Title	On the Vertical Profiling of High Resolution with a Conventional Radar
Author(s)	Belotsercovsky, V.Andrey; Divinsky, I.Leonid; Kuznetsov, D.Anatoly; KIKUCHI, Katsuhiro; UYEDA, Hiroshi
Citation	Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 11(1), 175-183
Issue Date	1998-03-20
Doc URL	http://hdl.handle.net/2115/8830
Type	bulletin (article)
File Information	11(1)_p175-183.pdf

Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 11, No. 1, 175-183, 1998.

On the Vertical Profiling of High Resolution with a Conventional Radar

Andrey V. Belotsercovsky, Leonid I. Divinsky, Anatoly D. Kuznetsov

Russian State Hydrometeorological Institute, St. Petersburg, Russia

Katsuhiro Kikuchi and Hiroshi Uyeda

Division of Earth and Planetary Sciences, Graduate School of Science,
Hokkaido University, Sapporo 060-0810, Japan

(Received November 30, 1997)

Abstract

Considered is an attempt to render a conventional meteorological radar an ability of continuous vertical profiling of high temporal and spatial resolution. Two chief obstacles that keep a conventional radar from proper vertical profiling are pointed. First one is an antenna construction that causes essential power side lobes and thus ground clutters interference and expands first Fresnel zone beyond 1 km range. The second one is a peculiar amplitude response of the conventional radar's receiver tract that, on the one hand, enables the radar to process back scattered pulses from both remote and close targets, but on the other hand, causes a bias in estimation of average power values for the fine radar reflectivity analysis. Two inexpensive ways to overcome the obstacles are proposed. The adjusting procedure to make the reflectivity estimates unbiased is developed using statistical simulation procedures. Vertical pointing is substituted with scanning along the close vertical line with corresponding modification of data processing hardware and algorithms. Testing results of actual snowfall field observations showed that the profiling permits to analyze and correlate fine reflectivity details with precipitation particles structure. That suggests potential of conventional radar for applications to remote precipitation analysis both separately or combined with validation problems.

1. Introduction

There are many cases in radar meteorology requiring a vertical profiling with high temporal and spatial resolution. A study of fine precipitation structure, a validation of satellite observations can be examples of those cases. Whereas vertically pointed specialized profilers can perform the task well, a conventional meteorological radar often can not. However, the specialized profiler is not always available and problem of supplementing the conventional radar with high resolution profiling ability is of practical importance. Combining features of different devices in a single conventional radar set can significantly reduce experimental costs as well.

There are two chief obstacles that keep a conventional radar from proper vertical profiling. Both of them are mainly resulting from the high output power and wave length needed for the long range observations and wide area surveillance the conventional radar is designed for.

The first one is an antenna construction. The size of antenna is large to shape a low beam pattern width to keep high angular resolution at long range observations. The consequences are the following: 1) there are essential antenna side lobes, which leads to ground clutter interference and 2) the spatial expansion of the first Fresnel zone, in which the antenna beam pattern takes shape, is greater than 1 km in height. That makes vertically pointed observations correct only from heights greater than 1-6 km depending on the ground clutters.

The second one is a peculiar amplitude response of the conventional radar's receiver tract. The amplitude response is linear for weak signals and logarithmic for high level signals to enable the radar process back scattered pulses from both remote and close targets. That leads to a bias in estimation of average power values for the fine radar reflectivity analysis.

The objective of the study has been to try to overcome the obstacles and enable the conventional radar to vertically profile with high spatial and temporal resolution. To compensate the bias, some theoretical and statistical simulation research has been done. To avoid influence of the ground clutters along with overcoming the first Fresnel zone limitations, the scanning along the vertical line distant from the radar side instead of antenna vertical pointing has been performed with appropriate modification of signal processing procedures. The research has been carried out in close collaboration between Hokkaido University and Russian State Hydrometeorological Institute.

2. Correction of radar reflectivity estimation for a spatially distributed target

Result of conventional radar observations is a radar reflectivity spatial distribution. The radar reflectivity is assessed from output voltage of the receiver. In the conventional radar, an amplitude response is linear-logarithmic and there is a noise combined with the signal at the output.

If there is a spatially distributed target with a reflectivity η, a power of back scattered signal at the radar antenna output is a random variable submitting to an exponential distribution with mean value $\bar{P}_S$.

$$\eta=\frac{\bar{P}_S R^2}{P_n C_\lambda}, \tag{1}$$

where R is a distance to a target, C_λ is a radar potential, P_n is the receiver minimal discernible signal.

Density function for back scattered signal power P_S is defined with a relation (Dulevich, 1970 ; Skolnik, 1976)

$$w(P_S)=\begin{cases}0 & \text{for } P_S\leq 0\,;\\ \dfrac{1}{\bar{P}_S}\cdot\exp\left(-\dfrac{P_S}{\bar{P}_S}\right) & \text{for } P_S>0.\end{cases} \tag{2}$$

The receiver's input voltage is related to the antenna output power as follows

$$U_{in}=K_{ant}\sqrt{P_S}, \tag{3}$$

where K_{ant} is an antenna coefficient.

If the receiver assumed to be a non-linear, time lag free and noiseless converter, we obtain the following approximating analytical expression

$$U_{out}=U_i\cdot ln\left(\frac{K_{ant}\sqrt{P_S}+U_1}{U_1}\right), \tag{4}$$

where U_0 and U_1 are constants chosen along with K_{ant} in such a way as for analytical relation $U_{out}=f(P_S)$ to fit the real amplitude response of the radar's receiver.

There has also been assumed that the noise at the receiver's output is the random variable submitted to the Rayleigh distribution.

$$w(U_n)=\begin{cases}0 & \text{for } U_n\leq 0\,;\\ \dfrac{U_n}{U_m^2}\cdot\exp\left(-\dfrac{U_n^2}{2U_m^2}\right) & \text{for } U_n>0,\end{cases} \tag{5}$$

where U_n is the modal value of the receiver's noise.

Assessment of target parameters is performed by averaging results of sequential single measurements. Average value of the voltage at the receiver's output $\hat{U}_{out}$ after n measurements can be obtained as follows

$$\hat{U}_{out}=\frac{1}{n}\sum_{i=1}^{n}\left(U_{out\,i}+U_{n\,i}\right), \tag{6}$$

where $U_{out\,i}$ is i-th realization of the receiver's response to the input power of back scattered signal $P_{S,i}$; $U_{n\,i}$ is i-th realization of the receiver's noise.

The estimate of the input (back scattered) signal $\hat{P}_S$ can be obtained using relation (4)

$$\hat{P}_S=\left\{\frac{U_1}{K_{ant}}\cdot\left[\exp\left(\frac{\hat{U}_{out}}{U_0}\right)-1\right]\right\}^2. \tag{7}$$

To estimate the average power of back scattered signal $\hat{P}_S$, the Monte Carlo method for statistical simulation was used. The simulated data considered to be sample results of back scattered signals reception with known statistical characteristics by the radar's receiver with known characteristics of noise. The sample results were used in statistical analysis to determine a back scattered signal mean value, standard deviation, confidence intervals, skewness and

Table 1. Correcting factors.

True average power of back scattered signal at the radar antenna ouppt $\bar{P}_s$, W	Estimate of the average power of back scattered signal $\hat{P}_s$, W	The radar receiver's output voltage V	Average value of the receiver's output voltage V	Correcting factor k^*
1	2	3	4	5
10^{-14}	$1{,}63\cdot10^{-14}$	0.315	0.376	0,837
$3\cdot10^{-14}$	$3{,}85\cdot10^{-14}$	0.477	0.516	0,925
$5\cdot10^{-14}$	$6{,}01\cdot10^{-14}$	0.570	0.600	0,950
10^{-13}	$1{,}10\cdot10^{-13}$	0.713	0.726	0,981
$3\cdot10^{-13}$	$2{,}94\cdot10^{-13}$	0,975	0,961	1,015
$5\cdot10^{-13}$	$4{,}80\cdot10^{-13}$	1,11	1,08	1,020
10^{-12}	$9{,}24\cdot10^{-13}$	1,30	1,26	1,033
$3\cdot10^{-12}$	$2{,}58\cdot10^{-12}$	1,63	1,57	1,037
$5\cdot10^{-12}$	$4{,}26\cdot10^{-12}$	1,78	1,72	1,037
10^{-11}	$8{,}47\cdot10^{-12}$	2,00	1,93	1,035
$3\cdot10^{-11}$	$2{,}39\cdot10^{-11}$	2,36	2,27	1,040
$5\cdot10^{-11}$	$4{,}11\cdot10^{-11}$	2,52	2,44	1,033
10^{-10}	$8{,}05\cdot10^{-11}$	2,75	2,66	1,033
$3\cdot10^{-10}$	$2{,}45\cdot10^{-10}$	3,11	3,03	1,028
$5\cdot10^{-10}$	$4{,}03\cdot10^{-10}$	3,28	3,19	1,028
10^{-9}	$7{,}93\cdot10^{-10}$	3,51	3,42	1,028
$3\cdot10^{-9}$	$2{,}40\cdot10^{-9}$	3,88	3,79	1,024
$5\cdot10^{-9}$	$4{,}07\cdot10^{-9}$	4,05	3,96	1,022
10^{-8}	$8{,}11\cdot10^{-9}$	4,28	4,19	1,021
$3\cdot10^{-8}$	$2{,}41\cdot10^{-8}$	4,65	4,56	1,020
$5\cdot10^{-8}$	$3{,}99\cdot10^{-8}$	4,82	4,73	1,020
10^{-7}	$8{,}16\cdot10^{-8}$	5,05	4,97	1,017

excess of probability distribution. There has been revealed significant deviations of the power estimates from its true values reaching maximum 75% caused by logarithmic amplitude response of the receiver and depending on the two working into opposite directions factors, a true average power of the back scattered signal and average receiver's noise.

To correct the bias in the estimation, the quadratic multiple regression equation has been developed. The regression coefficients were estimated with the Monte Carlo method as well. The bias is compensated with the correcting factor k^* to be multiplied by the measured (biased) power at the receiver's output. The regression coefficients were tabulated for various combinations of the receiver's noise and average output power and were used to calculate the correcting factor to make the average power estimates unbiased. Table 1 is for the correcting factor depending on average value of the radar receiver's output voltage under the characteristic noise level of 0.25 V.

The similar tables were pre-calculated for various noise levels. The correcting procedure enables the conventional radar receiver to be used as accurate radar reflectivity meter for nearly located meteorological targets.

3. Elimination of ground clutter influence

As it has been mentioned, the vertical profiling by conventional radar with transmission of sounding impulse in vertical direction cannot provide correct results due to two reasons.

First, the spatial expansion of the first Fresnel zone R_F, in which the radar beam pattern takes shape, is equal to

$$R_F=\frac{2D^2}{\lambda}, \tag{8}$$

where D is a diamter of the antenna system, λ is a wavelength of the sounding impulse.

For conventional meteorological radar R_F is usually greater than 1000 m. That sets the lowest height at which the radar reflectivity can be measured, should the antenna be zenith-pointed. At closer distances, the antenna beam pattern has uncertain parameters.

On the other hand, direct vertical pointing of conventional radar antenna causes ground clutters to mask the vertical profile information at the low altitudes due to antenna side lobes and high power radar output at operational wave length. The conventional way to minimize the clutters influence is the volume scan to acquire the complete information about the 3D radar reflectivity field and to retrieve the vertical profiles from the obtained data by special processing. The disadvantage of the conventional approach is a relatively long time required for complete volume scan, which usually takes 6-7 minutes, and poor spatial resolution. High temporal resolution vertical profiling requires by an order of magnitude greater sampling rate.

To achieve that goal the conventional radar was supplemented with a processing unit that enabled to perform scanning in elevation angle and selective processing of back scattered impulse so that only radar reflectivity along the given vertical line was measured. The reflected signal at the output of the receiver was converted to 8-bit binary numbers with the 10 MHz ADC. Depending on the position of the antenna beam maximum, a delay between sounding impulse transmission and reception of the scattered signal varied. That significantly increased the sampling rate (an averaged profile could be obtained every 30 sec) and provided the height resolution of 100 m for the imaginary line distanced at 10 km from a radar site. The distance could be set up arbitrarily.

4. Testing results

The conventional meteorological radar MRL-5 was used in a vertical profiling mode during the January 1997 complex observations on snow clouds in St. Petersburg, Russia in framework of Hokkaido University International Scientific Research Project (WANTS-ARCTIC). The radar was supplemented with the special processing unit and algorithms for reflectivity data processing included bias correction functions. The radar worked in the continuous vertical profiling along the same vertical line. Every hour the radar was switched to the volume scan mode and then resumed profiling. At the surface point that corresponded to the beginning of the profiling vertical line there was a station for snowflakes close-up photographing. The snow collecting plate was exposed for 2, 3, 4, 5 or 8 minutes depending on the snowfall intensity. The pictures of snowflake samples were taken every 15 minutes. Another in situ meteorological measurements contained surface temperature, humidity, pressure and wind data accompanied with twice-daily radio sounding data.

Some characteristic example of the observation results is shown in Figs. 1-4. In Fig. 1, the averaged over an hour (over 120 sequential profiles) vertical radar reflectivity profile of snow cloud taken on January 10, 1997, 09 : 00-10 : 00 UTC is shown whereas the close-up picture of snowflakes on the surface corresponding to the same time interval is shown in Fig. 2. The Figs. 3 and 4

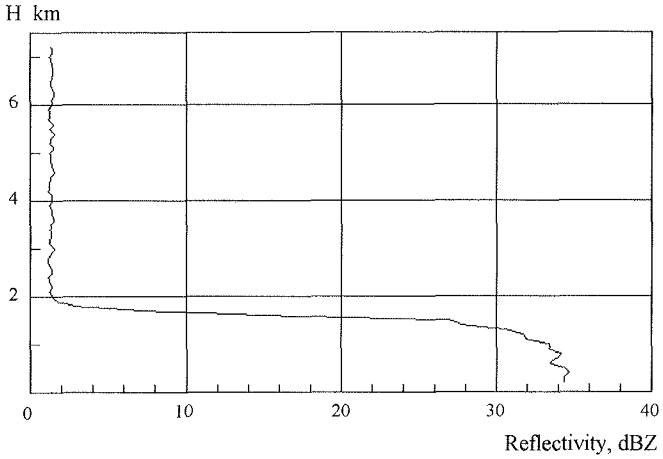

Fig. 1. The vertical radar reflectivity profile of snowfall averaged over an hour (120 sequential profiles), January 10, 1997, 09 : 00-10 : 00 UTC, St. Petersburg.

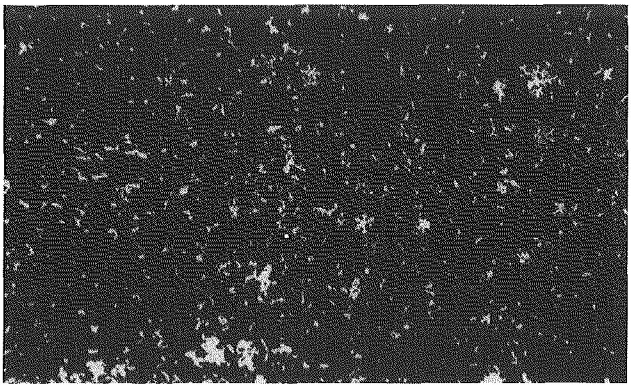

Fig. 2. The close-up picture of snowflakes on the surface, January 10, 1997, exposure time 09 : 30-09 : 32 UTC, St. Petersburg.

represent the same character of data only averaged over the consequent hour, 10 : 00-11 : 00 UTC. From the figures comparison there can be seen a dramatic change in the shape of snow crystals. Those snowflakes fallen an hour later (Fig. 4) are characterized with the structure more typical for lower temperature conditions of snow formation. The change in shape is accompanied with growth of radar reflectivity at the upper level of 6 km (Fig. 3). Apparently, the snow formation area was situated in the upper, colder area of clouds, which results in the snowflakes shape. On the other hand, the fine reflectivity profile

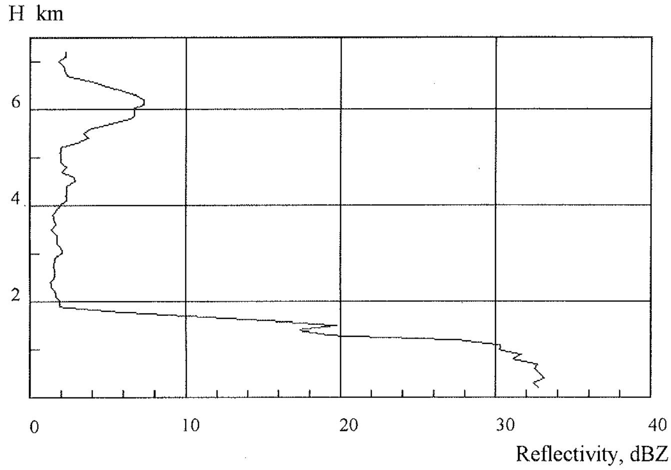

Fig. 3. The vertical radar reflectivity profile of snowfall averaged over an hour (120 sequential profiles), January 10, 1997, 10 : 00-11 : 00 UTC, St. Petersburg.

Fig. 4. The close-up picture of snowflakes on the surface, January 10, 1997, exposure time 10 : 30-10 : 32 UTC, St. Petersburg.

could indicate the snowflake shape to be expected. That period of time from 09 : 40 to 10 : 10 UTC was characterized with steep change of the surface parameters as well.

5. Conclusions

Supplementing a conventional meteorological radar with the simple interface unit combined with modification of radar reflectivity assessment algorithm makes possible vertical profiling with high temporal and spatial resolution along the distant vertical line. The profiling permits to analyze and correlate fine reflectivity detalils with precipitation particles structure. That suggests potential of conventional radar for applications to remote precipitation analysis both separately or combined with validation problems.

Acknowledgments

The authors would like to acknowledge gratefully Dr. Y. Asuma, Hokkaido University, Dr. N. Grigorov, Mr. G. Sviridov and Mr. A. Semakin, Russian State Hydrometeorological Institute, for help at various stages of hardware and software development, data acquisition and analysis. This work has been supported by the Ministry of Education, Science, Sports and Culture of Japan.

References

Dulevich, V. (Ed.), 1970. Theoretical fundamentals of radio-location. Moscow, Sovetskoe Radio (in Russian).

Skolnik, M. (Ed.), 1976. Handbook on radio-location. Moscow, Sovetskoe Radio (in Russian).