Processing algorithms for finding the boundaries of areas of dangerous wind shear for on-board weather radar

Yu A Novikova and M B Ryzhikov
Saint-Petersburg State University of Aerospace Instrumentation, 15, Gastello street, Saint-Petersburg, Russia

1 E-mail: Nov-Jliana@yandex.ru

Abstract. This report considers the results of the development of algorithms for processing radar data when working in the mode of detecting dangerous areas of wind shear, which use binary values of hazard signs in each direction of sensing as input parameters, are presented. The first of them implements data processing for each individual direction, and the second - joint processing in all directions. As a result of their work, it is possible to identify dangerous areas of wind shear that meet the spatial requirements of the international standards ARING-708A and DO-220.

1. Introduction
Improving the safety of small aircraft flights at low altitudes, as well as at the take-off and landing stages, is directly related to the introduction of a small-sized weather radar station that warns about the presence of dangerous phenomena along the flight path: thunderstorms, turbulence, wind shear [1-4]. The applied algorithms for processing the radar signal [5] are aimed at obtaining data on the radial velocity of wind flows in each range cell in the horizontal plane located at the flight altitude. To quantify the degree of danger of wind shear, the value is introduced [6]:

\[ F = F_h + F_v = \frac{U'}{g} - \frac{W}{V_a}; \quad F_h = \frac{U'}{g}; \quad F_v = -\frac{W}{V_a}, \]

where \( U' \) is the acceleration for horizontal flow motion (\( \text{m}/\text{s}^2 \)), \( g \) is the acceleration of gravity (\( \text{m}/\text{s}^2 \)), \( W \) is the vertical component of the air flow velocity (\( \text{m}/\text{s} \)), \( V_a \) is the air velocity of the aircraft (\( \text{m}/\text{s} \)). Negative values of \( F \) have a beneficial effect on the aerodynamic properties of the aircraft, as opposed to positive ones. They are the basis for calculating the hazard assessment for the range cell with the number \( n \) [5]

\[ FBAR_n = \frac{1}{B+1} \sum_{b=n-0.5N}^{b=n+0.5N} F_k, \]

where \((B+1)\) is an odd number of range cells, the total length of which is close to 1 km in space, \( b \) – the numbers of cells in the sliding window in which the averaging is taking place. For glider aircraft flights, the wind shear hazard threshold is recommended to be equal to \( Thr=0.13 \). As a result, for each range cell, the rule of forming a binary danger value is used.
This article presents the results of the development of an algorithm for further information processing, which is aimed at obtaining data on the presence of dangerous areas in cases of asymmetric or multiple areas of wind shear. Its necessity is due to the fact that according to the standards DO-220 and ARING-708A and, any detected and visualized hazardous area must meet the following spatial requirements: the radial length of the horizontal section of the wind shear area must be at least 750 meters; the horizontal cross-sectional area of the wind shear area should be at least 0.2 km².

In addition to them, it is logical to form other additional requirements for combining multiple wind shear areas into one, provided that they are close. This processing includes processing an array of binary data received per radar frame. The following data processing algorithm does not require storing and processing the entire binary array, which, according to the requirements of the standard ARING-708A, contains more than 15000 elements (512 elements of range cells and about 30 or more azimuthal directions). It is implemented by forming data matrices that initially contain only the values Bin\textsubscript{WS}\textsubscript{a}=1 of the near and far boundaries of the intervals, containing values for each subsequent scanning direction in the viewing area, determined by the ordinal number \(j\).

2. Algorithms for processing data in one direction and for frame

The algorithm presented below serves both for combining adjacent intervals in range, and for removing those intervals whose length is \(R_{\text{max}}-\delta R \Delta N \leq 750\) meters (\(\delta R\) – the length of one cell in range, \(\Delta N\)– the number of range cells). In addition, the parameter sum is set – the module of the difference between the numbers of the range cells. It meets the criterion of combining hazard intervals if the distance between the nearest extreme elements of the intervals is less sum. As a result of the work of the algorithm, the following data is generated: \(N_{\text{new}_{i,j}}\) – a matrix that contains in each row the numbers of the range cells corresponding to the near boundaries of the range interval with a number \(i\) for the scanning direction with a number \(j\); \(F_{\text{new}_{i,j}}\) – matrix that contains the numbers of the range cells corresponding to the far boundaries of the range interval; \(L_{\text{new}_{i,j}}\) – matrix that contains the number of range cells in the interval with a number \(i\) for the direction of scanning with a number \(j\); \(V_{\text{new}_{i,j}}\) – vector that contains the number of range intervals for the scanning direction with a number \(j\). Here is a description of the developed algorithm for processing all range cells (with a number \(N_{\text{max}}\)) in one scanning direction. The algorithm in the form of pseudocode is presented.

\[
Bin_{n} = \begin{cases} 
1 & \text{if } FBAR_{k} \geq Thr; \\
0 & \text{if } FBAR_{k} < Thr.
\end{cases}
\]

\[
k = -1; \quad t = 0; \quad \text{If } Bin_{0} = 1 \quad \text{then } k = k + 1; \quad L_{k} = t + 1; \quad \text{EndIf}
\]

\[
\text{FOR } n = 1 \quad \text{up to } n = N_{\text{max}} - 1;
\]

\[
\text{If } Bin_{n} = 1 \quad \text{and } Bin_{n+1} = 1 \quad \text{then } t = t + 1; \quad L_{k} = t + 1; \quad \text{EndIf}
\]

\[
\text{EndFOR}
\]

\[
K_{\text{new}} = k + 1; \quad \text{If } K_{\text{new}} > 0 \quad \text{then } k = -1; \quad \text{If } Bin_{0} = 1 \quad \text{then } k = 0; \quad \text{Near}_{k} = 1; \quad \text{EndIf}
\]

\[
\text{FOR } n = 1 \quad \text{up to } n = N_{\text{max}} - 1; \quad \text{If } Bin_{n} = 1 \quad \text{and } Bin_{n+1} = 1 \quad \text{then } k = k + 1; \quad \text{Near}_{k} = n + 1; \quad \text{EndIf}
\]

\[
\text{EndFOR}
\]

\[
K_{\text{new}} = k + 1; \quad \text{If } K_{\text{new}} > 1 \quad \text{then } FOR \quad t = 1 \quad \text{up to } t = N_{\text{max}} - 1; \quad \text{If } L_{k} < 0 \quad \text{then break} \quad \text{EndIf}
\]

\[
\text{FOR } k = 1 \quad \text{up to } k = N_{\text{max}} - 1; \quad a = a + 1; \quad s = \Delta \text{sum} + 1;
\]

\[
\text{If } L_{k} \geq s \quad \text{or } L_{k+1} \geq s \quad \text{and } \quad \text{Near}_{k} - 1 - \text{Far}_{k+1} \leq s \quad \text{then } e = e + 1; \quad \text{Far}_{k+1} = 0; \quad L_{k+1} = \text{Far}_{k-1} - \text{Near}_{k-1} + 1;
\]

\[
\text{FOR } i = k \quad \text{up to } i = k + 1; \quad \text{If } i + 1 \leq K_{\text{new}} - 1 \quad \text{then } \text{Far}_{i} = \text{Far}_{i+1}; \quad \text{Near}_{i} = \text{Near}_{i+1}; \quad L_{i} = L_{i+1}; \quad \text{EndIf}
\]

\[
\text{EndFOR}
\]

\[
K_{\text{new}} = K_{\text{new}} - a; \quad e = 0; \quad i = -1; \quad \text{FOR } k = 0 \quad \text{up to } k = N_{\text{max}} - 1;
\]

\[
\text{If } L_{k+1} \geq \Delta \quad \text{then } \quad i = i + 1; \quad N_{\text{new}_{i,j}} = \text{Near}_{i}; \quad F_{\text{new}_{i,j}} = \text{Far}_{i}; \quad L_{\text{new}_{i,j}} = L_{k};
\]

\[
e = e + 1; \quad V_{\text{new}_{j}} = e; \quad \text{EndIf}
\]

\[
\text{EndFOR}
\]

\[
K_{\text{new}} > 0.
\]
The algorithm can be used to structure data streams of the same type with distances between information features in time, wavelength or frequency [7-9].

After receiving the data in each direction of the scan, it should be made sure that the area of the wind shear area allocated for flight exceeds the value \( S_{\min} = 0.2 \, \text{km}^2 \). In addition, for each selected danger area, coordinates should be given in the form of the near and far boundaries by range, as well as the right and left boundaries by angular coordinates to form the final image of wind shear area on the sector scan in the coordinates “range” – “azimuth of scanning”. In the course of data analysis, it is necessary to combine areas that are separated from each other by a distance \( \Delta D \leq 1 \, \text{km} \). The number of range cells that corresponds to this distance will be \( \Delta n_r = \text{ceil}(\Delta D \, \delta R^1) \).

The algorithm determines the output matrix of the following data: \( D_{k,0} \) and \( D_{k,1} \) – the near and far borders of the hazard area with an ordinal number (in meters); \( D_{k,2} \) and \( D_{k,3} \) – the right and left borders of the hazard area with an ordinal number (in radians). The scanning law is given by the relations:

\[
\alpha(j) = \alpha_{\min} + j \Delta \alpha; \quad j \in \{0; N_a - 1\},
\]

\( \alpha_{\min} \) – the minimum value of the angle of the viewing area; \( \Delta \alpha \) – the scanning step along the angle in the viewing area; \( j \) – the step number; \( N_a \) – the total number of angular directions. The following is an algorithm for processing data from all angular directions in the viewing area, written as a pseudocode.

\[
p = -1; \, NN = 0; \text{FOR} \ j = 0 \ \text{up to} \ j = N_a - 1; \quad NN = NN + Vnew_j;
\]

\[
\text{If } Vnew_j > 0 \ \text{then FOR} \ k = 0 \ \text{up to} \ k = Vnew_j - 1; \quad p = p + 1; \quad \text{FarFr}_{p,0} = \text{Far\_new}_{k,j}; \quad \text{FarFr}_{p,1} = j;
\]

\[
\text{NearFr}_{p,0} = \text{Near\_new}_{k,j}; \quad \text{NearFr}_{p,1} = j; \quad \text{EndFOR} \ \text{EndIf} \ \text{EndFOR}
\]

\[
\text{If } NN = 0 \ \text{then} \ D_{k,0} = 0; D_{k,1} = 0; D_{k,2} = 0; D_{k,3} = 0; \quad \text{EndIf}
\]

\[
\text{If } NN > 0 \ \text{then}
\]

\[
\text{FOR} \ k = 0 \ \text{up to} \ k = NN - 1; \quad \text{FOR} \ p = 0 \ \text{up to} \ p = NN - 1;
\]

\[
\text{If } p = k \ \text{then} \ Mra_{p,k} = k + 1; \quad \text{EndIf} \ a = \text{FarFr}_{p,1}; \quad b = \text{FarFr}_{k,1};
\]

\[
\text{If } |a - b| \leq 1 \ \text{then}
\]

\[
\text{NearFr}_{p,0} - 1 \leq \text{FarFr}_{k,0} \leq \text{FarFr}_{p,0} + 1 \ \text{or} \ \text{NearFr}_{k,0} - 1 \leq \text{FarFr}_{p,0} \leq \text{FarFr}_{k,0} + 1 \ \text{then}
\]

\[
Mra_{p,k} = k + 1; \quad \text{EndIf} \ c = |\text{NearFr}_{p,0} - \text{FarFr}_{k,0}|; \quad d = |\text{NearFr}_{k,0} - \text{FarFr}_{p,0}|;
\]

\[
\text{If } 1 < c \leq \Delta nr \ \text{or} \ 1 < d \leq \Delta nr \ \text{then} \ Mra_{p,k} = k + 1; \quad \text{EndIf} \ \text{EndFOR} \ \text{EndFOR}
\]

\[
\text{FOR} \ z = 0 \ \text{up to} \ z = NN - 1; \quad \text{FOR} \ i = 0 \ \text{up to} \ i = NN - 1; \quad k = z + 1;
\]

\[
\text{If } k \leq NN - 1 \ \text{then} \ j = z + 1 \ \text{up to} \ j = NN - 1;
\]

\[
\text{If } Mra_{z,j} = Mra_{j, z} \ \text{and} \ Mra_{z,j} \neq 0 \ \text{then FOR} \ k = 0 \ \text{up to} \ k = NN - 1;
\]

\[
\text{If } Mra_{j,k} \neq 0 \ \text{then} \ Mra_{j,k} = \text{Mra}_{j,k}; \quad Mra_{j,k} = 0; \quad \text{EndIf} \ \text{EndFOR} \ \text{EndFOR}
\]

\[
\text{EndFOR} \ \text{EndIf} \ \text{EndFOR} \ \text{EndFOR}
\]

\[
g = -1; \quad \text{FOR} \ k = 0 \ \text{up to} \ k = NN - 1; \quad \text{FOR} \ m = 0 \ \text{up to} \ m = NN - 1;
\]

\[
\sum_{m=0}^{NN} Mra_{k,m} \neq 0 \ \text{then} \ g = g + 1; \quad \text{FOR} \ z = 0 \ \text{up to} \ z = NN - 1; \quad M_{z,t} = Mra_{k,z};
\]

\[
\text{EndFOR} \ \text{Break} \ \text{EndIf} \ \text{EndFOR} \ \text{EndFOR}
\]

\[
Nnew = g + 1; \quad \text{MaxFar} = 0;
\]

\[
\text{FOR} \ k = 0 \ \text{up to} \ k = Nnew - 1; \quad \text{Max} = 0; \quad \text{FOR} \ m = 0 \ \text{up to} \ m = NN - 1;
\]

\[
\text{If } M_{k,m} \neq 0 \ \text{and} \ \text{FarFr}_{m,0} \geq \text{Max} \ \text{then} \ \text{Max}_k = \text{FarFr}_{m,0} - 1; \quad \text{Max} = \text{FarFr}_{m,0}; \quad \text{EndIf}
\]

\[
\text{If } \text{Max} \geq \text{MaxFar} \ \text{then} \ \text{MaxFar} = \text{Max}; \quad \text{EndIf} \ \text{EndFOR} \ \text{EndFOR}
\]
FOR \( k = 0 \) up to \( k = \text{Nnew} - 1 \); \( \text{Min} = \text{MaxFar} \);

FOR \( m = 0 \) up to \( m = \text{NN} - 1 \);
If \( M_{k,m} \neq 0 \) and \( \text{NearFr}_{m,0} \leq \text{Min} \) then
\( \text{MinI}_k = \text{NearFr}_{m,0} - 1 \); \( \text{Min} = \text{NearFr}_{m,0} \); EndIf
EndFOR
EndFOR

FOR \( k = 0 \) up to \( k = \text{Nnew} - 1 \); \( \text{Max} = 0 \); FOR \( m = 0 \) up to \( m = \text{NN} - 1 \);
If \( M_{k,m} \neq 0 \) and \( \text{FarFr}_{m,1} \geq \text{Max} \) then \( \text{MaxJ}_k = \text{FarFr}_{m,1} - 1 \); \( \text{Max} = \text{FarFr}_{m,1} \) EndIf
EndFOR
EndFOR

FOR \( k = 0 \) up to \( k = \text{Nnew} - 1 \); \( \text{Min} = \text{N}_{\alpha} - 1 \); FOR \( m = 0 \) up to \( m = \text{NN} - 1 \);
If \( M_{k,m} \neq 0 \) and \( \text{NearFr}_{m,1} \leq \text{Min} \) then \( \text{MinJ}_k = \text{NearFr}_{m,1} - 1 \); \( \text{Min} = \text{NearFr}_{m,1} \) EndIf
EndFOR
EndFOR

FOR \( k = 0 \) up to \( k = \text{Nnew} - 1 \);
\( g = -1 \); FOR \( k = 0 \) up to \( k = \text{Nnew} - 1 \);
\( S = 0.5 \Delta \alpha \left( \text{MaxI}_k^2 - \text{MinI}_k^2 + 2 (\text{MaxI}_k - \text{MinI}_k) \right) \delta R^2 (\text{MaxJ}_k - \text{MinJ}_k + 1) \); 
If \( S \geq S_{\text{min}} \), then \( g = g + 1 \); \( \text{D}_{g,0} = \text{MinI}_k \delta R; \text{D}_{g,1} = \text{MaxI}_k \delta R; \text{D}_{g,2} = \alpha (\text{MinJ}_k); \text{D}_{g,3} = \alpha (\text{MaxJ}_k) \) EndIf
EndFOR
EndFOR

\( NN > 0 \).

The algorithm can be used to combine matrix data of the same type with different distances between information features in time, wavelength or frequency [10-13].

3. Simulation results
Verification of the correctness of the implementation of the developed algorithms was carried out by modeling the case of detecting several binary areas of dangerous wind shear.

![Figure 1. The initial field of wind flows and the boundaries of the initial areas of wind shear and the boundaries of the areas selected as a result of the algorithms.](image)

Figure 1 shows the boundaries of the initial wind shear regions of various lengths and areas, and the dotted rectangles show those boundaries that are highlighted as a result of the work of the developed algorithms that meet the spatial hazard criteria presented in ARING-708A and DO-220.

4. Conclusion
A processing algorithm has been developed for the detection of dangerous areas of wind shear in the onboard meteorological radar. It is implemented in each direction of sensing and uses as input a binary vector for a given threshold of the wind shear hazard coefficient. As a result of his work, closely spaced hazard intervals are combined into one interval and those whose length is less than 750 meters are filtered. The output data obtained in one direction of sensing are only the near and far boundaries for each selected interval.
An algorithm has been developed that starts upon completion of probing in all directions of the radar viewing area. It serves to highlight the boundaries of dangerous areas of wind shear with a proximity check for combining and filtering those that have an area of less than 0.2 km$^2$. Its input data is data on the boundaries of the intervals for each direction of sensing.

It is shown by mathematical modeling that when processing multiple areas of wind shear, the boundaries of only dangerous areas that meet the spatial requirements of international standards ARING- 708A and DO-220 are distinguished.

Acknowledgement
The work was supported by the Russian Foundation for basic research (RFBR, project No. 19-07-00205)

References
[1] Ryzhikov M B, Novikova Y A, Kucherova E V and Kulik R V 2019 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF) 8840584 1-5
[2] Kryachko A F, Novikova Y A, Ryzhikov M B and Kucherova E V 2019 Research of perspective materials for thin optical films for the mid-IR Inter. Sem. on Electron Devices Design and Product (Prague: IEEE) 8798436 1-4
[3] Bestugin A R, Ryzhikov M B, Novikova Y A and Kirshina I A 2021 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF) 947069
[4] Bestugin A R, Ryzhikov M B, Novikova Y A and Kirshina I A 2020 J. Achievements of Modern Radioelectronics 74(11) 23-9
[5] Wang L, Liu Y and Su D 2019 International Conference on Meteorology Observations (ICMO) Chengdu China 1-5
[6] Proctor F, Hinton D and Bowles R 2020 Range and Aerospace Meteorology Orlando Florida American Meteorology Society 482-7
[7] Kotlikov E N, Novikova Y A and Tereshchenko G V 2020 IOP Conf. Ser.: Materials Science and Engineering 919(2) 022033
[8] Novikova Y A 2019 J. of Phys: Conf. Ser. 1399(2) 022042
[9] Kotlikov E N and Novikova Y A 2013. J. of Optic. Techn. (A Translation of Opticheskii Zhurnal) 80(9) 571-6
[10] Kryachko A F, Novikova Y A, Ryzhikov M B and Kucherova E V 2019 Research of perspective materials for thin optical films for the mid-IR Inter. Sem. on Electron Devices Design and Product. (Prague: IEEE) 8798436 1-4
[11] Bestugin A R, Krasyuk V N and Ryzhikov M B 2014 J. Radioelectr. and Comm. Syst. 57(11) 495-501
[12] Vaganov M A and Novikova Y A 2020 IOP Conf. Ser.: Materials Science and Engineering 862(2) 022028
[13] Bestugin A R, Ryzhikov M B, Svanidze V G and Novikova Y A 2019 Proc. of the Antennas Design and Measurement Int. Conf. (Saint-Petersburg: LETI) 8969300 67-71