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Forecasting of Hazardous Weather Phenomena in a Complex Meteorological Support System of UAVs

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***Abstract*—**In order to make a general weather prediction for UAVs missions, we had to prepare the significant estimation of hazardous atmospheric phenomena such as ceiling, visibility and icing, etc. On the other hand, the forecasting of the mentioned phenomena is based on both statistical and numerical weather predictions. In our Integrated Aviation Weather Prediction System (IAWPS) for UAVs, we applied a large aviation climate data base with analog forecasting method to predict the visibility and ceiling and a WRF-based numerical calculations to the same and other parameters for UAV missions. We had to test our weather prediction results in a 3D space so we developed a complex meteorological sensor system for an UAV airplane with the temperature, humidity and pressure values, too.

***Keywords*—**Unmanned aircraft system (UAS), airborne meteorological measurement, visibility prediction, meteorological support.

I. Introduction

BOTH civil and military applications of the UAVs have been increasing around the world. Because of rapid growing of military UAV operations, the number of trained UAV operators and pilots were higher than number of manned aircraft pilots in the US Air Force in 2011, first time in its history [1]. On the other hand, the impacts of weather are significantly greater on UAVs than the manned ones due to their different characteristics. In order to reach a higher flight safety level for the mentioned UAVs, we proposed to set up a complex, aviation meteorological support system (IMSS, UAV met) which is able to provide weather information for planning and operating UAV flights anytime, anywhere.

It is clear the exact knowledge of some meteorological factors such as visibility, ceiling, gust, turbulence, wind-shear and icing is a fundamentally important thing during the UAVs missions because these factors can be highly dangerous for the UAV flight itself. On the other hand, they are able to cancel the execution of the given special UAV missions, too (e.g. reconnaissance, target-tracking).

Our work is based on the freely available meteorological reports (METARs) and often (worldwide) used WRF numerical weather prediction (NWP) model so therefore this system is easily adaptable [2]. The support system contains statistical and dynamical approaches to predict some very important atmospheric parameters such as:

- visibility and ceiling for the main Hungarian airports are based on statistical methods and
- visibility, ceiling, and other meteorological parameters for everywhere inside the prognostic region which are computed by WRF model and with the help of WRF outputs post-processing, too.

In the future, the mentioned supporting system will also be suitable to optimize flight paths reducing harmful weather impacts on UAVs.

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II. Meteorological Support System for UAVs

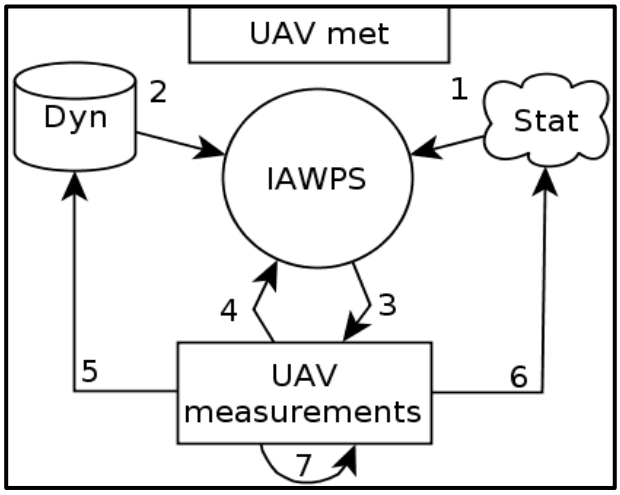

Figure 1 The structure of the meteorological support system for UAVs (IMSS)

Our developed meteorological support system for UAVs (UAV met) contains four main parts in itself (**Figure 1**). The statistical modeling sub-system (Stat) is based on a large aviation climatic data base and an analog forecasting searching method to predict two most important aviation meteorological parameters such as visibility and ceiling for the four main airports in Hungary. Moreover, the dynamical model sub-system (Dyn) uses the special implemented WRF (Weather Research Forecasting) model for the Carpathian basin. This model can give 96 hours forecasts for the mentioned region twice a day with 00 UTC and 12 UTC initializations. The Integrated Aviation Weather Prediction System (IAWPS)

contains an integration module with a learning algorithm which has to make the best final weather prediction of special and basic aviation meteorological parameters such as visibility, ceiling, gust, turbulence, wind-shear and humidity, temperature, air pressure etc., too.

The aviation weather forecast made by our system is able to yield accurate meteorological support [3] for the UAV operations (UAV), which in turn supplies the developers of the IAWPS with feedback from the user side [4]. In addition, the measured data can be utilized both by the Dynamical Modeling System [5] and Statistical Modeling System [6] for verification and model development because experiences of prior measurements can benefit for the development of the UAV measurement system and methodology itself [7]. In order to getting more accurate atmospheric data for the verifications we also develop a UAV-based meteorological sensor system.

III. Data Base and Forecasting Methods

A. *Data Base*

To manage our predictions for UAVs in connection with important factors such as visibility and ceiling, we firstly had to collect a large aviation climatic data set based on METAR reports over Hungary. The mentioned data base contains the half-hourly measured aviation meteorological data (wind, visibility, significant weather, clouds, air temperature, dew-point temperature and QNH air pressure) for the main four airports in Hungary (LHBP-Budapest, LHSN-Szolnok, LHKE-Kecskemét and LHPA-Pápa) between 2005 and 2013. The data base has more than 30 variables because it includes the parameters in elemental and derived format as well (e.g. year, month, day, hour, minute vs. Julian date), making the subsequent processing easier. The records are more than 99% complete. The locations of these airports can be seen is **Figure 1**. Based on the collected data set, we can produce some aviation climatic attributes of the mentioned airports, and predictions of the visibility and ceiling by applying a special analog forecasting method.

It is very important the whole database is re-generable from the METAR reports in short time by our applied script. It gives a special value for this system, because raw METARs are free-for-all information, so the database is easily creatable for any airport with available weather reports over the world [3].

B. *Analog Forecasting Method of Visibility and Ceiling*

A Fuzzy logic-based analog forecasting method is an effective tool during ultra-short term weather forecasting because it usually gives significant assistance in forecasting of derived outputs of numerical weather prediction models. Predicting of meteorological parameters such as visibility and ceiling is one of the greatest challenges for the operational forecasters [4]. There are some useful analog forecasting methods over the world (e.g. the Canadian operational fuzzy logic-based analog forecasting system called WIND-3). Its theoretical background can be found in Hansen's paper [5]. The success of the mentioned prediction system gave us the motivation to develop a similar system in Hungary which can give effective meteorological support in UAV operations because the visibility and ceiling parameters can have key role in the success of UAV missions. Usually the operational minimum of UAV flights is lower than the weather minimum of special mission execution. For example, during reconnaissance or surveillance tasks, poor visibility and low ceiling can be determinative factor completing the mission but they do not restrict the flight necessarily itself. Our primary goal was to develop an analog forecasting system which is able to give accurate and timely forecast of airports with relevant climatic database to support UAVs.

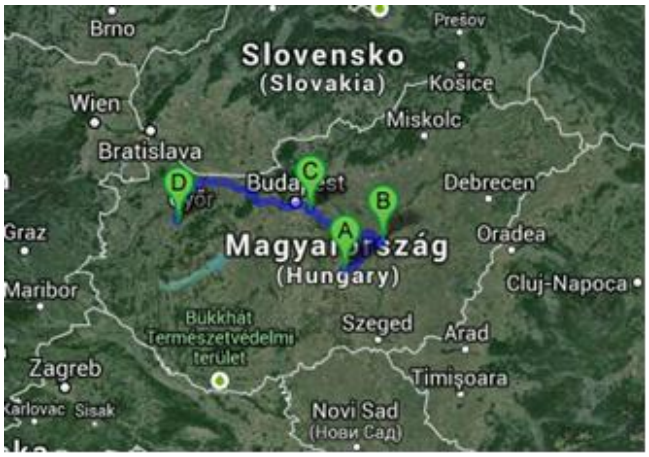

Figure 2 Locations of main Hungarian airports: A: LHKE-Kecskemét; B: LHSN-Szolnok; C: LHBP-Budapest and D: LHPA-Pápa

The basic principle of analog forecasting is to find similar weather situations in the past to the current and recent conditions and rank them according to the degree of their similarity in the interest of giving relevant information for weather forecasts. The applied fuzzy logic-based algorithm is measuring the similarity between the most recent conditions and the appropriate elements of our collected database. During the examination of every single weather situation, the model uses the current and the five previous METARs' content. The algorithm compares the meteorological variables of every examined time step using fuzzy sets.

Because of the large number of variables, the direct determination of weights was excluded. We have found a widely used technique in different fields of life except meteorology. This is Analytic Hierarchy Process (AHP) which was introduced by T. L. Saaty [6]. This method is mainly used in multi-criteria decision making, especially in solving complex problems from most different fields [7]. Its main idea is to model the problem as a hierarchy.

After finding the most similar weather situations, we can compose a deterministic prediction from the consecutive observations of the chosen cases with an appropriate method. The model collects the 30 most similar situations which are used for producing deterministic forecast. In the semi-operational phase we used the 30^{th} percentile value of the chosen parameter as prediction following Hansen [5]. But we found that the percentile value is not independent from the

examined parameter and the category limit of dichotomous forecast. We plan to investigate that the verification results can be improved by dynamically changing percentile value in the function of category limits.

To find the most similar combinations in the available database, we use our own supporting software which is based on a fuzzy similarity theory as we can found in earlier publications and our own test results, too [8].

C. Numerical Prediction of Important Aviation Meteorological Factors

In order to develop a proper meteorological support system for UAV operations, we also had to apply a suitable dynamical meteorological model because the above mentioned statistical approach cannot work properly in all cases. We had chosen the Weather Research Forecasting (WRF) model for this application since it is open source and freely available and suitable for using it in a broad range of applications [9], [10].

In order to achieve high resolution and accuracy model output that is suitable for the needs of the UAVs, we designated the resolution with several kilometers in the target domain. Since global model (GFS) data for input as initial and boundary condition is available on a half degree horizontal resolution, and downscaling cannot be applied abruptly so the resolution of the first domain was 30 km. In order to avoid "sweeping" effect and boundary issues, we utilized two levels, telescoped two-way nests with horizontal resolution of 7.5 km and 1.875 km, for domains d02 and d03, respectively (**Figure 3**).

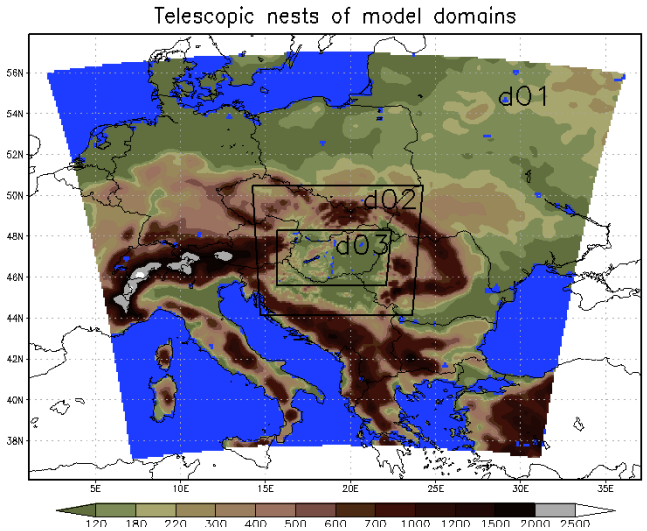

Figure 3 The applied two-way nested WRF domain system with 7.5 km (d02) and 1.875 (d03) km horizontal resolutions. The color scheme represents the terrain of Central Europe

The model vertical grid (terrain-following hydrostatic pressure-based σ-coordinate system) had also been modified to better resolve near surface features. Number of vertical levels had been increased to 20 in the bottom 200 hPa, and decreased above the 300 hPa level. Total numbers of vertical levels were 38.

Model calculations are performed two times every day. We make a 96 hours model runs which are based on the 0:00 UTC and 12:00 UTC global analysis by NCEP.

As we know, most of the dangerous weather phenomena that affect flight operation are not directly predicted by meteorological models. For this reason, the model outputs should be submitted to proper post-processing procedures. Scales of turbulence and icing processes are much below the resolution of a numerical meteorological model. Even smaller thunderstorms or the rotor flow associated with the mountain wave process are beyond the capabilities to be resolved by such meso-scale model. Visibility and low cloud are also pretty difficult to predict even from the outputs of a high resolution meteorological model.

For example in case of prediction of in-flight icing phenomena, we have to apply additional methods described by Bottyan [11].

The post-processed model outputs are posted as public web interface such as meteograms, maps and tables which can be accessed for authorized users with a simple web browser. The user can analyze them through custom speed animation map sequences of the different variables or she/he can select a location and download different meteograms of the selected location as well. The currently available numerical meteorological products are detailed in the next chapter.

IV. Results and Verification of Our Statistical Prediction Approach – Preliminary Results

Demonstrating the usefulness of our analog similarity-based method, we show a case study situation in connection with Szolnok-LHSN airport which is located in the middle of the Great Hungarian Plan (**Figure 2**). At 06:15UTC 23 January 2013 in Szolnok (LHSN) airport the weather situation was: 27005MPS 0800 +SN BKN005 OVC017 M02/M03 Q1006 NOSIG RMK AMB=. This means the visibility was poor with 800 m value and intensive snow was able to observe with low ceiling of 500 feet (underline in the presented METAR). We examined the ten most similar cases and averaging the values of each successive hour of the mentioned cases using our analog method. After that we were able to make a prediction and could compare it with the observations.

It is well observed that the prognostic applications of the mentioned method are significant because during the first six hours the predicted and the measured values are very close to each other (**Figure 4**). The differences between the predicted and measured visibilities are smaller than 1000 m in the six hours interval but during the first four hours the same values are smaller than 500 m. If we can illustrate the n pieces of the most similar cases as usual in ensemble forecasting, we can estimate the probability the given visibility categories, as well.

As we mentioned earlier, derived outputs of NWP models (for example WRF model) usually provide less accurate forecasts. That is why we selected horizontal visibility for detailed verification first. Heidke skill score (HSS) uses all of the elements of a given contingency table and it remains correct with verification of rare events which is typical in case of low visibilities [12]. We have to note the HSS value measures the success of different forecasts: if the HSS value equals 1 the prediction is absolute perfect but if this value equals zero the forecast is totally useless.

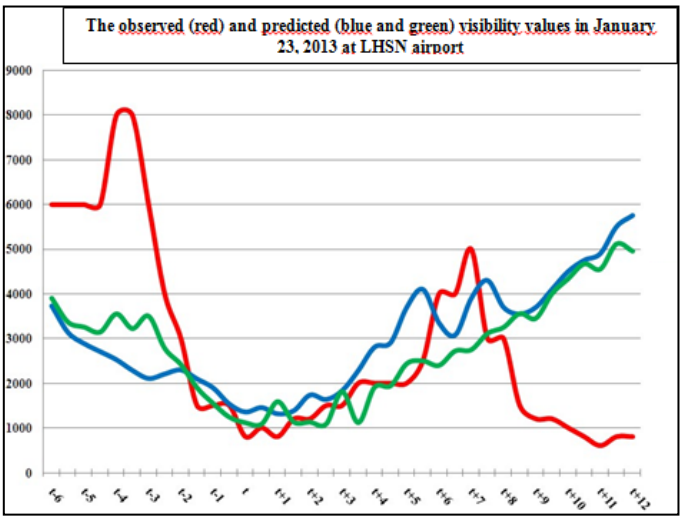

Figure 4 The observed and predicted visibility in January 23, 2013 at LHSN airport

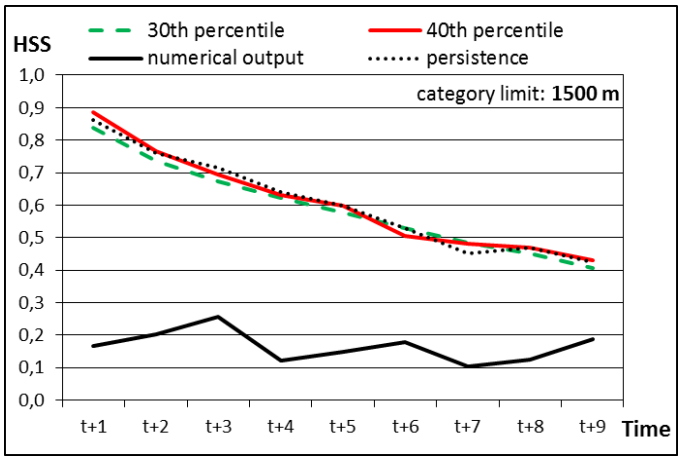

Figure 5 HSS of Szolnok airbase (LHSN) for visibility predictions (with AHP weights) of category limit of 1500 m for the period from 17 December 2012 to 22 February 2013

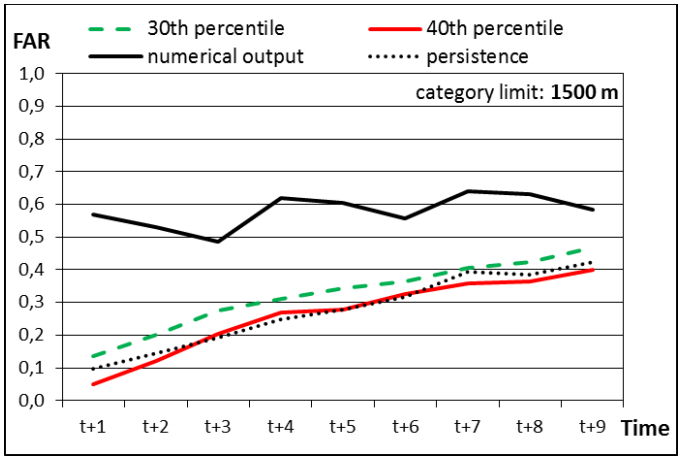

Figure 6 FAR (False Alarm Ratio) of Szolnok airbase (LHSN) for predictions (with AHP weights) of category limit of 1500 m for the period from 17 December 2012 to 22 February 2013

Some naive forecasts (e.g. persistence) can be a standard of reference [12], or in other words, a competitive benchmark [13] in the field of short term forecast verification. Thus, we show the verification results of persistence forecast on every figure for the comparability of outcomes. **Figure 5** demonstrates the weakness of NWP model in prediction of visibility. To raising the success of our prediction, the AHP weights were applied during the analog forecasting process. The period covered is not arbitrarily selected: currently this is the shared period of the regular runs of the NWP model and the control period for verification of analog forecasting. As we can see, the HSS of 30th and 40th percentile give similar performance for the category limit of 1500 m (**Figure 5**). On the other hand, if we examine the FAR (False Alarm Ratio) values of our analog predictions, it is seen clearly the FARs of them are significantly lower than numerical one for the whole 9-hour projection period (**Figure 6**). The high values of HSS and low values of FAR of 40th percentile show us the usefulness of our analog forecasting of visibility applying the AHP method. Against our analog forecasting, the direct horizontal visibility output of the NWP model has very poor results (with HSS values of 0.25 and lower) and its FAR values (between 0.49 and 0.63) are much higher than 40th percentile of analog ones (between 0.06 and 0.40). It means our analog forecasting –in in the visibility prediction– are more accurate than numerical (WRF) ones.

The other important meteorological factor in the aviation is the ceiling. In case of HSS values, the applied analog forecasting method is much more accurate against the numerical predictions during the first six hours if the ceiling is 300 m or lower. The HSS values of analog predictions during the first four hours are between 0.45 and 0.77 but the same values of numerical predictions are mainly less than 0.3 during the same period (**Figure 7**). In case of FAR values, the analog method is more accurate than numerical one. Applying the 40th percentile of analog values, our forecast is far better than numerical one because the false alarm ratio values are less than 0.4 during the first six hours periods against the numerical model values of 0.6 and higher during the same period (**Figure 8**). On the other hand, the mentioned analog prediction has the similar and less FAR values than the same values of persistence during the whole period! Our analog verification results were based on the Szolnok (LHSN) airport METAR data during the three-month winter time interval from 17 December 2012 to 22 February 2013.

As we saw earlier, the statistical predictions of visibility and ceiling are better than numerical ones mainly in the beginning hours of forecasting. The time-dependent divergence of similarities of analog situation results the analog predictions will be weaker in time. In order to give the best prediction results, we merged the two prediction methods. In case of ceiling from the initial time to the 7th hour, we applied the analog forecast and after that the numerical ones (**Figure 7**). But we used the analog forecasting during the first 9 hours in case of visibility predictions (**Figure 5**). We have to note at present we work on a special post-processed visibility forecasting method that is based on WRF numerical model but we have not enough time series to verify it in this paper.

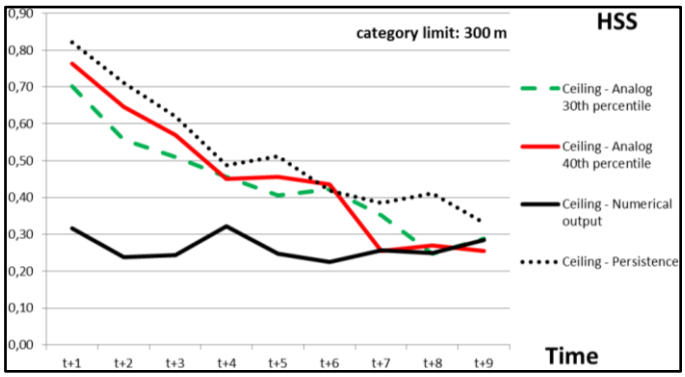

Figure 7 HSS of Szolnok airbase (LHSN) for ceiling predictions (with AHP weights) of category limit of 300 m for the period from 17 December 2012 to 22 February 2013

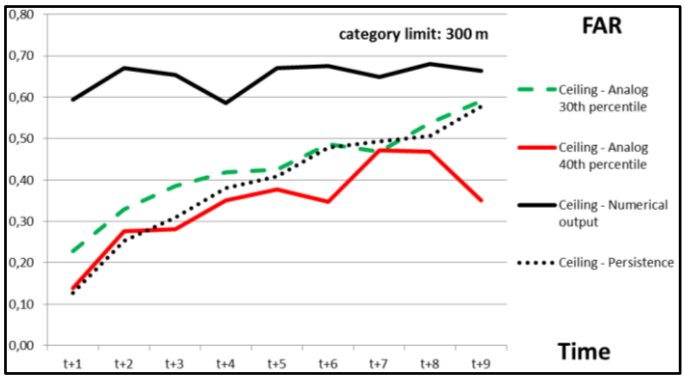

Figure 8 FAR (False Alarm Ratio) of Szolnok airbase (LHSN) for predictions (with AHP weights) of category limit of 300 m for the period from 17 December 2012 to 22 February 2013

V. Numerical Weather Prediction Products in the UAV Met System

For the UAV operations, we can present another numerical (WRF) and post-processed model product, too. It is very important to know how the weather will change at a given airport in time. In order to show this process, we can make meteogramms for the airports which represent the changing of the meteorological parameters during the prognostic time interval (**Figure 9**). As it can be seen, the given airport is LHSN, the sunrise and sunset time with the airport elevation are seen in the upper right corner. The horizontal axis represents the prognostic time interval (in this case from 00:00 UTC, 24 February 2013 until 24:00 UTC, 26 February 2013) and the vertical one represents the values of the predicted weather parameters such as amount and height of clouds, precipitation, temperatures, wind speed and directions, and QNH pressures. As it can be seen well, there are two periods of precipitations during the prognostic time interval: the earlier is between 02 UTC 24 February 2013 and 12 UTC 25 February 2013, and the other is between 08 UTC 26 February 2013 and 08 UTC 27 February 2013. On the other hand, the predicted temperature is higher than 0 ℃ so the precipitation will be mainly rain. The forecasted wind direction is mainly 40° - 90° (NE-E). The QNH pressure will increase at the LHSN airport during the examined period (**Figure 9**).

Of course in our UAV met system, we can predict the icing potentials and turbulence, too. For example, we can see a tropospheric icing potential prediction for UAV users in Szolnok (LHSN) airport during a 96-hour time interval from 00 UTC 17 January 2014 to 00 UTC 21 January 2014 (**Figure 10**). The red, orange and green colors represent the severity of in-flight icing potential such as severe, moderate and light, respectively in the troposphere [11]. As it can be seen, there will be a dangerous zone with severe icing (signed with red color) over Szolnok at the level between 2500 m and 4500 m during the mentioned period.

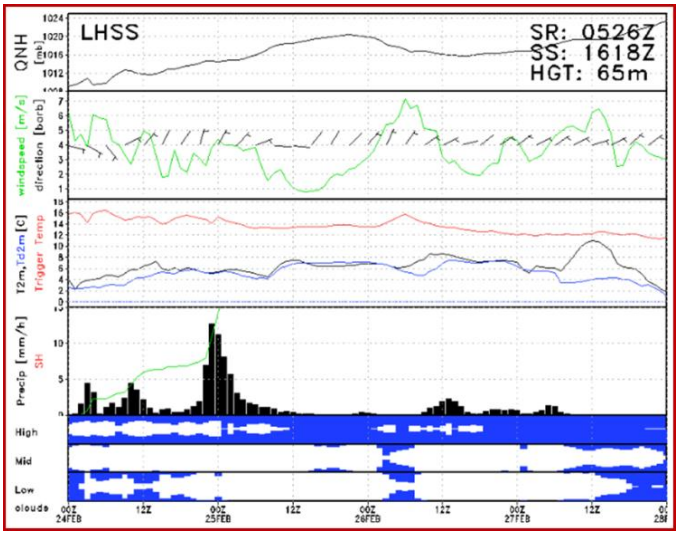

Figure 9 Meteogramm of the predicted meteorological parameters for the LHSN airport from 24 February 2013 until 27 February 2013

Figure 10 The predicted vertical icing potential in the LHSN airport from 00 UTC, 17 January 2014 until 00 UTC, 21 January 2013. The color codes represent the severity of icing (red: severe, orange: moderate and green: light)

VI. UAV Measurements Testing and Numerical Model Verification – Preliminary Results

To verify our numerical meteorological predictions, we use a BXAP15 UAV which is a fully Hungarian developed system by Bonn Hungary Ltd. The mentioned system consists of airborne and ground-based units. The ground control software is a user friendly GUI, displaying real time, main flight characteristics, such as air speed, ground speed, altitude, telemetry, etc., a map

or satellite picture, showing flight track, telemetric and other technical information. The airframe is made using the latest composite technology (glass, carbon and Kevlar, or para-aramid fiber) and reliable on-board electronics. It is easily transportable, recoverable without special equipment and features easy assembly and operation (**Figure 11**).

Figure 11 Our meteorological measurement system with the applied experimental Hungarian UAV airplane on its catapult

Figure 12 The applied experimental Hungarian meteo UAV with its sensor systems mounted on the fuselage

Real time video stream down-link, robust communication at C band, on-board flight data logging provide high flexibility and utility. Further characteristics are catapult or winch launching system, aircraft self-rescue system parachute for emergency landing.

The device is controlled by an autopilot system, which governs the airframe towards each successive way points. Flight data is transmitted to the ground station and is logged both by the on-board flight data logger (black box functionality) and by the ground system as well [14]. For our verification and further data assimilation purposes, an extensive meteorological measurement (fast response thermocouple thermometer, humidity sensor and inertial measurement unit (called IMU unit), a multi-hole pressure probe and a Vaisala meteorological sounding unit) has been designed and developed (**Figure 13**).

On 19 October 2012, the system firstly reached 3500 meters above mean sea level (AMSL) and still featured positive climb rate. The flight plan did not permit higher altitudes then, but this experience promises great opportunities for atmospheric research applications. Vertical profiles of temperature and dew point temperature were showing proper fit to modeled results. Temperature however was showing a delay in the vertical variation, i.e., cooling and warming with height was measured to occur higher than predicted by the model. Further analysis of the measurements showed that this feature in the shift of data from different sources was a result of the delay of the thermometer sensor (**Figure 13**).

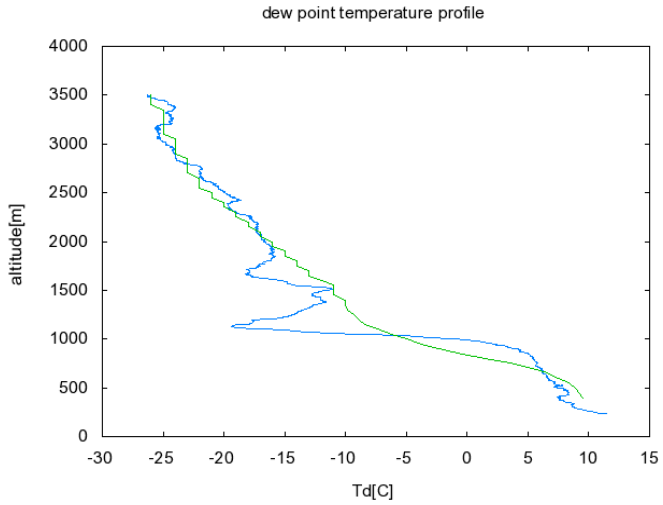

Figure 13 WRF predicted (green) and UAV measured (blue) dew point temperature profiles on 19 October 2012 in the Dunakeszi airport

Last year between 26-28 November 2013 –during an international airborne measurement campaign that was organized by National University of Public Service and Eötvös Lorand University– in Szeged Airport (LHUD) Hungary, we made several UAV flight to collect some meteorological information about the state of atmospheric planetary boundary layer (PBL) in order to verify our model results.

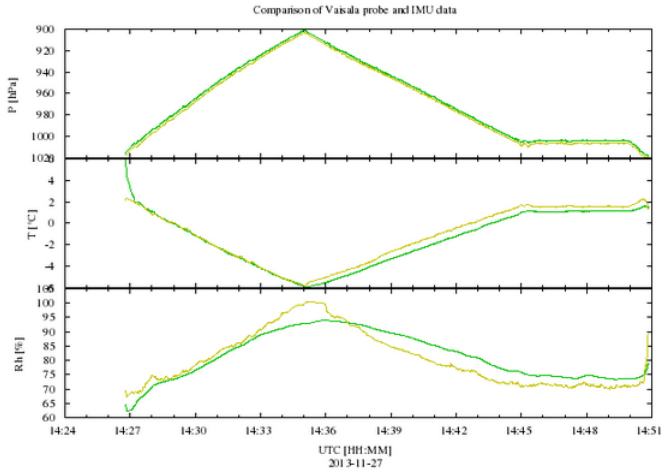

Figure 14 Comparison of air pressure, temperature and relative humidity data of Vaisala sounding and IMU unit during the flight was made on 27 November 2013 in Szeged airport, Hungary (the green line: IMU and the yellow line: Vaisala)

Because our UAV was equipped with two independent meteorological sensor systems (IMU and Vaisala sounding units), we could firstly compare their values (**Figure 14**). As we can see, the measured data of mentioned two units are close enough to each other during the whole flight that was made on 27 November 2013 in Szeged airport, Hungary. The total flight time was 24.1 minutes and our UAV reached the maximum height of 1030 m. The differences between measured air pressure, temperature, and relative humidity data were less than 1 hPa, 1 ℃ and 8 %, respectively. These relatively little differences between two units represent the usefulness of our IMU unit because the Vaisala sounding unit was a calibrated meteorological sensor applied by Hungarian Meteorological Service, too.

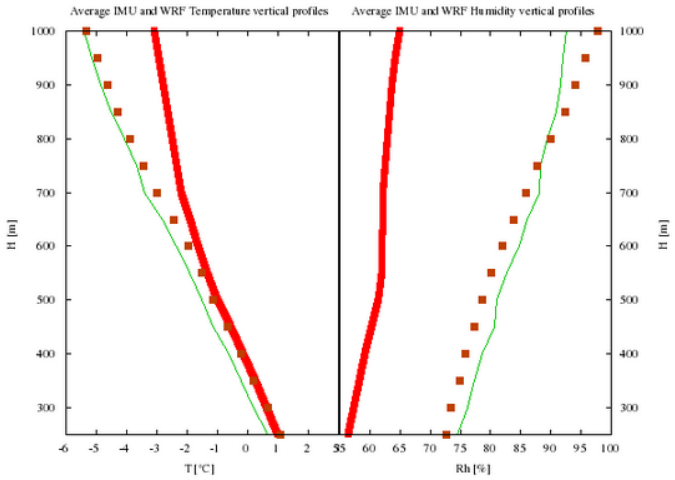

Figure 15 Comparison of temperature and relative humidity profiles of IMU unit and WRF prediction during the flight was made on 27 November 2013 in Szeged airport, Hungary (the green line: IMU measured data, red square: averaged IMU data and the thick red line: WRF prediction)

As it can be shown, the predicted temperature profile and the measured one looks very similar with the difference less than 1 ℃ in the lower 700 m atmospheric layer. Above 700 m, the difference was higher but not more than 2.2 ℃ (at 1030 m maximum height). On the other hand, our numerical prediction underestimated the real relative humidity values by 20-40 % (**Figure 15**). It means our temperature forecasting was adequate but the relative humidity prediction was a little bit poor. We have to note the tendencies of measured and predicted relative humidity profile was very similar (increasing with the height) but the values were different. The possible cause of this underestimation: smaller moisture advection values were computed by the WRF model with its applied parameterization than the real ones.

Nevertheless our analog statistical and numerical (WRF) weather predictions are well-used but we have to develop our complex meteorological support system to produce more accurate weather forecasts for the UAV users.

VII. Conclusion

The proper, detailed and significant meteorological support is essential in the planning and executing phases of the UAV missions, too.

Our meteorological support for the UAV missions is based on the following parts:

- an adequate data base of the main airports which contains the METAR data;
- the applied static and dynamic statistical methods which can help us to give prognostic information for the UAV pilots and specialists;
- the WRF based numerical weather model which can give us high resolution weather prediction;
- the applied post-processing methods which are based on WRF products to predict some dangerous weather phenomena such as low visibility and ceiling, etc.;
- a special web site where we can access the adequate meteorological information in some graphical, text and other formats via (mobile) internet connection.

Nowadays, the most important task is to link the statistical weather predictions with the numerical ones to give better combined approach in connection with the prediction of real weather situation for the UAV missions. Based on our early work, we also develop an easily accessed (from mobile smart phones) web-based high resolution meteorological support version to the UAV pilots and experts in the Carpathian basin.

On the other hand, we develop a flight path optimization routine to minimize the weather hazards of the UAV flight. During the development of our meteorological system, we are able to support our UAV flights themselves with it, too.

Acknowledgment

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