P2B.10 **APPLICATION EXPERIENCE OF ATTENUATION-TUNED *Z-R* RELATION IN RADAR RAINFALL MEASUREMENTS**

Yuri B. Pavlyukov *

Central Aerological Observatory, Moscow Reg., Russia

1. INTRODUCTION

In the paper we examine performance of two-wavelength radar method of rainfall estimation accuracy improvement in following formulation.

The radar observation is executed in non-attenuated λ_1=10 cm and attenuated λ_2=3 cm bands simultaneously. For rainfall rate calculation the conventional relation $\boldsymbol{R=(Z_{l1}/A)^{1/b}}$ is used, but with variable DSD-depending ***A-b*** coefficients. These coefficients are determined from two-wavelength radar observation model identification procedure called *calibration*. As follows from our comparative analysis of radar and gauge daily accumulation datasets (Melnichuk and Pavlyukov, 30th AMS Radar Conference, 2001): for the ***b*** values in the range 1.4÷1.7 there is always a corresponding value of coefficient ***A***, that provides the complete agreement of rainfall data. For this reason we fixed ***b***=1.6 and determine ***A*** by the calibration.

Generally, the uniform coefficients using for total reflectivity field of radar observation zone is not ideal solution and do not reflect all of raindrop size distribution variations in space but this is the first-order approximation of variations.

2. THEORETICAL BASIS

In our dual-wavelength radar observation there are two radial reflectivity profiles: non-attenuated S-band and attenuated X-band. It is well known (Hitschfeld and Bordan, 1954) that reverse problem solution of calculation ***Z(r)*** from $\boldsymbol{Z^{Att}(r)}$ is very unstable, therefore we considered direct formulation.

These reflectivity profiles are connected by means of the attenuation law:

$$Z_{l_2}^{Att}(r) = Z_{l_1}(r)\cdot \mathrm{e}^{-2\int_{r_0}^{r} k_{l_1}(s)\,ds}, \quad (1)$$

where $k_{l1}\,[km^{-1}] = K_{l1}\,[dB\,km^{-1}]/4.343$ *is* specific attenuation coefficient, depending on the DSD parameters**,** raindrop temperature and wavelength l_1 , r_0 is the distance of cloud frontline. Exponent in (1) in logarithmic notation is path-integrated attenuation (***PIA***). This is directly defined by dual-wavelength measurements as difference between ***Z*** and $\boldsymbol{Z^{Att}}$ profiles integrated on the range [r_0,r]. The bulk variables ***R***, ***Z*** and ***K*** can be approximated by two semi-empirical power-law equations

$$\boldsymbol{Z} = \boldsymbol{A}\boldsymbol{R}^{\boldsymbol{b}}, \qquad \boldsymbol{K} = a\,\boldsymbol{R}^{g}, \quad (2)$$

Attempts to define the ***A, b,*** a**,** g coefficients independently are senseless because of their binding through DSD and therefore for conjunction our model we use Atlas-Ulbrich "Rain Parameter Diagram" which is self-consistent by DSD. For the exponential model (that is correct for enlarged averaging scales), there is the analytical approximation (Doviak and Zrnic, 1984)

$$\boldsymbol{K} = e_1\boldsymbol{Z}^{e_2}\boldsymbol{R}^{e_3},\ \ e_1 = 8.61\times10^{-4},\ e_2 = 0.405,\ e_3 = 0.595, \quad (3)$$

Using (2) we can express a and g in terms of ***A*** and ***b***

$$a = e_1\boldsymbol{A}^{e_2}, \qquad g = e_2 b + e_3, \quad (4)$$

Substitution (2) and (4) into (1) gives the following equation for calculated attenuated profile $\boldsymbol{Z^{Att}(r)}$ from true reflectivity profile ***Z(r)***

$$\boldsymbol{Z}_{l_2}^{Clc}(r,\boldsymbol{A},\boldsymbol{b}) = \boldsymbol{Z}_{l_1}(r)\times \times\exp\left(-\frac{0{,}461\cdot e_1}{\boldsymbol{A}^{e_3/\boldsymbol{b}}}\int_{r_0}^{r}\left[\boldsymbol{Z}_{l_1}(s)\right]^{(e_2+e_3/\boldsymbol{b})}ds\right), \quad (5)$$

This self-consistent by coefficients equation describes rain attenuation effect on true reflectivity profile. On the other hand, equation (5) can be regards as a basis for its coefficients estimation by assigning the reflectivity profiles **Z(r)** and $\mathbf{Z^{Att}(r)}$ as the input information. In this case the ***A*** and ***b*** parameters in (5) are averaged over the calibration range [$\mathbf{r_0}$,**r**].

For the parameter identification by Eq. (5) a least mean squares fitting procedure is applied.

3. CALIBRATION METHOD DESCRIPTION

Calibration procedure implements to original reflectivity data in spherical coordinates for each 10-min radar observation after clutter suppression.

We restrict our observation by azimuth directions with $\boldsymbol{Z_{max}} \le$ 45dbZ, for which reflectivity difference in X- and S-band does not exceed ~0.2 dB due to non-Rayleigh scattering.

To avoid problems with non-Rayleigh scattering from mixed-phase precipitation in the melting layer we restrict the calibration range length so that the far end position of the range wouldn't exceed the isotherm 0°C

In the calibration ***PIA*** is estimated by two-wave method. Radar MRL-5 has ***H*** and ***V*** polarization for 10-cm and 3-cm channels respectively. In our calculations we use "mean" relation $\mathbf{Z_{dr}(Z_H)}$ for differential reflectivity as exp-like trend. The residual variance relative to this trend (~1 dB) we consider as an additional error of ***Z*** measurements.

The standard errors in $\boldsymbol{Z_{l1}}$, $\boldsymbol{Z_{l2}}$ measurements are estimated as about 1 dB (for log-type receiver and 32 averaged samples in each range bin for our processing algorithm) that means errors in ***PIA*** by dual-wave method equal ~1.5 dB.

Taking into consideration polarimetric variance, total error in ***PIA*** and ***Z*** measurements can reach up to 1.7-2 dB. This error amount does not permit to reliable estimation of the ***A*** coefficient at each point on the profile

* *Corresponding author address:* Yuri B. Pavlyukov, Central Aerological Observatory, Dept. of Radiometeorology, Dolgoprudny, 141700, Russia, e-mail: yupav@orm.mipt.ru

But, the comparison of whole profiles in least square sense by Eq.(5) gives the possibility to reduce the influence of measurement errors and to estimate mean value of A coefficient. This calibration procedure is applied to a number of azimuthal directions with sufficient PIA. That provides a set of ***A*** coefficient estimations for current reflectivity field.

4. CALIBRATION SENSITIVITY TO NOISE

Accuracy of the ***A*** value estimation by (5) depends on errors level of input datasets $\boldsymbol{Z}(\mathbf{r})$ and $\boldsymbol{Z}^{Att}(\mathbf{r})$.

In order to know the calibration sensitivity of this estimation with respect to errors level the numerical simulation of two-wavelength radar measurement and calibration implementation were carried out.

At the first simulation step the initial profile of the reflectivity $\boldsymbol{Z}(\mathbf{r})$ and the input model parameters A_0 and b_0 were assigned. Then the attenuated profile of the reflectivity $Z^{Att}(\mathbf{r})$ was calculated by (5). At the second step $Z(\mathbf{r})$ and $Z^{Att}(\mathbf{r})$ were used as the input information for the calibration algorithm.

The accuracy of calibration was evaluated on the agreement of the rain rate profile $R_0(\mathbf{r})=\{Z_{10}(\mathbf{r})/A_0\}^{1/b0}$ calculated by the initial data and profile calculated with using calibration values A_C by $R_?(\mathbf{r})=\{Z_{10}(\mathbf{r})/A_?\}^{1/b?}$.

In the experiments both the input parameters of the model A_0 and b_0 coefficients and the initial reflectivity profile $Z_0(\mathbf{r})$ were varied.

Input model profile of reflectivity was specified as (i) uniform distribution $Z(\mathbf{r})$, (ii) the sinusoidal wave with several humps, and some others.

In the A_0-b_0 parametric space we investigated on A_0=100-500 and b_0=1.4-1.7 region which includes the most of 69 Battan's ***Z-R*** relations.

Each numerical simulation was organized in a Monte-Carlo fashion: a number of calibrations by (5) with randomly disturbed input profiles $Z_3(\mathbf{r})$? $Z_{10}(\mathbf{r})$ was calculates for every input parameter dataset.

The input profiles were disturbed by the Gaussian noise under the assumption of uncorrelated and unbiased measurement error distribution.

Example of the simulation is displayed in **FIG.1.** Each point corresponds to single calibration with random disturbed input reflectivity profile $Z(\mathbf{r})$ assign as sinusoidal wave: Z_{max}=40, Z_{min}=30 dbZ, wave period= 10 km, range length 40 km, the profile has 4 humps of the curve. ***PIA*** on the range is equal ~13 dB and input parameters are A_0= 200, b_0= 1,6. The amplitude of a normal noise in $Z(\mathbf{r})$ and $Z^{Att}(\mathbf{r})$ was equal s_Z=1,5 dB. Shaded regions in the **FIG.1** represent the boundaries of 95% confidence intervals for the sample average which was calculated: under the assumption about the normality of the A_C estimation distribution (3), and in accordance with Chebyshev's inequality without any assumption about kind of distribution (4). The histogram of estimation spectrum is presented in inset (**A**).

The dispersion of single estimations can be reduced by averaging of estimations for several azimuth directions. We can see in **FIG.1** that the sample average <A_C> rapidly (averaging on 10-15 azimuthal estimations) attains an equilibrium in the limits $A_0 \pm 50$ with 95% probability according to Chebyshev's criterion.

The A_C spectrum substantially degrades due to:

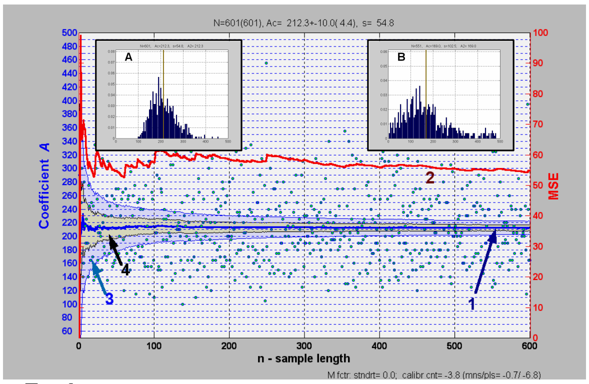

FIG.1. *Monte-Carlo simulation of dual-wave calibration application for model reflectivity profile. The horizontal axis is a sample length of averaging estimations, line 1 is the sample average coefficient <**A_C**> (left axis), line 2 is the sample standard deviation (MSE) (right axis). In the insets A and B histograms of the **A_C** calibration estimations are presented.*

(1) shortening of calibration range, (2) decreasing of ***PIA*** in calibration range and (3) increasing of noise amplitude s_Z. The dispersion of the A_C estimations of coefficient increases with the degradation of spectrum. Development of the degradation results in sample average bias appearance. Suitable example is presented in inset (**B**) for the case: calibration range length 20 km, only 2 humps of ***Z*** profile, ***PIA***≈7dB.

The reason for the bias is not clear and additional investigation of our model (5) properties is required.

5. CONCLUSION

The numerical simulation of the calibration procedure application reveals considerable sensitivity of the calibration ***A*** coefficient estimation to the noise level in input data. The basic conclusions are :

- in noise absence conditions the calibration accuracy on the average is high (better than 1% on bias of <***R***>) and it does not depend on the input profile $Z(\mathbf{r})$ and input model parameters A_0, b_0,
- with an increase of noise amplitude s_Z in the input ***Z*** profiles, the quality of the calibration estimation of coefficient A_C depends on: (1) the value of calibration ***PIA*** for the specific reflectivity profile, (2) the calibration range length, (3) the number of calibration estimations for separate azimuth directions N_{Ac},
- for assigned error level s_Z≈ 1.5÷2 dB in the radar measurements the permissible minimum calibration ***PIA*** is 5÷8 dB depending on the input ***Z*** profiles, the length of calibration range must be not shorter than 20-25 km, and the number of calibrated azimuthal directions N_{Ac} must be not less than 20÷25.

The calibration method application for real data processing of the radar observations in summer season 2000 in Moscow demonstrates that abovementioned calibration conditions are realized not so often: only for 2 of 18 examined events we have obtained the continuous series of calibration estimations A_C.

For obtaining the reliable estimations of coefficient ***A*** in ***Z-R*** relation by the proposed method it is necessary either to substantially decrease total error of reflectivity measurement or to eliminate the bias in sample average for small ***PIA*** and short calibration range.