Electromagnetic wind radar simulator validation using meteorological data and a zenith X-band radar

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***Abstract*—this paper presents the validation of an electromagnetic radar simulator based on Large Eddy Simulations of the turbulent atmosphere. The simulator has been developed by UCL in the frame of the FP7 UFO project aimed at improving the Wake-Vortex Advisory Systems by the analysis, design and development of innovative technologies for Ultra-Fast Radar and Lidar used as wind and Eddy Dissipation Rate sensors. Experimental trials have taken place at Toulouse airport giving access to concurrent collocated X-band radar data and meteorological data. The simulator is validated against radar and meteorological values of Eddy Dissipation Rate, showing a good agreement, with a trend to have meteorological values somewhat higher than radar measured and simulated values.**

***Keywords*—Wind radar simulator; turbulence, Eddy dissipation rate**

I. Introduction

The UFO FP7 project (Ultra Fast wind sensOrs) [1] [2] was aimed at improving the Wake-Vortex Advisory Systems by the analysis, design and development of innovative technologies for Ultra-Fast Radar and Lidar used as wind and Eddy Dissipation Rate ($\varepsilon^{1/3}$) sensors. These sensors are used for Wake-Vortex hazards mitigation but also for wind sensing and more specifically cross-wind, air turbulence and wind-shear detection on runway for increasing the aviation safety and reducing the safety margin of wake vortex separation between aircrafts during landing and take-off. Experimental trials have taken place at Toulouse and Munich airports.

In the frame of the project, UCL has developed a radar electromagnetic simulator for RCS (radar cross-section), wind and EDR ($\varepsilon^{1/3}$) retrieval, in clear air and in the presence of rain. The simulator is based on refractive index calculated from Large Eddy Simulations (LES) of the turbulent atmosphere in the boundary layer, for selected values of $\varepsilon^{1/3}$ representing various turbulence intensity, and Brunt-Vaïsala frequency (N) representing stratification levels. The refractivity is then used for the calculation of the radar cross-section of the turbulences as well as the power received by the radar and the Doppler spectrum.

Using the same X-band radar for the detection of the wake vortices and wind necessitates a careful analysis of the signal received by the radar in clear air due to its low value. The feasibility of using radar and Lidar for the detection of wake vortices and the determination of Eddy Dissipation Rate has been shown experimentally [3][4]. The wind measurement in clear air being the critical point, only clear-air simulation is validated in this paper.

During the measurement campaign in April –May 2014 at the Toulouse airport, various radar and Lidar data were made available, as well as meteorological data from various sources, the most complete source being issued from high resolution Weather Forecast model of Meteo France (MHRPS, HARMONIE) [14]. The originality of this paper is to present the validation of the radar electromagnetic simulator in clear air using refractive index calculated from Large Eddy Simulation of turbulent atmosphere with respect to Meteo France meteorological data and data from a vertically pointing CURIE X-band radar from LATMOS [5]. In a second phase, the simulator will be compared with the measurements of the Thales radar at low elevation and further used to determine the limit of detection of the radar in clear air.

A similar electromagnetic model has been developed and tested by UCL [9] and by ONERA [6] for the simulation of radar signal backscattered by wake vortices, using a simplified flow model.

II. Electromagnetic wind radar simulator based on LES data

A. *Large Eddy Simulation of the turbulent atmosphere*

The Large Eddy Simulation (LES) used in the UFO project provides realistic velocity, pressure, temperature and humidity fields to the electromagnetic simulator in order to simulate time series of the radar signal. Simulations are performed in a periodic domain and are then restricted to stable stratification classes. Unstable stratification generates convective instabilities that can span over the whole boundary layer and cannot be represented in a periodic box. This is a limitation with respect to the atmospheric conditions encountered during the trials. It is however expected that in the absence of plumes and large vertical instabilities, the stable stratification hypothesis will not be too restrictive. The LES model used has been developed by De Visscher and Winckelmans [7] for the study of the effect of turbulence on wake vortices. It has been extended in the frame of this project, to take into account the humidity transport and the presence of raindrops (not presented in this document). The input parameters of the model are the characteristics of the turbulence: turbulence intensity represented by the Eddy Dissipation Rate ($\varepsilon^{1/3}$) and stratification represented by the Brunt-Vaïsala frequency (N). Only a few combinations of parameters (Table I) have been simulated due to the computer time and space needed.

TABLE I. MATRIX OF THE LES SIMULATIONS

$\varepsilon^{1/3}$ (m^2/s^3)	N (s^{-1})		
	2.55 10^{-3}	***8.91 10^{-3}***	***1.27 10^{-2}***
2.15 10^{-2}	Case 1	Case 4	Case 6
7.93 10^{-2}	Case 2	Case 5	
2.15 10^{-1}	Case 3		

Before comparison with the radar measured data available in the trial data set, the actual atmospheric parameters ($\varepsilon^{1/3}$ and N) have to be carefully checked to select time periods corresponding to the simulated LES cases.

The LES simulations only represent the fluctuations, the mean values of the parameters have to be added using mean profiles, at the altitude of observation. The size of the LES simulation box has been chosen as L=200m, in order to have a sufficiently large domain with a reasonable resolution of 0.78m. 60s of continuous LES simulation with time step of 1s is available for each case. Higher resolution should necessitate too large storage capacity and computation time.

B. Radar backscattering of the turbulent atmosphere

The refractive index is calculated, using the pressure, temperature and humidity fields coming from the LES calculation, using the ITU-R formula [8]:

$$n = 1 + N * 10^{-6} = 1 + \left(\left(\frac{77.6}{T}\right) * \left(P + 4810\frac{e}{T}\right)\right) * 10^{-6} \quad (1)$$

where P and e are the atmospheric pressure and the water vapor pressure in hPa and T is the absolute temperature in K.

The electromagnetic field emitted by the radar is backscattered by irregularities of the boundary layer, more specifically eddies of the turbulent boundary layer. The Bragg scattering indicates that the radar is sensible to variations of the refractive index of the order of magnitude of half the radar wavelength. The model developed by UCL for the calculation of the backscattering of wake vortices [9] has been extended to be applied to the present application [12]. The method of Li used for the evaluation of the oscillatory integral is heavy and the method proposed by Muschinski [10] has been implemented in order to decrease the computation time. Muschinski starts from the expression of the time series of phase coherent complex signal received by the radar developed by Doviak and Zrnic [11],

$$I(t) = A\int W(r)n'(r,t)e^{-ik_B r_t}d^3r \quad (2)$$

where $W(r)$ is the radar's three-dimensional one-way weighting function, $n'(r,t)$ is the field of refractive index irregularities at time t in the radar resolution volume, k_B is the Bragg wave number and r_t is the distance between the integration point and the radar. The integral in (2) is rapidly oscillating. Assuming that the LES grid cells are much smaller than the radar resolution volume, $I(t)$ can be written as the sum of the contributions of each LES cell and, assuming the statistical independence of the phases of the various contributions in the radar resolution cell, the final formula is proposed [10]

$$I(t) = A\sqrt{0.033k_B^{-11/3}}\sum_{p=1}^{N} W_p\sqrt{[C_n^2(t)]_p V_p}\,e^{-j\varphi_p(t)} \quad (3)$$

$$C_n^2 = \frac{\langle[n(r+\delta)-n(r)]^2\rangle}{|\delta|^{2/3}} \quad (4)$$

where A is a constant linked to the radar parameters, W_p is the value of $W(r)$ in the LES cell of volume V_p.

$$A = \frac{G}{\lambda r_0^2}\sqrt{\frac{P_t}{2R}} \quad (5)$$

G is the antenna gain, λ is the radar wavelength, r_0 is the distance between the radar and the center of the radar resolution cell, P_t is the emitted power, R is the receiver resistance, V_p is the volume of the LES grid cell, C_n^2 is the refractive index structure function and $\varphi_p(t)$ is the phase of the signal backscattered by the p^{th} grid cell. The phase of the contribution of the p^{th} grid cell to the total, during the dwell time of the radar, is calculated as follows

$$\varphi_p(t_0+\tau) = \varphi_{0p} + k_{Bp}\cdot v_p(t_0)\tau \quad (6)$$

Where t_0 is the time of the LES snapshot, φ_{0p} is the initial phase, k_{Bp} is the Bragg wavenumber.

III. DESCRIPTION OF THE TOULOUSE AIRPORT DATASET USED FOR THE VALIDATION

A 2 months trials sensors campaign has been performed at Toulouse Blagnac Airport in the frame of the UFO project [13]. Various sensors and meteorological data were available:

- X-band Radar/1.5 micron Lidar sensors for monitoring Wind/EDR in Glide slope
- X-band Radar & Lidar Profilers by LATMOS for $\varepsilon^{1/3}$ Diurnal cycle study
- In-Situ Measurements of Experimental Techn. Univ. Braunchweig Aircraft
- Mode-S EHS Downlink Data post-processed by Dutch Meteorological Institute (KNMI)
- High Resolution Weather Forecast Models (MHRPS, HARMONIE [14]) made available by Meteo France

A fair comparison with radar simulation using LES data necessitates the knowledge of the state of the atmosphere and more specifically $\varepsilon^{1/3}$ (Energy dissipation rate) and Brunt-Vaïsala frequency (N). Only days where the High Resolution Weather Forecast Models data are available were used because $\varepsilon^{1/3}$ is directly available and N can be calculated; this makes a total of 8 clear days in April and 4 clear days in May during which the LATMOS CURIE radar data are also available. For those days, the time series of potential temperature, humidity, temperature, Turbulent Kinetic Energy (used for estimation of $\varepsilon^{1/3}$) , Brunt-Vaïsala frequency (N) and $\varepsilon^{1/3}$ from Meteo France data have been plotted in order to select the periods of time corresponding to the cases selected for LES simulation (Table

I). An example of such plots is presented in Fig. 1 and 2 for April 10, 2014, with the values of the parameters used in the LES cases described in Table I.

IV. VALIDATION OF THE SIMULATOR

The example shown in figs 1 to 3 is representative of the days available during the measurement campaign: the CURIE radar only detects clear air turbulence when $\varepsilon^{1/3}$ is large (LES cases 2, 3 and 5) and N is low. This happens during the daily hours, between 9 am and 6 pm. The level of reflected power should be large enough to allow an accurate estimation of $\varepsilon^{1/3}$ from the Doppler spectrum. So only the radar data showing a large signal-to-noise ratio are considered for validation of the simulator.

Since the power level of signal received by the radar oscillates in a quite wide range, it is necessary to introduce a signal-to-noise (SNR) threshold to cut off the measurements for which SNR is low. The SNR is directly obtained from the radar measurements because signal and noise levels are available. Time series of SNR for 3 adjacent levels of altitude were averaged in order to filter the variations.

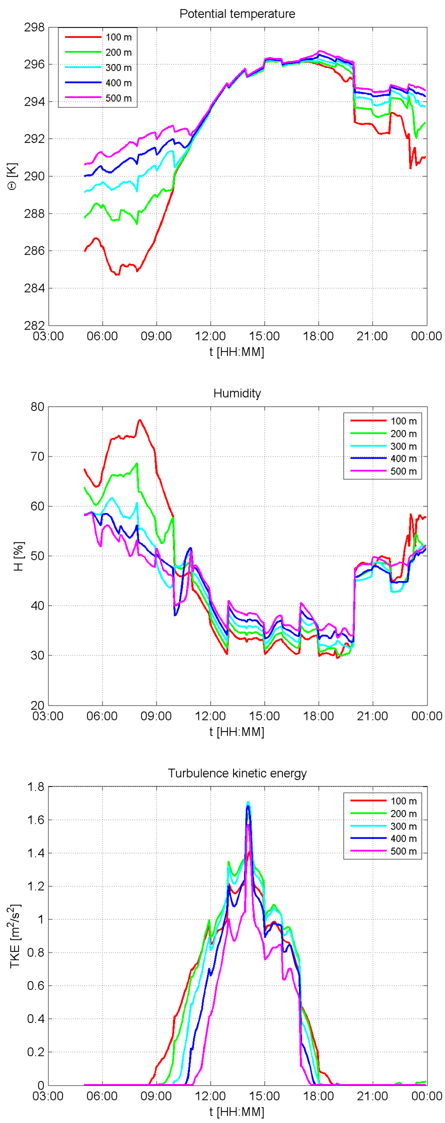

Fig. 1. Potential temperature, humidity and Turbulent Kinetic Energy (TKE) versus time, at various altitudes, extracted from the Meteo France Weather Forecast Models data for April 10, 2014.

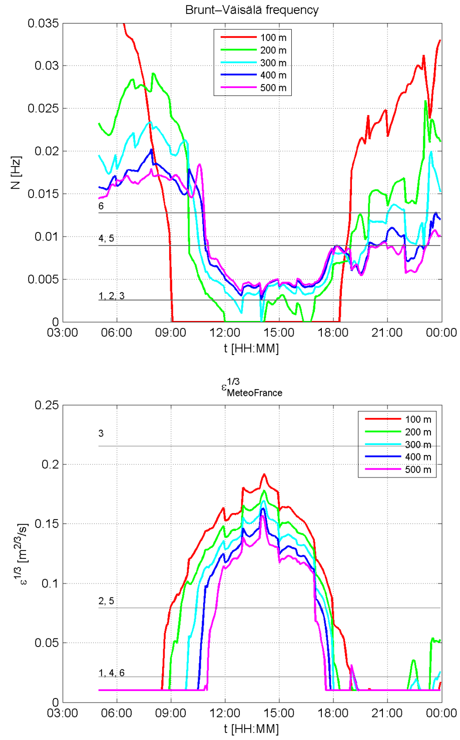

Fig. 2. Brunt-Vaïsala frequency and energy dissipation rate ($\varepsilon^{1/3}$) versus time, at various altitudes, for April 10, 2014. The horizontal lines represent the values of the parameters used for LES simulation of the various cases presented in Table I.

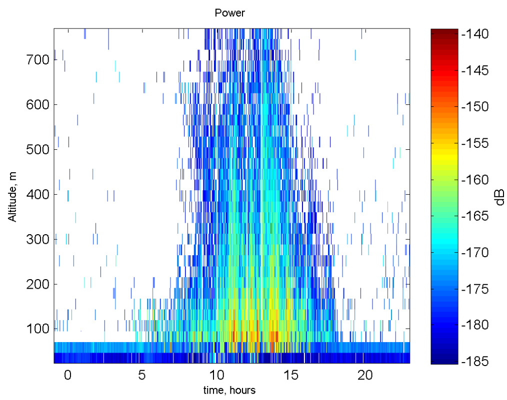

Fig. 3. Power received by the Curie radar in function of time and altitude during April 10, 2014.

Then the threshold is applied on SNR and measurements with SNR lower than the threshold are discarded. Furthermore, only time intervals with constant EDR are taken for the comparison. The scatterplots of EDR after filtering are introduced in Figure 4. The level of SNR threshold for this plot is 5.5 dB.

The turbulent kinetic energy is estimated from the broadening of the Doppler spectrum and $\varepsilon^{1/3}$ is inferred from the turbulent kinetic energy. Various extraction methods have been compared during the project [16]. The green dots in Fig. 4 show the scatterplot of $\varepsilon^{1/3}$ measured by LATMOS CURIE radar in ordinate and measured by Meteo France in abscissa. The red and black + and x are the mean and mean ± standard deviation for the two "packets" of points. The red dots represent the values used as input for the LES simulations (Table I), the blue circles represent $\varepsilon^{1/3}$ extracted from the Doppler spectrum calculated with the time series simulated using LES at 1s, 30s and 60s of the LES simulation for the corresponding case.

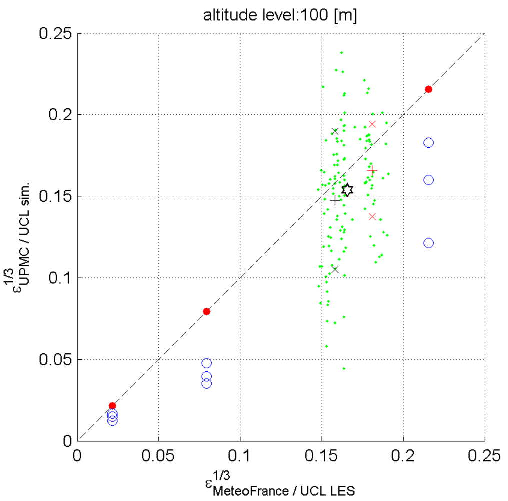

Fig. 4. Scatterplot of $\varepsilon^{1/3}$ measured by the LATMOS CURIE radar (ordinate) and issued from Meteo France High Resolution Weather Forecast Model (abscissa) on April 10 2014, 9h-16h30, represented by green dots, compared with the inputs of the LES simulation (red dots – Table I) and the values extracted from the Doppler spectrum calculated from the time series of the radar electromagnetic simulator using 3 different times of the LES simulation (blue circles). Mean and standard deviations of the scatterplot are represented by red and black + and x in the scatterplot.

The result of the simulated $\varepsilon^{1/3}$ is always lower than the $\varepsilon^{1/3}$ entered as input parameter in the LES calculation. The mean value of the measured data is also below the $\varepsilon^{1/3}$ measured by Meteo France.

Conclusion

For the first time an electromagnetic simulator based on LES simulation of turbulent atmosphere has been tested against radar measurements and meteorological data issued from High Resolution Weather Forecast Model. The preliminary analysis shows an underestimation of $\varepsilon^{1/3}$ by the radar. This is in agreement with a conclusion of the UFO project showing that below 500m the $\varepsilon^{1/3}$ from Harmonie is larger than $\varepsilon^{1/3}$ from the LATMOS CURIE radar. The final paper will present a complete quantitative validation for all the 12 days available.

In the near future, the tool developed will be further checked on all the available data to see the influence of the various parameters such as N, $\varepsilon^{1/3}$, the SNR threshold, C_n^2 and further comparison with Lidar if concurrent collocated data are available. New LES simulations are foreseen using as input data the values of energy dissipation rates and Brunt-Vaïsala frequency observed during the measurement campaign.

Acknowledgment

This work has been performed in the frame of the FP7 UFO project. The authors would like to thank the participants of UFO project and more specifically Meteo France for their data and T. U. Delft for opening the UFO server for accessing the trials datasets. D. Vanhoenacker-Janvier and D. Kovalev are especially grateful to Dr. C. Pereira who developed the first version of the radar simulator and Dr. M. Duponcheel who updated the LES simulator, for their work and their availability for discussion.

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