming the following initial conditions:
- Case 1: all parameters (*L,dTrop,z*) change,
- Case 2: the parameters (*L,z*) change, parameter *dTrop* is constant,
- Case 3: the parameters (*L,dTrop*) change, parameter *z* is constant.

Figure 2 shows a simulation of impact of the ionospheric delay, of the measured radar-aircraft slant distance, using different values of initial parameters. In accordance with Equation (1) in calculations was assumed that:

- the value L changes from 0 km to 100 km,
- the value *VTEC* changes from 0 TECU to 100 TECU.
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the radar-aircraft slant distance measurement varies from 0 m to 2.69 m. Values of the parameter *dl* are respectively equal to: under 0.02 m at a distance between an aircraft and an aerodrome of up to 20 km, under 0.04 m at a distance an aircraft and an aerodrome of up to 30 km, above 0.07 m at a distance between an aircraft and an aerodrome of up to 40 km, above 0.12 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.20 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.34 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.57 m at a distance between an aircraft and an aerodrome of up to 80 km, above 1.08 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 2.69 m at a distance between an aircraft and an aerodrome of up to 100 km. Therefore, it can be observed that impact of the ionospheric delay is quite significant in radar measurements at a distance between an aircraft and an aerodrome of above 90 km.

Figure 3 shows another simulation of impact of the ionosphere delay on the measured radar-aircraft slant distance, assuming that the ionosphere correction is constant in the calculations. In accordance with Equation (1) in calculations was assumed that

- the value L changes from 0 km to 100 km,
- the value *VTEC* equals 100 TECU.
- the maximum zenith angle changes from 0^0 to 85^0.

In this specific case, the measurement error of the radar-aircraft slant distance varies from 0 m to 2.69 m, respectively. Values of parameter *dl* are under 0.08 m at a distance between an aircraft and an aerodrome of up to 20 km, above 0.12 m at a distance between an aircraft and an aerodrome of up to 30 km, under 0.18 m at a distance

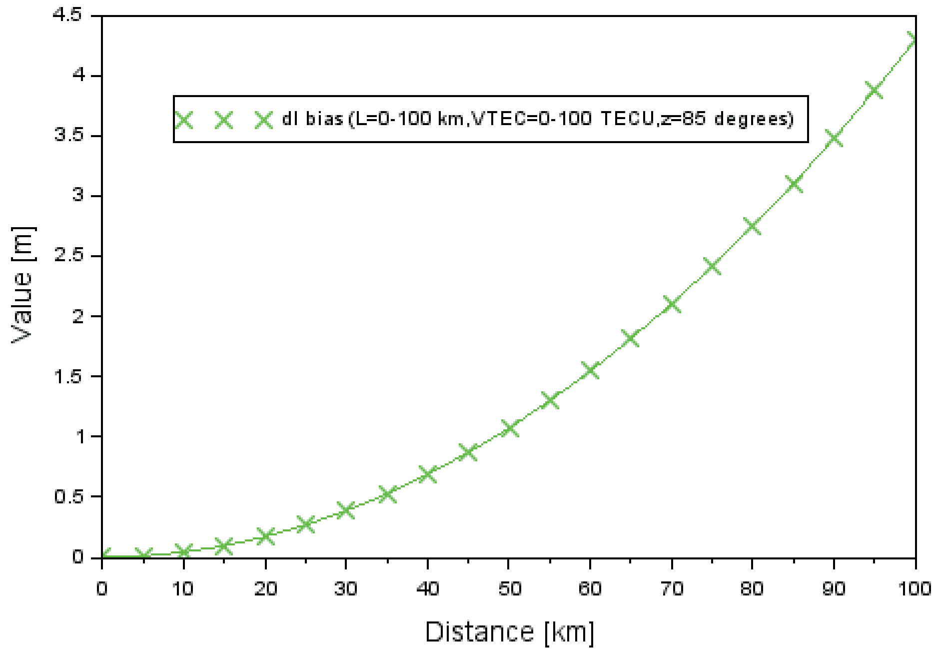

Figure 4 *Impact of the ionospheric delay in a radar measurement (case 3: L=0÷100 km, VTEC=0÷100 TECU, z=85⁰)*

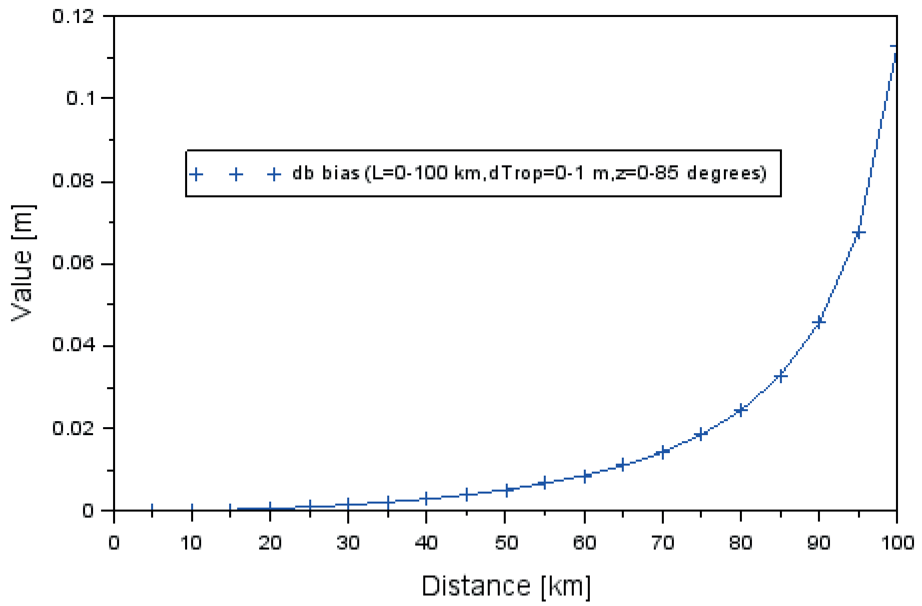

Figure 5 *Impact of the tropospheric delay in a radar measurement (case 1: L=0÷100 km, dTrop=0÷1 m, z=0÷85⁰)*

between an aircraft and an aerodrome of up to 40 km, below 0.25 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.34 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.48 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.72 m at a distance between an aircraft and an aerodrome of up to 80 km, above 1.20 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 2.69 m at a distance between an aircraft and an aerodrome of up to 100 km. Therefore, it can be observed that impact of the ionospheric delay is quite significant in radar measurements at a distance between an aircraft and an aerodrome of above 90 km.

Figure 4 shows another simulation illustrating impact of the ionospheric delay upon the measured radar-aircraft slant distance, assuming that the zenith angle is constant in the calculation. In accordance with Equation (1) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $VTEC$ changes from 0 to 100 TECU.
- the maximum zenith angle equals 85^0.

In the analyzed case, the radar-aircraft slant distance measurement changes from 0 m to 4.29 m. Values of the parameter *dl* are as follows: over 0.04 m at a distance between an aircraft and an aerodrome of up to 10 km, above 0.17 m at a distance between an aircraft and aerodrome of up to 20 km, above 0.38 m at a distance between an aircraft

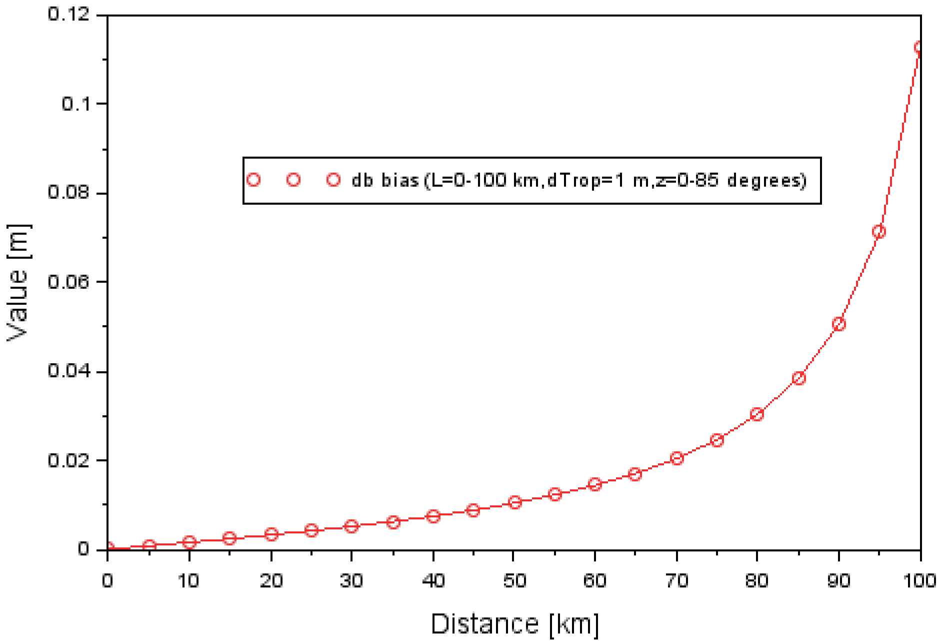

***Figure 6** Impact of tropospheric delay in a radar measurement (case 2: L=0÷100 km, dTrop=1 m, z=0÷85^0)*

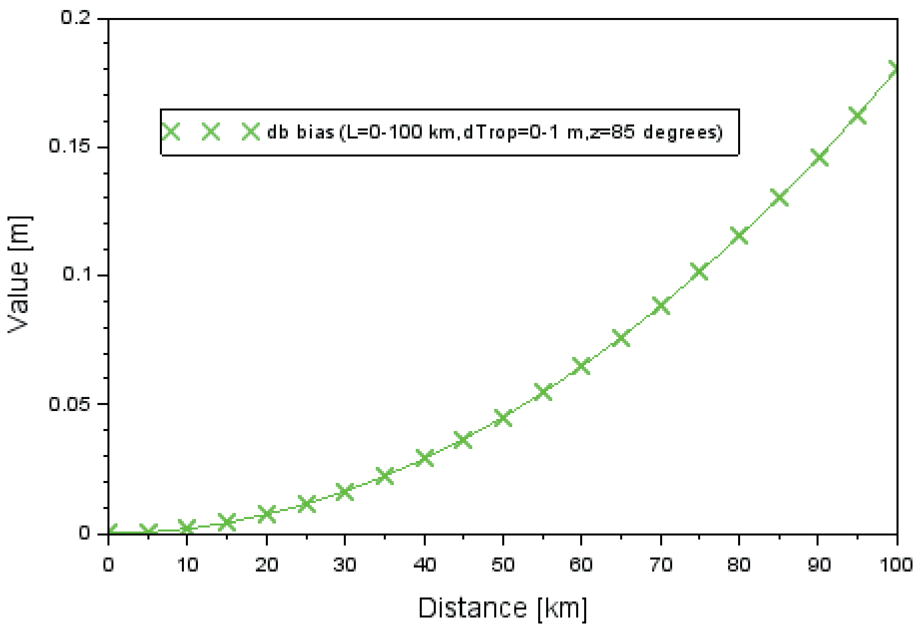

***Figure 7** Impact of the tropospheric delay in a radar measurement (case 3: L=0÷100 km, dTrop=0÷1 m, z=85^0)*

and an aerodrome of up to 30 km, above 0.68 m at a distance between an aircraft and an aerodrome of up to 40 km, over 1.07 m at a distance between an aircraft and an aerodrome of up to 50 km, more than 1.54 m at a distance between an aircraft and an aerodrome of up to 60 km, more than 2.10 m at a distance between an aircraft and an aerodrome of up to 70 km, above 2.74 m at a distance between an aircraft and an aerodrome of up to 80 km, above 3.47 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 4.29 m at a distance between an aircraft and an aerodrome of up to 100 km. Based on the conducted simulations, it was found that the impact of the ionospheric delay is already quite significant from 50 km in a radar measurement, assuming that the zenith angle is constant.

Figure 5 shows a simulation of impact of the tropospheric delay of the measured radar-aircraft slant distance, using different values of the initial parameters. In accordance with Equation (2) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $dTrop$ changes from 0 m to 1 m,
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the radar-aircraft slant distance measurement changes from 0 m to approximately 0.12 m. Values of the parameter db are less than 0.01 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.01 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.02 m at a distance between an aircraft and an aerodrome up to 80 km, less than 0.05 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 0.12 m at a distance between an aircraft and aerodrome of up to 100 km. Thus, it can be observed that impact of the tropospheric delay is quite small in radar measurements at a distance between an aircraft and an aerodrome ranging from 0 km to 100 km.

Figure 6 shows another simulation of impact of the troposphere delay on the measured radar-aircraft slant distance, assuming that the tropospheric correction is constant in the calculations. In accordance with Equation (2) in the calculations, it was assumed that

- the value L changes from 0 km to 100 km,
- the value $dTrop$ equals 1 m,
- the maximum zenith angle changes from 0^0 to 85^0.

In the analyzed case, the error of radar-aircraft slant distance measurement changes from the value 0 m to 0.11 m. Values of the parameter db are as follows: over 0.01 m at a distance between an aircraft and an aerodrome of up to 60 km, above 0.02 m at a distance between an aircraft and an aerodrome of up to 70 km, above 0.03 m at a distance of an aircraft and an aerodrome of up to 80 km, above 0.05 m at a distance between an aircraft and an aerodrome of up to 90 km, approximately 0.11 m at a distance between an aircraft and an aerodrome of up to 100 km. Thus, it can be observed that in the analyzed example, impact of the tropospheric delay is also quite small in radar measurements at a distance between an aircraft and an aerodrome ranging from 0 km to 100 km.

Figure 7 shows another simulation of impact of the troposphere delay upon the measured radar-aircraft slant distance, assuming that the zenith angle is constant in the calculations. In accordance with Equation (2) in calculations was assumed that:

- the value L changes from 0 km to 100 km,
- the value $dTrop$ changes from 0 m to 1 m,
- the maximum zenith angle is equal to 85^0.

In the analyzed case, the error of radar-aircraft slant distance measurement changes from the value 0 m to 0.18 m. Values of the parameter db are as follows: over 0.01 m at a distance between an aircraft and an aerodrome of up to 30 km, below 0.03 m at a distance between an aircraft and an aerodrome of up to 40 km, below 0.05 m at a distance between an aircraft and an aerodrome of up to 50 km, above 0.06 m at a distance between an aircraft and aerodrome of up 60 km, under 0.09 m at a distance between an aircraft and an aerodrome of up to 70 km, more than 0.11 m at a distance between an aircraft and an aerodrome of up to 80 km, below 0.15 m at a distance between an aircraft and an aerodrome of up to 90 km, 0.18 m at a distance of an aircraft and an aerodrome of up to 100 km. Based on this, it can be observed that in the considered example, the impact of the troposphere delay to determine radar-aircraft slant distance is the largest. However, this effect seems to be small in comparison to impact of the ionospheric delay in radar measurements.

5 Conclusions

The paper presents numerical simulations, which determine the effect of atmospheric delays in radar measurements in aviation. An experimental test was conducted for the primary surveillance radar AVIA-W located on the grounds of the military aerodrome EPDE in Deblin. All the computer simulations were performed for the basic radio-navigation parameters of the AVIA-W radar, taking into account the frequency of the carrier wave and the maximum radar range. The article presents findings of the numerical calculations of impact of the ionospheric and tropospheric delays upon the radar-aircraft slant distance measurement. In the case of the effect of the ionospheric delay upon radar-aircraft slant distance, the following were found:

- the impact of the ionopheric delay in radar measurements is clearly visible at a distance between an aircraft and an aerodrome of above 90 km,
- the ionospheric disturbance equal to 100 TECU is noticeable in radar measurements at a distance between an aircraft and an aerodrome exceeding 90 km,
- the influence of the zenith angle equal to 85^0 causes an error in a radar measurement of even more than 4 m.
- In the case of the tropospheric delay effect upon the slant distance radar aircraft, the following were found:
- the impact of the tropospheric delay in radar measurements is small, exceeding 0.10 m at a distance between an aircraft an aerodrome equal to 100 km,
- the impact of the tropospheric delay of 1 m is small in radar measurements, exceeding 0.10 m,
- the impact of the zenith angle equal to 85^0 causes a radar measurement error under 0.20 m.

Among many parameters applying in numerical simulation, the zenith angle is a crucial factor in computations. The zenith angle can be expressed as a function of a radar range distance and radar altitude range. If the radar altitude range will be changed then influence of atmosphere delay will be different. The theoretical research with radar altitude range can be carried out for AVIA-W radar only to elevation angle equaling to 45 degrees, e.g. for maximum altitude of 100 km. It should be noticed that altitude of 100 km is a lower layer of ionosphere zone in atmosphere. Moreover, if the ionosphere state of 100 km layer will be disturbed, then it will be visible in radar measurements, as well.

The obtained findings of computer simulations for the AVIA-W radar are crucial in planning an air operation and during its execution. The ionospheric disturbance results in shortening a radar-aircraft slant measurement, which in turn leads to a decrease in the accuracy of determining the aircraft's horizontal coordinates. Besides that, a tropospheric disturbance also causes a decrease in the accuracy of determining the aircraft horizontal position. The results are extremely important in radar measurements and can be used in the GNSS satellite technology, within the GBAS augmentation system in aviation. Therefore, in the future the authors plan to perform numerical simulations on the impact of atmospheric delays also with regard to application of the GNSS satellite technology in aviation.

Acknowledgements

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Annex

Abbreviation	Full name
Radar	Radio Detection and Ranging
PSR	Primary Surveillance Radar
SSR	Secondary Surveillance Radar
ATC	Air Traffic Control
TMA	Terminal Manoeuvring Area
ILS	Instrument Landing System
NDB	Non-Directional Beacon
TACAN	Tactical Air Navigation
VOR	VHF Omni-directional Range
VTEC	Vertical TEC
UWB	Ultra Wide-Band
TECU	Total Electron Content Unit
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System