Detection of turbulence generated by convective motions by an X-Band Doppler Radar: The DTCOR Method

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I. INTRODUCTION

Atmospheric turbulence, a scientific subject that challenges many research fields, has a direct impact on aviation safety and thus deserves a close investigation.[Proctor 2002]

Indeed, one of the most leading causes of in-flight injuries is atmospheric turbulence. The current state of the art of turbulence detection with radar doesn't efficiently detect and quantify aircraft turbulence hazards in areas characterized by small radar reflectivities[Hamilton 2002].

The present work is devoted to the development and evaluation of a new real-time detection method of turbulent structures generated by convection using Doppler information from an X-band radar. The typical size of these turbulent structures, whose impacts on aircrafts are meaningful, ranges between 100m and 3000m. These turbulent structures result from gravity waves triggered by convective activity and propagating horizontally outside this area far away (till several tens of kilometers).

This method is referred to hereafter as DTCOR (Detection of COnvective Turbulence by Radar) and described in Section II. Preliminary evaluation of the method is presented in Section III.

II. PRINCIPLE OF DTCOR:

The present version of the method considers that radar signals are available in the zone of turbulence. This version 1 of DTCOR can be described in three steps which in fact are performed simultaneously by using a variational mathematical formalism.

The first step retrieves the horizontal components of the wind (U,V) and the divergence term DIV= dU/dx + dV/dy from radial velocity measurements in a retrieval domain D located in front of the aircraft and in an horizontal sectorial scan (with null fixed elevation) performed by the radar. The distance of this zone D from the aircraft is chosen to allow a sufficient detection time of the turbulence prior to its penetration. The method also estimates the stretching deformation (DET= dU/dx - dV/dy) and the shearing deformation (DES= dU/dy + dV/dx) which can be also used to detect shearing zones produced by density currents or downbursts produced by storms (these zones can suddenly change the lift force during a landing). In the following, we will only consider the wind and the divergence components which can be used as a first alarm of strong turbulence (by a strong variability).

The horizontal components of the wind (U, V), the divergence (DIV), and the shearing deformation (DES) are retrieved by least square minimization between the radial velocities in the domain D and the analytical form of these radial velocities using a linearity assumption for the horizontal wind in the domain D (other assumptions such as quadratic or sinusoidal winds will be considered in the future). The interest of this assumption is that it requires a very low computational cost in agreement with the required real-time constraint.

Under this assumption, we can write the analytical form of the radial velocity:

$$Vr_i = \left(U_0 + U'_x(x_i - x_0) + U'_y(y_i - y_0)\right)\cos(az_i) + \left(V_0 + V'_x(x_i - x_0) + V'_y(y_i - y_0)\right)\sin(az_i) \quad (2.1)$$

with (x_0 , y_0) the coordinates of the centre of the domain D, (U_0 , V_0) the horizontal wind at the point (x_0 , y_0), U'_x, V'_x, U'_y and V'_y are first derivatives of U and V with respect to x and y respectively.

This Equation (2.1) can be rewritten:

$$Vr_i = b_1\cos(az_i) + b_2\sin(az_i) + b_3(x_i - x_0)\cos(az_i) + b_4(y_i - y_0)\cos(az_i) + b_5(x_i - x_0)\sin(az_i) + b_6(y_i - y_0)\sin(az_i) \quad (2.2)$$

where $b_1 = U_0$, $b_2 = V_0$, $b_3 = U'_x$, $b_4 = U'_y$, $b_5 = V'_x$, $b_6 = V'_y$

We can show that the only attainable terms are b1, b2, b3, b6 and (b4+b5).

To obtain these b_k and thus the two components of the wind U,V, DIV, DES and DET a least square minimization is done between the measured radial velocities Vr_i in the domain D and the analytical form of these radial velocities expressed by eq (2.2):

$$S = \sum_i \left(\hat{V}r_i - Vr_i\right)^2 \quad (2.3)$$

This minimisation of S with respect to the unknown bk ($\frac{\partial S}{\partial b_1} = 0$, $\frac{\partial S}{\partial b_2} = 0$,…and $\frac{\partial S}{\partial b_6} = 0$) leads to a linear system of M equations writing as: A.B= C

Where:

A is a matrix containing analytical information (MxM)

B is a vector of the unknown parameters (1xM)

C is a vector containing measured radial velocities (1xM).

The second step used the mass continuity equation for ice (or water) content Q derived from the measured radar reflectivity Z using an empirical relation (Q(Z)). This equation can be written:

$$\frac{DQ}{DT} = \frac{dQ}{dt} + U\frac{dQ}{dx} + V\frac{dQ}{dy} + (W - V_T)\frac{dQ}{dZ} = 0 \quad (2.4)$$

Where V_T is the terminal velocity of fall also derived from Z.

The simplified assumption used to establish this equation is that the process of condensation or evaporation is slow compared to the radar sampling time scale. Other

simplifications of this equation can be also considered according to the magnitude of horizontal variations of Q compared to vertical ones.
Thus this equation allows us to estimate W from the two wind components, U and V, and from two measurements of Z in time and according to the vertical.
In this case, two sectorial scans with two distinct elevations or several successive scannings during the aircraft flight are needed.
The last and third step consists in using the continuity equation of air mass linking the vertical wind W to horizontal divergence DIV:

$$\frac{dW}{dz} - \frac{W}{H} = DIV \quad \text{where H is a height scale.}$$

These three steps are performed simultaneously using a variational formalism with constraints (least square minimization of radial velocity, mass continuity equation Q and continuity equation).

III. RESULTS AND CONCLUSIONS

To evaluate DTCOR, a software simulating the aircraft flight pattern and the radar sampling has been developed. This software generates radial velocities from given wind and reflectivity fields verifying the previous physical constraints. An example of evaluation is given in the following. Others examples using more complicated fields deduced from numerical simulations performed using a cloud-system-resolving model will be discuss during the conference.
The total considered domain is

$$x \in [x_{\min}, x_{\max}] = [0,75] \quad (km)$$
$$y \in [y_{\min}, y_{\max}] = [-40,40] \quad (km)$$
$$z \in [z_{\min}, z_{\max}] = [0.19,7.89] \quad (km)$$

The resolutions of the grid following x, y and z are respectively, $\Delta x = 0.5km$, $\Delta y = 0.5km$ and $\Delta z = 0.35km$.
The used three-dimensional wind field is [Protat 1998]:

$$U = A_1(1-\frac{z}{H})\sin(\frac{2\pi}{\lambda}x)$$

$$V = A_2(1-\frac{z}{H})\sin(\frac{2\pi}{\lambda}y)$$

$$W = z\left[\left(\frac{2\pi A_2}{\lambda}\sin(\frac{2\pi}{\lambda}y)\right)-\left(\frac{2\pi A_1}{\lambda}\sin(\frac{2\pi}{\lambda}x)\right)\right]$$

Where: H is scale height; A1 and A2 are constants to be defined; λ is a wavelength taken in the interval of turbulence between 50m and 3000m (the wavelength where a plane is most sensitive is around 400m).
This illustration will be given using the following parameters: A1 = A2=5m/s H = 8km and λ = 40km.
-The radar is in front of the aircraft
-The characteristics of the scanning are:
- Horizontal sectorial scanning
-Sampling in azimuth: -30° to 30° by step of 3°
-Elevation fixed to 0°.
The figure1 gives on a horizontal cross section the corresponding three-dimensional field on the total sampled domain.
Figure 2 give the retrieved wind field (in blue) superimposed on the initial one in the domain D of 8km x 8km centred at (x_0, y_0) = (40, 0) (i.e. 40km ahead of the aircraft).
As explained previously, the assumption used in the present retrieval is the linearity of the wind field in D. The validity of this assumption is of course mainly dependent on the size of D compared to the considered wavelengths and sensitivity of the retrieval accuracy to this size is presently being evaluated and will be discussed at the conference. The quality of this retrieval depends also on the co-linearity of the radial velocities in this domain D and thus depends on the size of D and its distance to the radar.
Figure 2 shows a good agreement between the simulated and retrieved wind field even if some significant differences are observed in some places, owing to departures from the linear assumption (because the first derivatives of the initial wind are not constant but are sinusoidal).
The quality of the retrieval can be improved using several scans carried out by the radar during the aircraft flight.

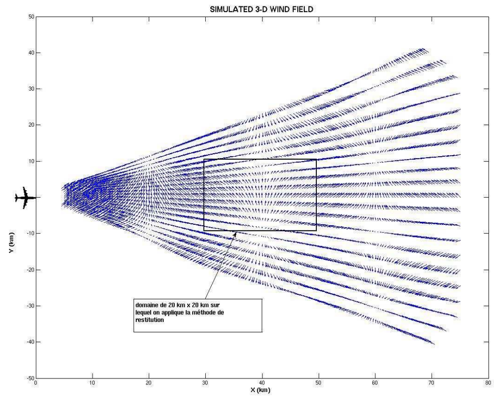

FIG. 1: Horizontal cross section of three dimensional fields

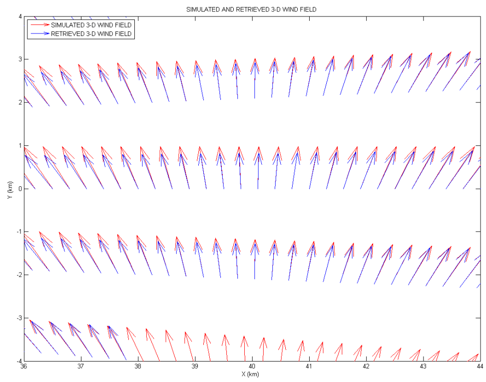

FIG. 2: Horizontal cross section of retrieved and simulated field

V. REFERENCES

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