Use of advanced airborne weather radar for flight trajectory optimization

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1 Introduction

Trajectory of civil aircrafts is typically optimized off-board and expressed in form of waypoints, i.e. latitude and longitude of significant points on the route, along with altitude and speed to be kept. Flight plans are pre-calculated before take off in order to optimize fuel consumption, using the information available from weather predictions. Changes to the route are decided by the pilot during after continuous updating of information during the flight, such as METAR and NOTAM updates. The retrieved updates are also accompanied by the detection of unexpected weather condition detectable from data collected by the weather radar installed on the nose of the aircraft. This weather radar provides to the pilot qualitative information on the presence and intensity or clue of convective clouds along the route. The main purposes of changing a route are: reducing the risks related to the flight and improve passengers' comfort. Pilot workload and effectiveness of route changes can be reduced having at disposal more reliable information sources (including an advanced – i.e. dual polarization - weather radar) and proper software implementing algorithms such as Quasi-Artificial Intelligence or Data fusion for appropriate usage of the information available aboard. These tools allow the pilot to run more sophisticated decision processes that include pollutants, being the most important chemical species emitted by aircraft engines carbon dioxide (CO_2), water (H_2O), nitrogen oxides (NO_x), and sulfur oxides (SO_x), and acoustic noise as well. Indeed, aircraft trajectory optimization is highly sensitive to atmospheric conditions; pressure, relative humidity, temperature, wind intensity and direction have various influences on thrust needed and the resulting air pollutant emissions (Serafino et al. 2012). The Management of Trajectory and Mission is a relevant part of "System for Green Operation" activity of the Clean Sky JTI (Joint Technology Initiative) launched by the European Union with the objective of developing breakthrough technologies to significantly increase the environmental performances of airplanes and air transport, resulting in less noisy and more fuel efficient aircraft, hence bringing a key contribution in achieving the Single European Sky environmental objectives. A wrong trajectory management, in response to meteorological hazard detected by the weather radar, could negatively affect the aircraft optimum route and result in additional fuel consumption and pollutant emission.

Relying on improved weather radar technologies and processing is a key component to reach this goal and for this reason several call for proposal launched within the Clean Sky JTI have addressed specific topics to airborne weather radars and their implication for greener flight operations. All the current state-of-the-art radar equipments follows specifications set by the ARINC Characteristics 708A standard. Typically, weather radars of most civil aircrafts are at X-band, whereas only larger airplanes use C-band radars and use 3° beamwidth flat antenna. X-band offers with respect to C-band the advantages of higher pulse energy, a narrower beam, and low power consumptions. Notoriously, attenuation at X-band is higher and in the presence of cluster of convective cells, the nearer cells attenuate returns, thus masking or underestimating returns from farther cells. Attenuation effects, if not corrected, could result in underestimation of reflectivity of intense convective cells, especially at longer ranges, determining a wrong input to the point of view of optimal trajectory detection. For this reason, the purpose of these instruments is "weather avoidance", rather than weather detection. Unfortunately, attenuation correction techniques applicable to single polarization radar are unreliable and strongly affected by radar calibration bias. Conversely, dual polarization technologies in ground based weather radar (Bringi and Chandrasekar, 2001) have demonstrated the capability of mitigating X-band attenuation based on differential phase shift measurements and therefore could be successfully employed for civil aviation weather radars.

Single polarization weather radars are calibrated to show to the pilot precipitation returns according to a few levels of reflectivity (represented as Black, Green, Yellow, Red, and Magenta, the latter corresponding to turbulence as detected from Doppler spectrum width radar measurements). The correspondence between color scale and rain intensity or radar reflectivity may be different depending on radar manufacturers. However, interpretation of standard radar images and consequent decision making is largely left to the pilot's experience. Dual polarization radar provides more information arising from the sensitivity to microphysical properties of particles that is commonly used in hydrometeor classification products. More information yields more workload for the pilot to make a decision. It is therefore necessary to simplify the information provided to pilot and to provide automated software able to process information from dual polarization radar. In the architecture developed in the project KLEAN an Electronic Flight Bag (EFB), (more specifically, a Class 2 EFB) implements dual-polarization classification maps from which risk maps are obtained (implemented a weather radar post-processor, hereinafter WRPP), which, in turns, are processed by a Q-AI software to suggest the pilot an optimal route. This paper focuses on the airborne weather radar processing chain and its demonstration through reconstructed flight scenario.

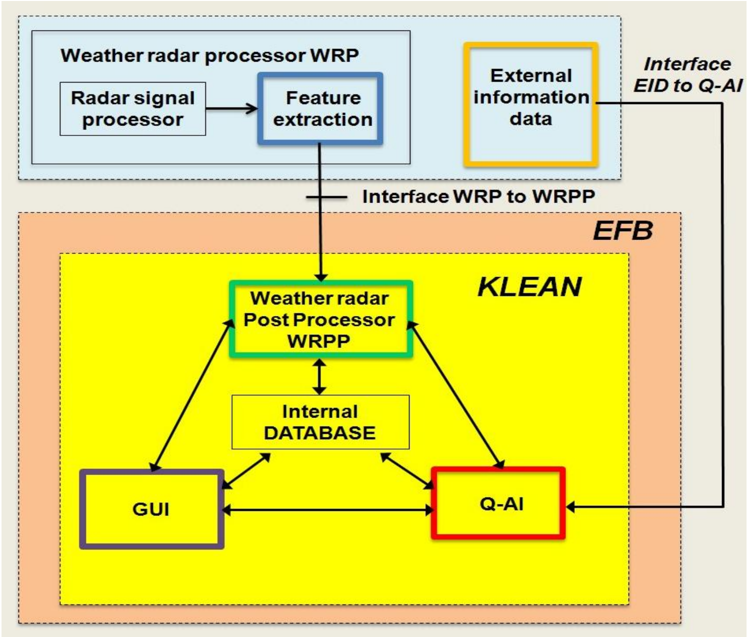

Figure 1:Architecture of KLEAN system

2 The EFB implementation of KLEAN weather radar postprocessor

To proof the technology readiness of this process, SELEX-ES technologies for WRPP and Q-AI implemented for EFB by CNIT are used as a starting point, with input provided by a radar simulator based on a weather model initiated with parameters relative to a real case. Figure 1 shows the KLEAN reference architecture that distinguishes between signal processors task and post-processing performed at EFB level. The overall objective is to show optimal trajectory to the pilot. The Quasi-Artificial Intelligence on-board trajectory optimization algorithm is based on a graph representation of the state space evolution of the aircraft and the optimizations are based on heuristic methods. The aim of the Q-AI module is to help the pilot in selecting the trajectory for the aircraft that produce reduced emissions of CO_2, NO_x and acoustic noise. Then, the computation of CO_2 and NO_x depends on the value of Temperature, Pressure and Relative Humidity of the air around the aircraft, so an accurate update of the forecasted value can lead to a better trajectory. Q-AI ingests a risk map that outlines spatial region to be avoided by the aircraft route due to meteorological or security reasons (i.e. the risk map due to post-processing classification of the avionic weather radar data). Figure 2 shows the EFB picture (a model by Astronautics Corporation of America, Milwaukee, WI, was used for implementation) . The EFB is composed by a display unit (shown on the right) and an electronic unit (shown on the left).

2.1 The weather radar post-processor

Within the KLEAN architecture, the WRPP implements a classification procedure based on radar measurements provided by WRP (Weather Radar signal Processor) that also performs a compensation of attenuation based on Differential Phase Shift. The WRPP takes as inputs the polarimetric observables (from WRP module), namely Z_H, Z_{dr}, K_{dp}, $|\rho_{HV}|$, and geolocation information (obtained from the Flight Management System of the aircraft) of observables provided by the matrices expressing Latitude, Longitude, Height. An estimation of 0° isothermal is obtained using a model of temperature vertical gradient and measurements of outside temperature. Although not shown, EFB can handle a predictive windshear system (PWS), or a Doppler based turbulence predictive system, using Doppler velocity spectrum moments. The polarimetric measurements are processed by the WRPP classifier that consists of a Support Vector Machine (SVM) classifier developed at the University of Siena trained offline. SVM was chosen because matches the EFB data transfer and processing constraints, has better performance in terms of processing time with respect to other classifiers, and finally, can be trained on any type of input data and therefore it is easy to reconfigure for further evolution of WRPP.

Figure 2: The KLEAN Electronic Flight Bag (EFB).

2.2 Weather scenario and weather radar measurements simulation

To simulate the meteorological event we need to use a Numerical Weather Prediction (NWP) code which provides in output the atmospheric quantities needed to extract the radar observables. Current NWSs consist of global atmospheric model ranging from 20-50 km of resolution to mesoscale-limited 10 km grid resolution. Current research has been going on to replace these models with non-hydrostatic ones and to provide horizontal resolution of 1-3 km able to simulate moist convection and advanced microphysical process. Research institutions all over the world have been working on the improvement of current models. Some of these centers have been collaborating for the development of the Weather Research and Forecasting model (WRF), which is intended to supersede existing advanced mesoscale models.

For testing the algorithms operating in the EFB, a supercell thunderstorm was simulated. The environmental wind makes a "quarter circle" when plotted on a hodograph, and is commonly referred to as "quarter circle shear". Two left and right moving supercells are produced. The default version of this test case uses a constant eddy viscosity for turbulent mixing. Strong hail and rain are present, with very high reflectivity factors. Probable strong turbulence with gust fronts is present. This is an extreme case, which can be used to validate hazard metrics and to test KLEAN classifier in a controlled environment. Area simulated is 6400 km^2. In our model we use the Millbrandt-Yau (2005) double-moment microphysical model, which permits the evaluation of ice accretion. Furthermore, the model includes two separate classes for graupel (smaller and softer hail) and hail. Figure shows the Mixing Ratios (in dimensionless unit [Kg/Kg] defined as the mass of hydrometeor per mass of dry air in a specified volume) that are one of the output of WRF, at 6000 m highlighting the prevailing presence of graupel particles denoting the convective nature of this event.

A comprehensive description of the dual polarization radar simulator can be found in Lischi et al. (2014), whereas a validation with respect to a case study observed by a C-band dual polarization radar can be found in Lupidi et al. (2014). Table 1 shows main characteristics of the X-band radar chosen for simulation, while scanning characteristics are shown in Figure . In particular, two trajectories are simulated, at 9000 and 6000 meters along the flight route from Paris to Nice (France). All tests are performed with the C-source code for EFB running on a Quad Core PC Intel-i7@3,40GHz. Classification takes a few tenths of a second to perform classification of a sweep.

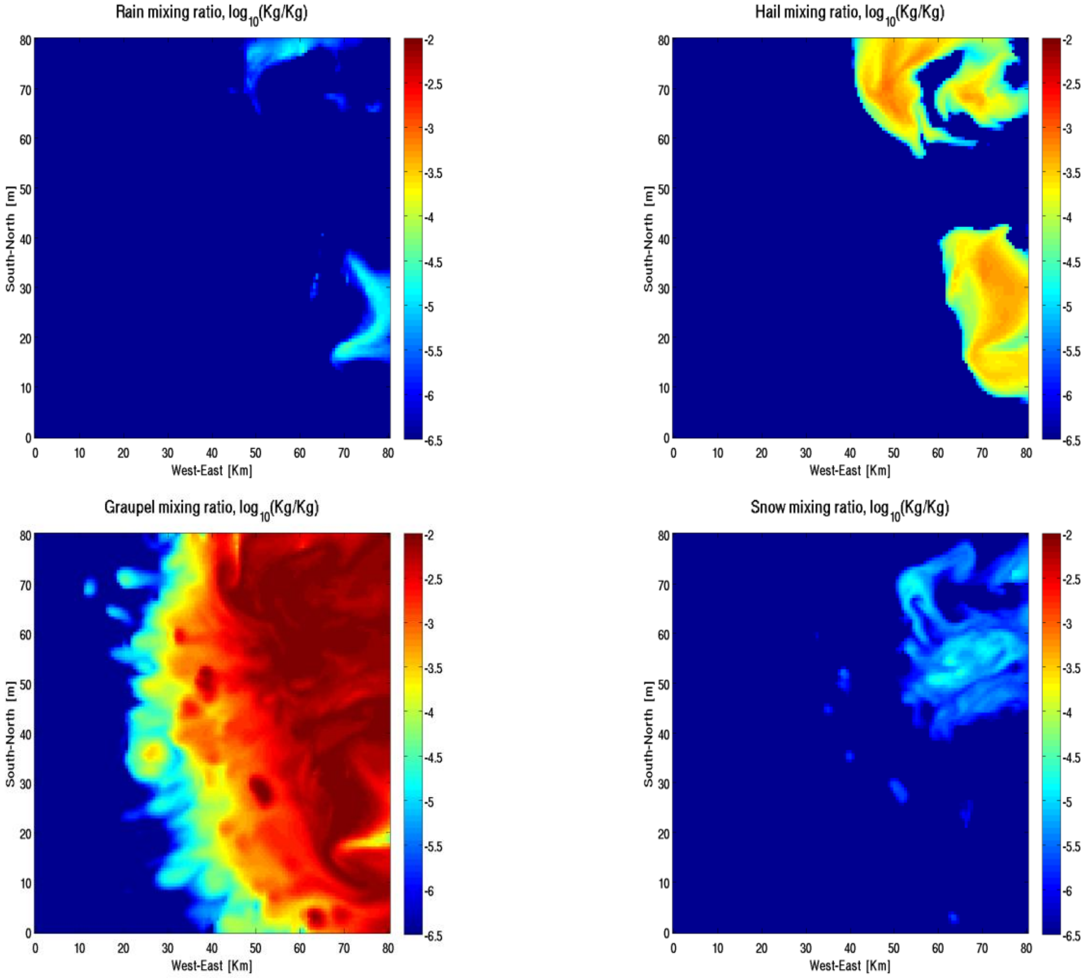

Figure 3: Mixing Ratios at 6000 meters of the simulated weather scenario

2.3 WRPP outcomes

Although WRPP provides classification maps at the radar resolution, this information is handled by EFB to derive a risk map, that, in turn, is the input of the Q-AI process. By default, EFB provides to the pilot a simple binary risk map. Optionally, a classification map can be shown as in Figure . The output of WRPP classification is shown at a coarser resolution with respect to that available from the radar also ergonomic reason. (It should be noticed that conventional, radar centric ARINC 708A display of weather radar is not replaced by the EFB screen). Different levels of zooms are available, with, or without an overlapping layer showing the flight route as shown by the EFB display by means of the graphical user interface developed by the CNIT research unit at the Department of Engineering, “Parthenope” University, Naples according to guidelines for EFB.

Table 1:Characteristics of dual-polarization radar used for simulations

Parameter	Value
Polarization	Linear H/V
Central frequency	9.353 GHz
Peak power	200 W
Pulse duration	1 µs
Pulse Repetition Frequency	1852 Hz
Antenna half power beamwidth	3 deg
Antenna gain	36.5 dBi
Antenna tilt angle	0 deg
Azimuth scan sector	± 60 deg
Antenna scanning speed	30 deg/s
Noise figure	3 dB

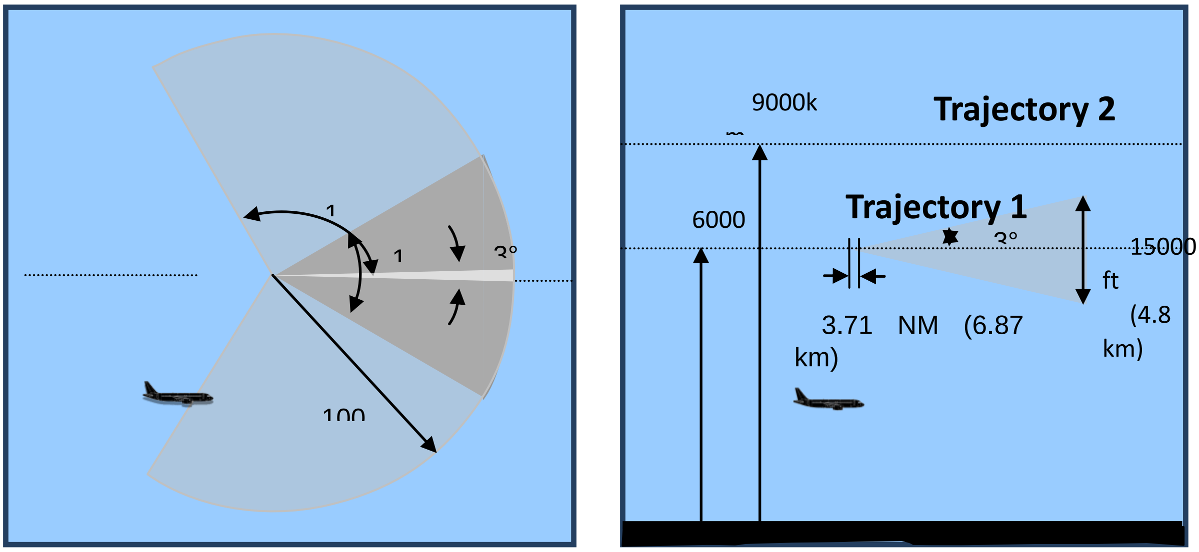

Figure 4:Flight and scanning parameters used in the flight simulation

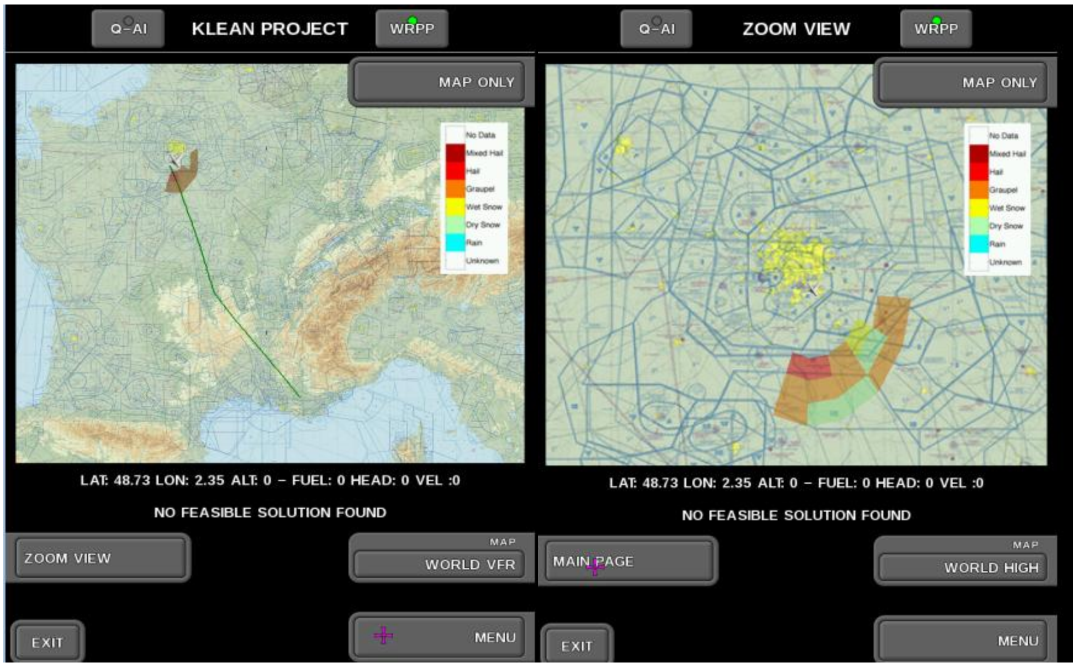

Figure 5:Classification output shown on the EFB screen at different levels of zoom.

3 Conclusions and future steps

Feasibility and technical readiness level of using a dual-polarization weather radar has been demonstrated by simulated scenarios. Further actions are ongoing to increase the technical readiness level for aircraft operations. A validation with real X-band dual-polarization data collected by an aircraft equipped with a looking-ahead radar is included in the ongoing X-Wald “Avionic X-band Weather signal modelling and processing validation through real data acquisition and analysis scenario” (D’Amico et al., 2014). Although the weather radar is maybe the most important real-time source of information on weather, re-planning the optimal flight trajectory may also consider, other sources available on-board, such as pressure and temperature sensors, icing detectors, GPS, TCAS and ADS-B. In fact, some aircraft are also equipped with supplemental sensing equipment, such as humidity sensors and lightning detection for instance. However, all those devices have been installed for safety of flight purpose only and are provided only to the navigation display equipment. In addition to the on-board instrument data available, thanks to the advanced connectivity means available today (Satellite, VDL-2, FIS-B, ..) and in the future, it is possible to provide in real-time updated weather and traffic information available on the ground to the aircraft. The sharing of information is currently studied through the development of the System Wide Information Management (SWIM) of the SESAR program. It is thus possible to deliver updates of regulatory weather products (METAR, SIGMET), regional traffic information (FIS-B), AIS information (NOTAMs), enable sharing of information between aircrafts (PIREPS and auto-PIREPS), provide update of Wind fields, or delivery of Ground Weather Radar or Satellite images in real-time to the flight deck. European weather forecast agencies that have developed a concept of 4D weather objects for distribution of forecast to Airspace Users (FP6 FLYSAFE, FP 7 SESAR projects and related standardization initiatives) contribute to raising awareness of unusual weather events occurring and thereby increase safety (Mirza et al. 2008). The role of data fusion is therefore relevant as it can affect significantly the consequent optimization phase. A further project (Win FC, Weather INformation Fusion and Correlation for weather and traffic situational awareness) will pursue such objective, there will be necessary to review the aircraft avionics structure, to enable distribution of sensor data to various on-board users.

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