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POLARIMETRIC AVIONIC WEATHER RADAR FOR INCREASING FLIGHT SAFETY AND EFFICIENCY

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Abstract

Current avionic weather radars cannot give accurate information about the weather hazards. Pilots avoid the potentially dangerous area with a greater detour, but only thirty percent of "red echo" radar returns represent actually a threat. These detours involve a longer trajectory and a greater impact on the environment. Instead, a polarimetric radar, which can discriminate for instance between rain and hail, can enhance pilot situational awareness and support trajectory optimization. In the framework of KLEAN project funded by CLEANSKY Joint Technology Initiative, a customized knowledge-based Electronic Flight Bag (EFB) was developed. This EFB, other than being capable to show the map, the flight trajectory and information about surrounding environment, it also implements a polarimetric radar data processor aimed to the assessment of the risk level of the phenomena encountered en route.

1 Introduction

Weather factors cause hazards to flight in any of its phases. Usually only a small fraction of accidents due to bad weather conditions occurs during the cruise phase, which is the largest part of an aircraft flight time. On the other hand, most accidents happen during the takeoff or the landing operations. Trajectory changes due to bad weather conditions, with related longer flight paths and increased fuel consumption, mainly occur in the cruise phase, including subsequent decision about detour on a different arrival airport [1]. Some studies highlight the possibility of a controlled trajectory change rather than a complete avoidance in case of bad weather event. Wu et al. stated in [2] that it appears that pilots do make an effort in maintaining a safe distance from weather when the encountered circumstances make it easy to achieve, such as when the initial trajectories were at the boundaries of the leading or trailing edges of the storms. When the encounter circumstances make it inefficient to fly around the hazardous region altogether, such as when the initial trajectories take them through the middle of a line of storm cells, pilots would be more willing to fly closer to the storms to trade off comfort for efficiency.
DeLaura et al. showed in [3] that often, due to the lack of precise information on weather structure, pilots make a large deviation in a region of benign weather, up to more than 100 km downwind from nearest convective cell. Moreover, they highlighted the fact that additional and relevant weather data, like a more precise information on the internal structure of the event or presence of organized versus disorganized convection is present, would be beneficial.

In this paper we present some enhancements for a class 2 type B EFB which consist if several aspects; the weather representation is extended with respect to classical weather radar acquisition with the introduction of radar

polarimetry. Using this technique it is possible to understand more accurately what lies within the core of a phenomenon, and to classify different types of hydrometeors like hail (one of the most dangerous weather phenomena), rain (usually non-dangerous) or snow [4]. Therefore, taking into account the estimated level of risk, it is possible to calculate more efficient routes. Furthermore, the use of polarimetry provides a stronger immunity against clutter and noise [5].
The system is implemented in a Nexis^{TM}Electronic Flight Bag developed by the Astronautic Corporation of America. The package is show in Fig.1

Fig. 1 Nexis^{TM}EFB system.

2 System Architecture and Functionality

Figure 2 depicts the architecture of the EFB. The system is composed by the Weather Radar Processor (WRP) and Post-Processor (WRPP), the internal database, the Quasi-Artificial Intelligence module (Q-AI) and the interactive Graphical User Interface (GUI). In this paper we focus mainly on the description of WRP and WRPP blocks.

2.1 Weather Radar Processor (WRP)

The weather radar Processor is an external block located between the output interface of the weather radar and the input interface of the EFB. Its main purpose is to process the raw data coming from the weather radar. The raw data consist of the complex I&Q polarimetric signals for each

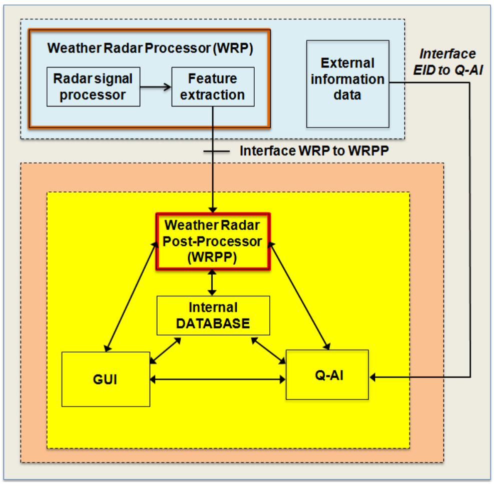

Fig. 2 KLEAN EFB architecture scheme.

of the polarimetric channels (HH, VV, VH/HV). The functionality of this block is to compute the most important polarimetric and Doppler weather radar observables, called level-1 features, and namely:

- Absolute Reflectivity (Z_h or Z_v)
- Differential Reflectivity (Z_{dr})
- Linear Depolarization Ratio (LDR)
- Specific Differential Phase (K_{dp})
- Co-polar Correlation Coefficient (ρ_{hv})
- Mean Doppler speed ($\bar{v}$)
- Doppler spectral width (σ_v)

These variable are directly linked to the characterization of the hydrometeors [4]. Rain usually shows high positive values of Z_{dr} up to 4 dB, a low LDR (usualy not over -25 dB), a high Correlation Coefficient and high K_{dp} up to 10 deg/km. Hail, instead, has complementary features, most notably, very low Z_{dr} if not negative. Other hydrometeors (graupel, snow) usually have intermediate feature values.
Figure 3 depicts an example of two level-1 features (Z_h and Z_{dr}) extracted from a simulated scenario.

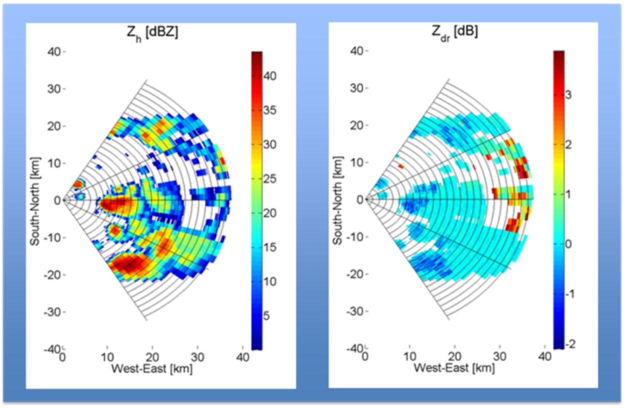

Fig. 3 Example of level-1 features.

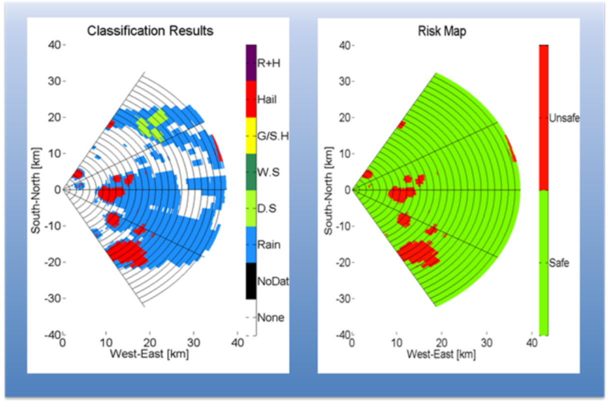

Fig. 4 Example of level-2 features and Risk Map.

2.2 Weather Radar Post-Processor (WRPP)

The Weather Radar Post Processor (WRPP) is a functional block integrated in the EFB.
The first functionality of the WRP is the correction of the attenuation of the radar signal due to the propagation into the rain medium. Often pilots encounter storm formations which, other than posing a risk themselves, prevent the pilot to know what lies behind and if there is a safe path behind the first perturbation front. Polarimetric weather radar processing algorithms are able to provide an estimate of the attenuation in order to perform a reliable correction of the attenuation in rain [4].
The main purpose of the WRPP is to process the level-1 features provided by the WRP, and possibly other features, for hydrometeors classification. The WRPP also interacts with the pilot GUI to provide simplified and easy-to-read reflectivity maps and detailed hydrometeors classification maps with related classification confidence intevals.
The final output of the WRPP is the geo-referenced Risk Map of dangerous weather situations, such as strong turbulence or presence of hail. The Risk Map, which is an extremely synthetic representation, is then passed to the Q-AI block in order to compute new optimized trajectories.
Figure 4 depicts in the left panel the classification results, named level-2 features, obtained from the simulated level-1 features. The relative Risk Map is shown in the right panel.

We adopted a supervised classification scheme based on Support Vector machines (SVM's) with a RBF (Radial Basis Function) [7]. The training phase is performed by composing a "ground truth", at first. In case of a simulated scenario, this operation is straightforward. In case of collected real data, the ground truth is created offline. In a specific spatial location of the dataset, we can find a single type of hydrometeor or a mixture of them, defined as *classes*. Each class is then described with a specific n-tuple of level-1 features. The training set is then processed to obtain the modeling parameters to be used in the classification step. Once the training is performed, the descriptors are stored in the database, until the classification starts.
The next step is the online classification phase, which is executed every time a set of level-1 features from the WRP is ready. The classifier has the following inputs: the descriptors (previously computed by the SVM training phase), the output classes (given by the user at the beginning of the whole procedure) and the current dataset.

2.3 Q-AI trajectory optimizer

The Q-AI trajectory optimizer module supports the pilots during normal and safe situations. The Q-AI module is activated by events that affect the planned trajectory. If the pilot can/must change the planned trajectory, Q-AI suggests a new trajectory. Suggestions of Q-AI are useful since pilots cannot evaluate the entire range of possible responses to the detected change. In fact, without Q-AI, a pilot cannot take into account all minor factors (but for example only the safety factors), conditions and constraints, e.g. the trajectory optimization for a minimum environmental impact. It is part of the DSS (Decision Support System) in charge of helping the pilot to select the better information about the new event and decreasing the decision time safely. Two main functionality are performed by the Q-AI module into the KLEAN EFB: Event Management and Trajectory Management. The events managed by the Q-AI module can be generated by the following sources:

- New data from the Weather Radar: typical scenarios can be the presence of an unforeseen storm during the flight, or of adverse weather conditions (e.g.: strong turbulence or hail) that lead the pilot to avoid the affected area.
- New data from the Flight Management System: for example, engine status, altitude, external pressure and temperature, aircraft position and asset.
- New ground information: for example NOTAM, Metar, ATC/ATM info, new forbidden areas, etc.
- New messages from other aircrafts: a typical case is when during the landing phase, another aircraft changes the terminal airport or the runway; in this case the pilot should check if this new trajectory affects its one and in that case a new trajectory should be produced taking into account the perceived noise by population living close to the airport.

A change in one or more of these external events may need an urgent decision making process.
The Event Management module analyzes if changes in dangerous areas and weather conditions have occurred and in case calls the Trajectory Management module.
The Trajectory Management Module is composed of the following applications:

- Trajectory Generation: identifies actions which could successfully control the change and takes action to adapt to it.
- Trajectory Validation: checks if the action proposed by the Trajectory Generator satisfies all constraints and then if the solution is feasible submits it to the Decision System.
- Trajectory Decision: shows to the pilot the optimized trajectory and the results in terms of noise and emission production, without loss of safety. This application implements a DSS and it will help the pilot in attitude and stress management and will improve and speed up the decisional process.

Figure 5 depicts an example of a trajectory generated by the Q-AI module inside a convective zone.

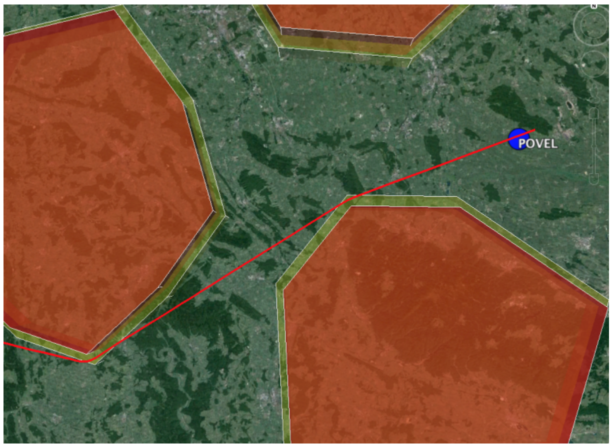

Fig. 5 Q-AI Trajectory example.

3 Interfaces among main blocks and external interfaces

The internal structure of the EFB considers a number of interfaces between internal and external blocks, whose functionality are briefly explained in this paragraph.
The interface between the WRP and WRPP is designed to assure the dataflow of the level-1 features between the two processors. The possibility of providing additional level-1 features will be

investigated in future works.
In order to evaluate the optimal trajectories that minimize emissions, the Q-AI retrieves information from the external connections, about: predefined route, allowed flight corridor (airspace where to look for alternative routes), no-flight zones, NOTAMs, forecasted and updated weather conditions (wind, temperature, pressure, rain, storms, etc.), aircraft performance models and parameters, flight condition (speed, altitude, aerodynamic state, engine state, etc.).
For the correct functioning of the trajectory decision algorithm, the Q-AI module requires some pre-assigned data which are provided by the internal database. These data consist of: predefined travel route, route way-points, departure and arrival airports, total travel time, aircraft type for thrust and fuel flow estimation, CO_2 and NO_x emissions and noise factor. From the Internal Database, the Q-AI acquires also some information about the current flight status, namely current position (latitude, longitude and height), speed, bearing and current time. Moreover, the Internal database provides also some information about the current weather and atmospheric status

- Weather conditions (initial input, to be updated with forecasts)
- Pressure, temperature, air density, relative humidity
- Wind field structure

The Internal Database is also linked with the WRPP in order to have access to some of the meteorological features. The interface with the WRPP provides also the forbidden flight zone due to dangerous weather situations, like strong turbulence or hail. The general reflectivity map can also be provided, in case of need, by ground based weather radar, where normally is provided directly from the on-board radar. The polarimetric features processing needs a front-end with the user (GUI). In this context, besides the other utility of the GUI, a section must be dedicated to the visual output of the resulting mapping and, after the interaction with the Q-AI module, the evaluation of the risk map. The latter, combined with the mapping of the phenomena, provides a degree of risk associated to a particular phenomenon occurring in a specific location of the observed space volume. The classification results can be also stored in the internal database in order to be constantly accessible by the Q-AI module if the pilot needs them.

4 Test Scenario, WRP and WRPP operation

For this test case a simulation of a supercell thunderstorm was produced over an area of 6400 km^2. The simulation was produced using the Advanced Polarimetric Weather Radar Simulator presented in [6]. 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 were produced. The default version of this test case uses a constant eddy viscosity for turbulent mixing. Heavy hail and rain are present, with very high reflectivity factors. Probable strong turbulence with gust fronts is present. This is an extreme convective case, which can be used to validate hazard metrics in a controlled environment. The simulated system is a pulsed X-Band fully-polarimetric (linear H-V) radar with an antenna beamwidth of 3 degrees. Figure 6 shows the simulated level-1 features as measured by the avionc weather radar at an altitude of 6000 meters (19600 ft). The first step of the trajectory is shown in Fig.7.

A first qualitative glance at the scenario shows the presence of two medium-high zone of reflectivity up to 43 dBZ. The analysis of the Differential Reflectivity indicates that in the zones where it is near 0 dB, the observed hydrometeor is probably iced (hail, graupel, snow). Higher Z_{dr} (but less than 1 dB) suggest the presence of a mixed iced hydrometeor area. Figure 8 depicts the result of the features extraction and classification algorithm performed by the WRPP.
The considered classes are: rain, dry snow (D.S.), wet snow (W.S.), graupel, hail and hail mixture (H.M). As expected, a mixed zone of iced precipitation is detected by the processor. The real danger is represented by the presence of hail and hail

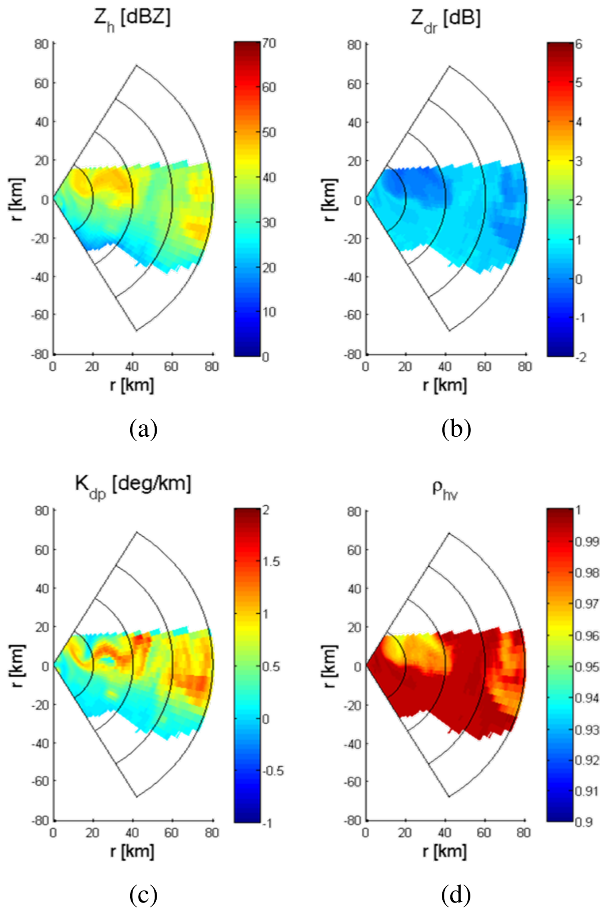

Fig. 6 Simulated polarimetric level-1 features.

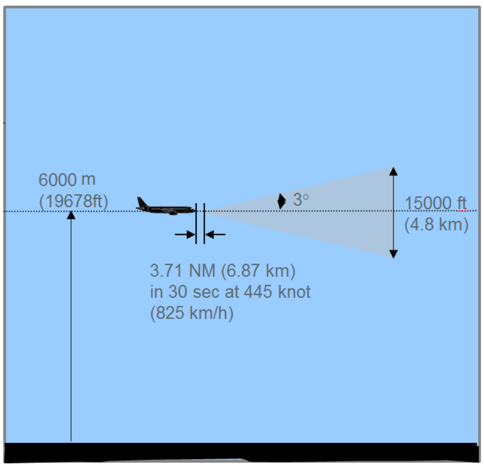

Fig. 7 Avionic radar acquisition geometry.

mixed with other kind of hydrometeors (H.M.), which are labeled as the risk event in Fig.9. The Risk Map and the classification data are then given as inputs to the trajectory decision algorithm. An example of what can be displayed in the EFB GUI is shown in Fig.10. At present time,

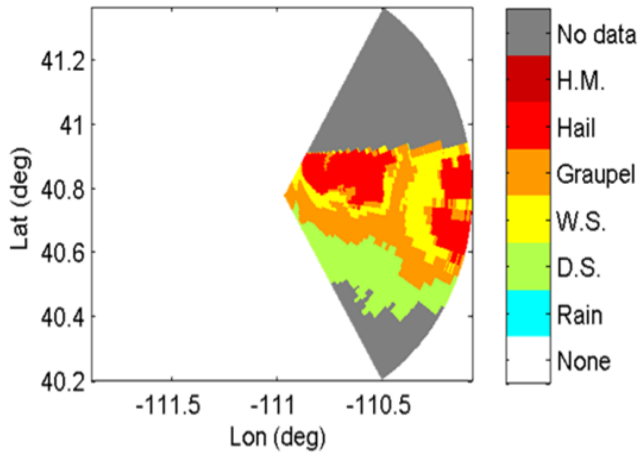

Fig. 8 WRPP classification with SVM.

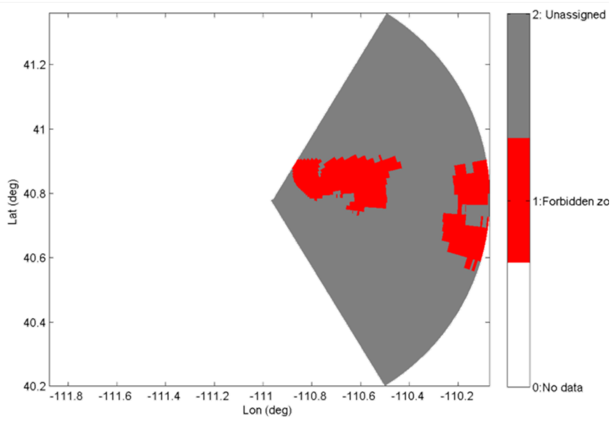

Fig. 9 Risk Map.

due to the ongoing development of the KLEAN project, the meteorological event is subdivided in coarse polygons, each carachterized by the color of the most probable class or the most dangerous, which has the highest priority. The detailed description of the Q-AI algorithm is out of the scopes of this paper (a reference can be found in [8]). However, it is clear that the use of a polarimetric radar can enhance the capabilities of the trajectory optimization software, which can be used to detect a safe path through non-dangerous zones or design a path around hazardous zones without too much detour.

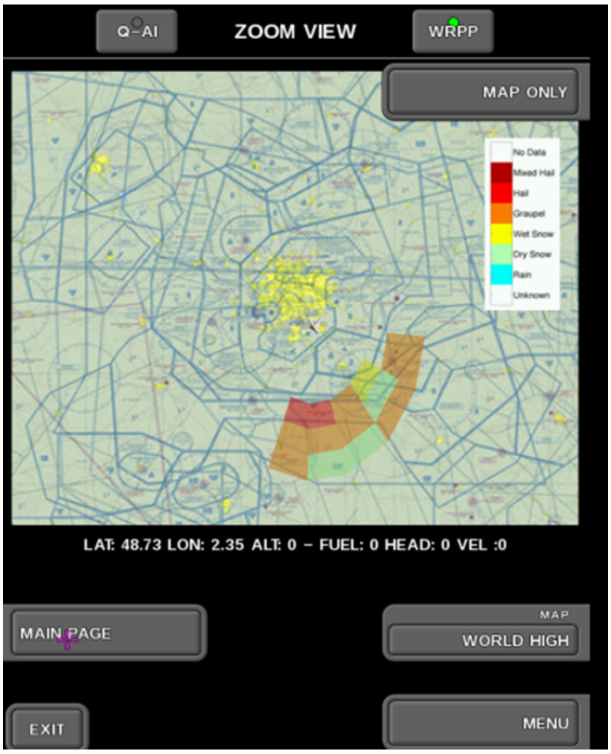

Fig. 10 Representation on GUI.

5 Conclusions

In this paper the possibility of using a Polarimetric avionic weather radar in combination with an onboard EFB system was show. The aim of this paper was to show that the information coming directly from the onboard polarimetric radar (which at present time are not in use on civil aircraft) can enhance the possibility of real-time trajectory optimization. The information are used to discriminate real hazardous zones from potential but safe ones, and reduce consequently detours from the predefined route or minimization of change of path, leading to an increased flight safety due to the enhanced situation awareness of the pilots. Moreover, in the framework of the CleanSky project, the minimization of route changes lead also to the reduction of fuel consumption and pollutant emission (like NO_x and CO_2) for a greener aviation. Moreover, the results of this project will be validated with real data acquisition campaigns in the subsequent CleanSky X-WALD project.

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