Wind and Temperature Networking Applied to Aircraft Trajectory Prediction

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***Abstract*—Trajectory prediction estimates the future position of aircraft along their planned trajectories in order to detect potential conflicts and to optimize air space occupancy. In the present paper we will try to improve the trajectory prediction by sharing the wind and the temperature information between aircraft. Based on the current performances of Air Traffic Control systems , controllers are able to efficiently detect conflict 20 minutes in advance ; for a larger time horizon (look-ahead time), the induced trajectory prediction uncertainty strongly reduces the reliability of the conflict detection. The goal of this work is to measure the potential benefit produced by sharing wind/temperature measures between aircraft (this concept will be called *Wind/Temp Networking (WTN)*). To reach this goal, aircraft measure (temperature and pressure) and calculate (wind and density) their local atmospheric data and broadcast them to the other aircraft. Having such distributed weather information, each aircraft is able to compute an enhanced local wind/temperature map as a function of location (3D) and time. These updated wind/temp fields could be shared with other aircraft and/or with ground systems. Using this enhanced weather information, each aircraft is able to improve drastically its own trajectory prediction. This concept has been simulated in the French airspace with** 8000 **flights. Comparisons have been investigated on trajectory prediction performances with and without wind/temp networking. Statistics have been conducted in order to measure the benefit of such concept in both time and space dimensions showing higher improvement in high traffic areas, as expected.**

I. INTRODUCTION

Initiatives, based on 1998 ICAO [1] Global ATM Operational Concept [1], have been taken to improve the safety and efficiency of air transportation through major projects like *NextGen* [2] in the USA, *SESAR* [3] in Europe and *CARATS* [4] in Japan. All these projects need to optimize the arrivals to airports through the emerging *Trajectory Based Operations (TBO)* concept. The TBO is based on knowing and sharing the current and planned aircraft positions. This means that aircraft are constrained in a spatio-temporal space, i.e a *4 Dimensions (4D)* space (3D+T). This 4D trajectory concept introduces a fourth parameter in the trajectory and time constraints on specific waypoints may be negotiated between the flight crew and the air traffic controllers, in order to sequence the traffic and to reduce congestion in sectors. This new concept introduces time-based management in all phases of flight. To address the flexibility requested by air carriers, these projects assume that a 4D trajectory is negotiated via a datalink between the ATC and the aircraft before push-back, during all flight phases and up to the arrival gate. The data are exchanged directly between the *Flight Management System (FMS)* and ground systems.

The flip side of the coin is that more precise information is required on the aircraft position at any given moment, i.e current position and predicted position, or in other words the look-ahead time must be increased. As explained in [5] errors in wind estimation lead to ground speed errors and cumulative along-track error between -8 NM and +8 NM when the wind has not been updated during the last 30 minutes. Practically for a jet flying at 0.8M it means 1 minute ahead or after schedule over the next half hour expected position.

Except at control towers in good visibility, controllers monitor the air traffic situation by surveillance system. This system is critical for all ATC operations. A key concept of future ATM systems is *Required Monitoring Performance (RMP)*, which is intended to specify an aircraft trajectory prediction capability and its related accuracy, integrity and availability of a monitoring system for a given sector of airspace and/or phase of operation.

Future flow management system goals to transition from a departure managed system to an arrival managed system of flow management. An accurate 4D trajectory prediction from departure to arrival enables a technology for strategic management by providing accurate state and intent information for long term path predictions. It is also an essential part for Air Traffic *Management Decision Support Tools (DST)*.

Our work tried to improve *Trajectory Prediction (TP)* accuracy, not by estimating the wind errors but by contin-

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[1] International Civil Aviation Organization

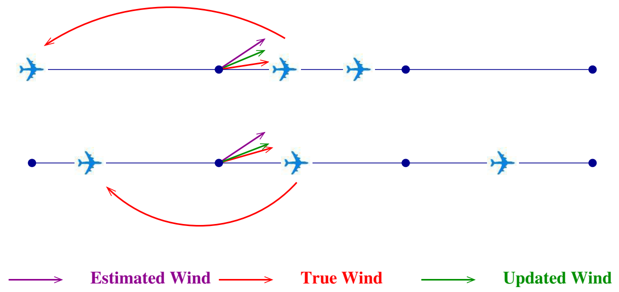

Fig. 1. Oceanic Wind Networking Concept

uously updating the wind data available on board using the wind data available from the neighboring aircraft. The wind data refresh cycle could be reduced to less than 15 minutes using this concept. This concept has already been studied for oceanic airspace and has produced very good results [6]. In this case, each aircraft back propagates its measured wind to the next following aircraft on the same oceanic track as shown on the figure 1. The benefit associated to such wind sharing concept reduces the time error at reporting position from few minutes to few seconds.

In the present work we propose to study the benefits of such a concept for tactical application mainly to improve the near term trajectory prediction. The first part of the paper introduces some backgrounds decribing how speed is computed by the FMS. The second part of the paper describes the wind/temp networking concept and how it could be applied to aircraft trajectory prediction. The third part presents the algorithm used to implement the Wind Temperature Networking (WTN) and proposes smooth vector interpolation approach. The fourth part introduces the framework used for our simulations and demonstrates the benefit of WTN of trajectory prediction for a large airspace (French airspace).

II. BACKGROUND

Before describing the concept of wind/temp networking one must introduce the different steps used for computing speed on board and show how temperature is critical in this process.

A. Aircraft operations

When considering high altitude flight (i.e above FL250 [7]), most jet transport aircraft are thrust limited and operated at constant Mach number (the ratio of air speed to speed of sound), and it has become conventional to use Mach number as an indication of flight speed. For example the *North Atlantic Tracks NATs* are operated at constant flight levels and constant Mach number to keep the aircraft separation without radar coverage.

All flights are flown with the autopilot engaged (at least to meet the *Reduced Vertical Separation Minimum RVSM* requirements) and when available with the auto-throttle engaged. Along its trajectory the *Outside Air Temperature OAT* changes, and so does its *True Air Speed TAS* as above the crossover altitude[2] the Mach number is the controlling speed. As the TAS changes the *Ground Speed GS* changes (even with constant wind) and the *Estimated Time of Arrival ETA* of each route way-point changes. Both the *Trajectory Prediction TP* calculated on board or by the ATC tools become false.

Outside TP concerns, OAT must be considered as airlines *Standard Operating Procedures SOP* recommend when flying at Optimum Altitude, that crews should be aware of temperature to ensure performance capability as available thrust depends on OAT. As *International Standard Atmosphere ISA* temperature increases, altitude capability is reduced.

To measure the impact of temperature changes on TP, we need to link the TAS to the temperature.

B. Speed Considerations

Air pressures and Mach number are related through the following equation :

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{p_t}{p_s}\right)^{\frac{\gamma}{\gamma-1}} - 1\right] \tag{1}$$

Where γ is the specific gas ratio constant (also defined as the abatic index - for air at standard conditions $\gamma = 1.4$ [8], [9]), p_t is the total pressure measured by a Pitot tube, p_s is the static pressure (also called stagnation pressure) obtained from a static pressure orifice or by some independent means. The speed of sound a in m/s is given by equation:

$$a = \sqrt{\gamma R T_s} \tag{2}$$

Where R is the air specific gas constant 287.05287 $J/(K.kg)$, T_s is the static air temperature in Kelvin and is related to the measured total air temperature T_t, by

$$T_s = \frac{T_t}{1 + \frac{\gamma-1}{2}M^2} \tag{3}$$

By computing the Mach number from Eq.(1), the static air temperature from Eq.(3) and the sound speed from Eq.(2), we can compute the air speed using the Mach number definition by :

$$TAS = aM = \sqrt{\gamma R T_s} M \tag{4}$$

On board trajectory prediction is calculated using inertial speed, GPS speed or both of them. These two speeds (or their combination) are relative to ground, called *ground speed GS* and given by :

$$\overrightarrow{GS} = \overrightarrow{TAS} + \overrightarrow{W} \tag{5}$$

[2] altitude at which a specified *Calibrated airspeed CAS* and Mach value represent the same TAS

where $\overrightarrow{W}$ is the wind vector. Combining Eq.(5) and Eq.(4) shows that the static air temperature (i.e OAT) affects GS, thus the trajectory prediction.

C. Trajectory Prediction Problem

A major concern when dealing with trajectory prediction is the ability to assess a goodness-of-fit value to the forecast trajectory compared with the original one. Many different factors may distort the prediction, their weights depend on the forecast time horizon. Theoretically, the knowledge of the flight dynamics equations for a given aircraft, the intended flight plan and exogenous parameters like temperature, wind and ATC controllers instructions should be enough to accurately model a trajectory from departure to destination. Unfortunately, many of these factors are unknown or partially known. A classical way of modeling such uncertainties is to assume that they are realizations of some random process (known from statistical estimators that can be computed using measured data). This induces a residual noise of trajectory prediction that comes after a time integration with a growing covariance matrix indicating that the estimated position is less and less accurate. The current limit is around 15 minutes if one wants to keep trajectory prediction usable, specially for early conflicts detection.

The problem of aircraft trajectory prediction involves many uncertain factors such as wind, temperature, pressure, aircraft weight, etc... Their influence strongly affects the quality of prediction when time horizon increases. Let us briefly describe some of them.

- Weight. Aircraft weight mainly depends on number of passengers, luggage, freight and fuel on board.
- Pilot Actions. Such actions are taken to follow the flight plan, to avoid adverse weather conditions or when controllers change the flight path for conflict resolution purpose.
- Wind. Wind is the major factor impacting trajectory prediction. Furthermore, wind uncertainty is spread in time and in space.
- Temperature. Air temperature is linked to air density (ρ) which drives aircraft drag $d = \frac{1}{2}c_x\rho SV^2$ where S is the wing surface, V is the aircraft air speed and c_x is a coefficient. It is also linked to the thrust limit of the engines. Maintaining a given Mach under increased temperature conditions equals increasing true air speed, and in warm temperatures thrust limit may prevent the crew from maintaining the flight plan mach number. As for the wind, temperature error is spread in time and space.
- Aircraft Trajectory Model. Several aircraft trajectory models can be applied for trajectory prediction with more or less accuracy. The more information about aircraft is available, the best the prediction will be produced by such a model. Any model induces a modeling error which has to be minimized in order to improve the trajectory prediction. In this sense, the aircraft model choice is also a limiting factor. All aircraft models, including tabular ones, are based on solving ordinary differential equations. The control input includes initial condition and model parameters. Refinement (and computational complexity) ranges from tabular to many degrees of freedom. There is always a trade-off between accuracy and smoothness.
- Measurement errors. The main measurement error is due to the radar trackers used to estimate the aircraft current position.

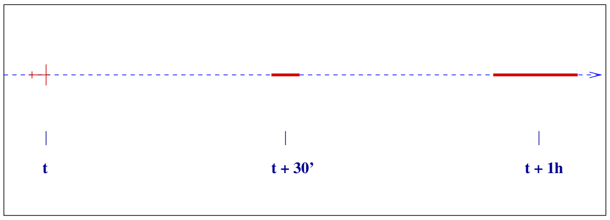

Fig. 2. Trajectory prediction limitations. Here t is the real current time, $t+10$ and $t+20$ denotes the future prediction horizon. Dark areas show the possible future aircraft positions.

Due to the stochastic nature of such perturbation factors, trajectory prediction becomes inefficient after a given period of time (about 15 minutes for conflict detection purpose). Figure 2 illustrates the trajectory prediction error evolving with time. Several efforts have been made to improve the trajectory prediction by better wind estimation [10], [11], [12], [13], [14]. In today ATM systems trajectory prediction is done using aircraft initial conditions, radar data (e.g aircraft GS, heading), filed flight plan data (e.g route, filed TAS or Mach number), Aircraft specific information and meteorological data. Without radar data, high uncertainty exists on aircraft GS, TP is biased and ATC increases aircraft separation (e.g NATs separations). Emerging *Automatic Dependent SurveillanceContract ADS-C* requires ADSC Reports. These reports include [15] :

- *Projected Profile* : next way-point, estimated altitude at next way-point, estimated time at next way-point (next+1) way-point, estimated altitude at (next+1) way-point, estimated time at (next+1) way-point.
- *Meteorological Information* : wind speed, wind direction, wind quality flag, temperature, turbulence (if available), humidity (if available).

Next step in ATM systems is the 4D trajectory negotiation between the ATC and the flight deck, which means accurate ETAs that can not be computed without reliable prediction of two spatio-temporal data : the wind and the temperature. Both data are requested through the ADS-C reports.

Above considerations show that future ATM systems will use part of the trajectory prediction computed on board, and part of the meteorological data measured on board. All these data are handled by the *Flight Management System (FMS)*.

D. FMS considerations

The FMS provides at least the primary navigation and flight planning for the aircraft. It includes navigation, flight planning and trajectory prediction functions. To support these interrelated functions, the FMS interfaces air data systems (e.g *Air Data Computer ADC*). The FMS becomes a primary player in the future ATM environment (*Request Navigation Performance RNP* airspace navigation, data-linked clearances and weather, aircraft trajectory-based traffic management, time navigation for aircraft flow control,...).

To compute the trajectory predictions, the FMS needs forecast conditions for temperatures and winds that will be encountered during the flight. The wind model is typically based on an entered wind magnitude and direction at specified altitudes, merged with the current sensed wind [16]. Future implementation of winds may be via a data link of a geographical current wind grid ground maintained database. Temperature profile is extrapolated from forecast temperature derived from the International Standard Atmosphere (ISA) [8] with an offset (ISA deviation) obtained from pilot entries and/or the actual sensed temperature [16]. Air pressure allows converting speed between calibrated airspeed, mach, and true airspeed using Eq.(1), Eq.(2), Eq.(3) and Eq.(4).

III. CONCEPT DESCRIPTION

The Wind/Temp Networking concept is based on modern aircraft capacity to measure atmospheric data through their *Air Data Computer ADC*. Plenty of accurate (i.e not derived from a numerical weather model) temperature wind data are available in every controlled airspace. We assume that in a near future aircraft will be able to exchange such information through aircraft to aircraft data link, or aircraft to ground data link [17].

During every controlled flight, an aircraft crosses control sectors and aircraft trajectories. If by any mean past data derived from its ADC is stored on board, it can be transferred to :

- other aircraft planning to fly a trajectory in the vicinity of the already flown trajectory,
- or to Air Traffic Control Center in charge of the already crossed airspace.

In order to illustrate the Wind/Temp Networking concept we will consider the B737 practical case. Most crews use a technical flight plan prepared by the company operations to fill the Flight Management System (FMS) route. Taking the example of Smith Industries B737 FMS, the crew is supposed to fill the *wind for the chosen cruising level (CRZ WIND)* field in the FMS which linearly interpolates the climb wind/temp from zero to the top of climb/temp wind value, and propagates it to the route legs if the route has already been entered. To verify the fuel balance and the *Estimated Times of Arrival (ETA)s* before take-off the crew is supposed to enter (or uplink) the predicted winds/temp in the FMS. On very short flights most of the time there is little reason to enter several en route winds/temp. On long range flights omitting forecast winds/temp, or filling the FMS with erroneous winds/temp, may lead up to erroneous fuel consumption predictions ending with a diverting flight. Obviously, as soon as airborne, accurate wind/temp values are needed to give most accurate ETAs and fuel predictions.

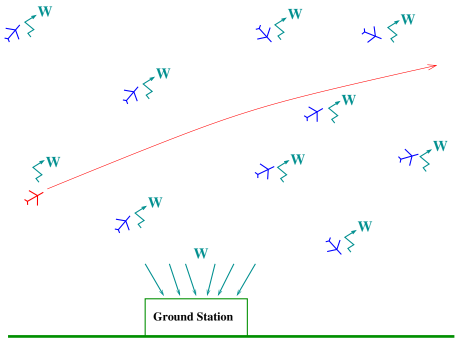

Fig. 3. Wind/Temp Networking Principle

Our concept is simple, each time a more recent wind/temp is available, it has to be “uplinked” to the FMS. This update is not limited to one flight level (e.g the currently or planned flight level), but provides an update of the predicted winds actually encountered by previous flying aircraft. Some advantages are better after take-off fuel consumption estimations (i.e better chances for a true optimal flight level), better trajectory prediction (e.g accurate ETA), better *Top Of Descent (TOD)* estimation for idle thrust descents [18] and *Continuous Descent Approach CDA* [19], [20] which also means less noise on overflown cities during the descend and approaches phases [21].

The concept may be summarized in both (see figure 3):

- near real time aircraft/aircraft wind/temp information sharing,
- near real time aircraft/ground wind/temp information sharing.

IV. ALGORITHM

The algorithm we have been developing to demonstrate the benefit of tactical wind/temp networking concept is based on wind prediction improvement by using wind measures from other aircraft in the 4D vicinity of a given aircraft. First we consider a large set of aircraft in order to have relevant statistical results. In our case, we will consider the traffic over a European country. For each trajectory sample, one must be able to locate the neighboring aircraft in a 4 dimensional space. The naive approach consists in a pairwise comparison which is dramatically inefficient. For instance, if we consider 8 000 trajectories over the French airspace with an average observation time of two hours, sampled every 10 seconds (radar period), we get $8\ 000 \times 2 \times 360 = 5\ 760\ 000$ samples. This means that if we want to find the neighboring aircraft for a given sample, we have to compute 5 760 000 distances, and identify the closest ones. Furthermore, this computation has to be done for every trajectory sample, meaning that the total distance computation is $5\ 760\ 000 \times 5\ 760\ 000 = 3,3 \times 10^{13}$. If one distance computation costs 10^{-9} second, the duration of the whole distances computation lasts $\simeq 9$ hour, which is too much. In order to avoid this brute force computation, a 4D grid has been built in which each trajectory sample has been inserted. Each point of the 8 000 trajectories is thus identified by four grid coordinates for which only local neigh boors in the grid are checked.In a first step, wind/temp maps are inserted in this 4D grid. Then, each trajectory is inserted in the grid and the computation of the trajectory prediction improvement is done into two steps. The first step updates, when possible, the wind/temp on each trajectories sample, meaning having some aircraft which has already measured some wind/temp in the current aircraft 4D neighborhood (in space and in time). For our application, neighborhood means areas where the wind/temp does not change too much with time. Then, each trajectory sample has three kinds of wind/temp (Predicted Wind/Temp, True Wind/Temp and the Updated Wind/Temp (in case of lack of neighbor, such Updated Wind/Temp is equal to the Predicted Wind/Temp, meaning there is no improvement)).

In order to improve the updated wind/temp computation process, a wind/temp interpolation algorithm has been included which interpolated the updated winds/temps. Having some wind/temp estimates on some points in the airspace located in the neighborhood of an aircraft, the next step is to build a local wind/temp field. In order to interpolate wind/temp measures we propose to use a non linear dynamical system modeling. We first consider measures from others aircraft blue arrows on figure 4. Then, a grid is built where the wind/temp fields will be computed (figure 4). To build such a wind/temp fields, non linear dynamical systems summarized by the following equation has been used :

$$\vec{W} = \dot{\vec{X}}(t) = \vec{f}(\vec{X}) \quad T = \theta(\vec{X}) \tag{6}$$

where $\vec{X}$ is the state vector of the system ($\vec{X} = [x,y,z]^T$), $\vec{f}$: C^2 the wind field representing and $\theta\vec{X}$ the temperature field.

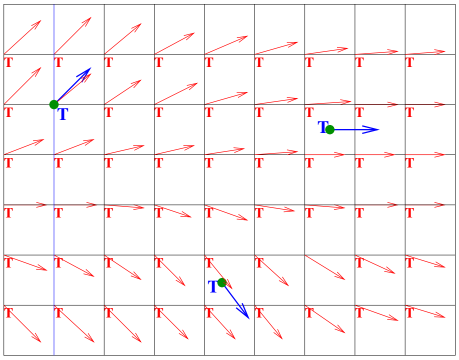

Fig. 4. Blue arrows correspond to the wind measures produced by other aircraft; at each point $\vec{X}_i$ we get also a temperature measure T_i. Red arrows represent the Wind/Temp field interpolation

These equations associate a vector speed $\dot{\vec{X}}$ and a scalar to a given position in the space coordinate $\vec{X}$. Based on the observations of the aircraft (positions, speed vectors), the dynamical systems have to be adjusted with the minimum error. This fitting is done with a Least Square Minimization (LMS) method for which the following criteria are used :

$$E_W = \sum_{i=1}^{i=N} \|\vec{W}_i - \vec{f}(\vec{X}_i)\|^2 \quad E_T = \sum_{i=1}^{i=N} \|T_i - \theta(\vec{X}_i)\|^2 \tag{7}$$

where N is the number of observations.

Our algorithm can be summarized by the following steps :

1) Generate predicted and true winds/temps in each 3D box
2) Set predicted and true winds/temps along each trajectory
3) For each trajectory sample check for neighboring aircraft in the spatial dimension. Among those neigh boors consider only the ones with a limited time horizon in the past.
4) Based on those neighbor wind/temp samples update wind/temp interpolation
5) For each trajectory update ETAs and compute difference between current and predicted ETAs

V. RESULTS

In order to validate this concept we have considered a day of traffic over France for August 12, 2014. For this day, 8543 flights have been registered and we had the wind:temp map predictions, thanks to Meteo France. We have considered the first map as the wind/temp prediction time stamped h, and in order to simulate a real wind/temp we have considered the second map time stamped $h+3$ hours as the true wind/temp. An example of such wind/temp map is given on figure 5. The 8 000 flights have been simulated with such winds and temperatures. Based on the associated flight plans, we first build the aircraft trajectories

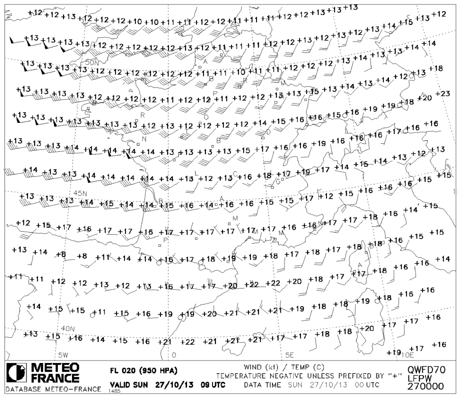

Fig. 5. Example of wind/temp map showing for a flight from Aberdeen to Paris at FL360 an OAT ISA deviation of 9° and a OAT variation of 14° along the flight path.

by using a fast time simulator based on Eurocontrol BADA data base. Such reference trajectories are simulated with the “true wind” and “true temperature”. For each trajectory, we compute the trajectory prediction by using the first wind/temp maps which corresponds to the “Pred-Wind” and “Pred-Temp”. Then, depending of the neighbor aircraft, the “updated wind” and “updated temp” are also computed at each trajectory sample. Based on those three wind/temp values, two performance analysis have been performed. The first one measures the benefit of the Wind Temp Networking on the wind/temp estimates along trajectories, the second one measures the associated benefits on the trajectory prediction performance.

A. *Wind/Temp Estimates Performances*

For each trajectory sample, three winds/temps value have been stored (the True Wind/Temp, the Predicted Wind/Temp, the Updated Wind/Temp).

Initially, the updated wind/temp is set to the Predicted Wind/Temp and if an aircraft has neighbors, this wind/temp is updated according to the winds/temps measured by the other aircraft. This updated wind/temp will be used for the trajectory prediction. Having those three winds/temp along the trajectory, it is possible to compute wind/temp errors. The error is linked to the predicted wind/temp (we will consider the norm) :

$$PredWindError = \|PredWind\| - \|TrueWind\|$$
$$PredTempError = \|PredTemp\| - \|TrueTemp\|$$

Having computed these errors for each trajectory sample, it is possible to build a “WindPredError map” (see Figure 6). The red dots represent the areas with the biggest errors and the blue dots those with the smallest errors. Similar map could be built for the temperature.

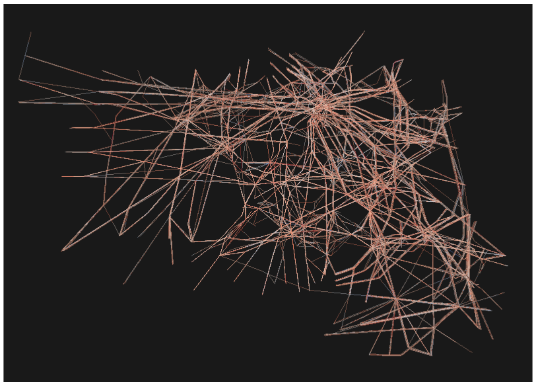

Fig. 6. This figure represents the wind prediction error on each trajectory sample. The former information is given in three dimensions but is here represented as a 2D graph. The error is computed in terms of norm. The red areas indicate an error of 15 knots.

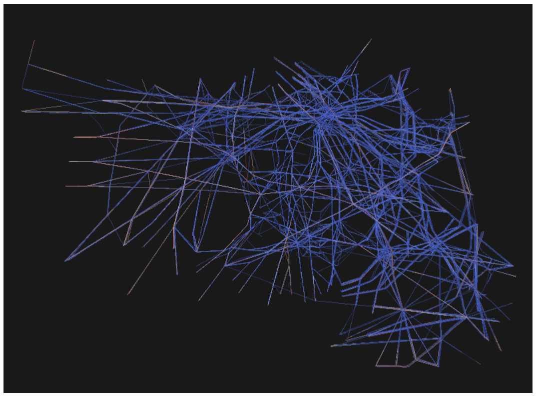

Fig. 7. This figure represents the updated wind error on each trajectory sample. As it can be noticed the red dots have disappeared in high traffic density areas. The aircraft located in low traffic density areas do not benefit from other aircraft data and do not improve their wind estimates (but their needs for wind updating is less critical as the conflict risk is lower because the traffic spreads out)

This computation has also been done for the UpdatedWindError (UpdatedTempError) :

$$UpdatedWindError = \|UpdatedWind\| - \|TrueWind\|$$
$$UpdatedTempError = \|UpdatedTemp\| - \|TrueTemp\|$$

The associated map (for the wind) is given on figure 7. We can notice that now we have much more blue areas, mainly in the high traffic density areas. The second analysis we have performed is linked to the impact of the number of aircraft on the Wind Temp Networking performances. For that we consider several aircraft densities and we compute the mean value of each error. The following tables summarizes those results. The first table (see table I) show wind/temp error statistics. For those experiments, we took the first 100 trajectories of the day, then the first 1 000 and so on. With the first 1 000 trajectories, the impact of the Wind Temp Networking is already significant, the

NbTraj	100	1 000	3 000	5 000	8 000
WindPredErr(kts)	5.11	5.13	5.12	5.11	5.14
WindUpd-Err(kts)	2.30	0.78	0.64	0.5	0.48
TempPredErr(dg)	3.00	3.01	3.01	3.01	3.01
TempUpd-Err(dg)	1.45	0.45	0.39	0.38	0.37

TABLE I
WIND AND TEMPERATURE ERRORS STATISTICS. THIS TABLE SHOWS THE EVOLUTION OF THE AVEARGE WIND-TEMP ERRORS WITH THE NUMBER OF AIRCRAFT IN AIRCRAFT..

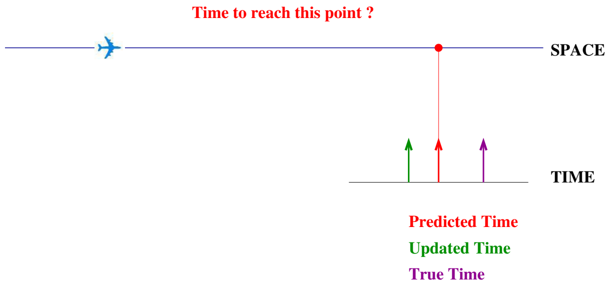

Fig. 8. At a given location, an aircraft predicts the time it will pass a given point on the future trajectory. Three times have been computed: The True Time, the Predicted Time and the Updated Time.

wind error drops down from 5.13 kts to 0.78 kts and the temperature error from 3.01 degree to 0.4 degree.

B. Trajectory Prediction Performances

In order to validate the trajectory prediction performance, we consider that aircraft has to predict their future position at a given horizon all along their trajectory. For a given location, three times are computed (the True Time, the Predicted Time and the Updated Time).

We compute also the following errors

$$PredTimeError = |PredTime - TrueTime|$$

$$UpdatedTimeError = |UpdatedTime - TrueTime|$$

For different prediction *horizon time (HT)*, we have computed the average Predicted Time Error and the associated Updated Time Error. The first simulation has been done by using Wind Networking only (see table II); in this case we consider that the predicted temperature is the same as the true temperature and only wind prediction undergoes errors (which is not the case in the real world). As we can see on the table the impact of the Wind Networking concept is significant for all time horizon. The same experiment has been done by considering Temp Networking only (see table III); in this case we consider that the predicted wind is the same as the true wind and only temp prediction undergoes errors. Finally both prediction errors have been included in the simulation which is the case for the real situations (see table IV); Wind and Temp errors together (real situation)

HT(minutes)	5	10	15	20	30	45
PreDErr(sec)	4.5	9	13.3	16.8	20.3	22.4
UpdErr (sec)	0.4	0.8	1.3	1.8	2.2	2.7

TABLE II
AVERAGE TIME ERRORS FOR DIFFERENT PREDICTION HORIZON TIMES. THE FIRST LINE SHOWS THE AVERAGE TIME PREDICTION ERROR WITHOUT WIND NETWORKING, THE SECOND ONE WITH WIND NETWORKING.

HT(minutes)	5	10	15	20	30	45
PreDErr(sec)	1.99	3.91	5.78	7.32	9.15	10.34
UpdErr (sec)	0.47	0.97	1.54	2.06	2.7	3.33

TABLE III
AVERAGE TIME ERRORS FOR DIFFERENT PREDICTION HORIZON TIMES WITH AND WITHOUT TEMP NETWORKING.

VI. CONCLUSION

In this paper we have developed a Wind/Temperature Networking concept in order to improve the trajectory prediction. In a first part, this concept has been described and we have investigated the potential applications for Air Traffic Management. We have proposed an algorithm to simulate this concept, in which we have also proposed a methodology for wind measures interpolation.

The concept has then been tested on a realistic airspace (France) with 8 000 flights, including short, medium and long haul ones. The improvement on both wind/temperature estimates and trajectory prediction has been demonstrated with very hopeful results.

Future research will also measure the impact of the Wind/Temperature Networking Concept on the route and cruising flight level optimization. Flight safety will also be concerned as aerodynamic characteristics of lifting surfaces and entire airplanes are significantly affected by the ratio of the airspeed to the speed of sound, which is a function only of air temperature. Due to its effect on air density, and on engines thrust, temperature sharing may prevent airplane upsets by offering the crew a better temperature awareness, to ensure aircraft performance capability. Rapid changes in temperature may affect the airplane capacity to stay within the buffet boundary charts, or alert the crew on a possible Clear Air Turbulence (CAT).

HT(minutes)	5	10	15	20	30	45
PreDErr(sec)	5.2	10.42	15.68	20.20	25.97	29.0
UpdErr (sec)	0.7	1.41	2.21	3.10	3.83	4.75

TABLE IV
AVERAGE TIME ERRORS FOR DIFFERENT PREDICTION HORIZON TIMES WITH AND WITHOUT WINDTEMP NETWORKING. IT MUST BE NOTICED THAT IN THIS CASE INITIAL PREDICTION ERROR IS THE BIGGEST DUE TO THE EFFECTS OF BOTH ERRORS (WIND AND TEMPERATURE).

REFERENCES

[1] OACI. *2013-2028 Global Air Navigation Plan - Doc 9750-AN/963*. International Civil Aviation Organization, fourth edition, 2013. ISBN 978-92-9249-365-3.

[2] Joint Planning and Development Office JPDO. *Concept of Operations for the Next Generation Air Transportation System*. July 2006.

[3] Consortium SESAR. Sesar master plan. Technical report, April 2008.

[4] CIVIL AVIATION BUREAU OF JAPAN. The Long-Term Vision of Future Air Traffic Systems in Japan - CARATS, 10 November 2010.

[5] Stéphane MONDOLONI. Aircraft trajectory prediction errors. Technical Report Version 0.2, July 2006.

[6] Olga Rodionova, Daniel Delahaye, Mohammed Sbihi, and Marcel Mongeau. Aircraft trajectory prediction in North Atlantic Oceanic Airspace by Wind Networking. In *DASC 2014, 33rd Digital Avionics Systems Conference*, Colorado Springs, United States, October 2014. Best Paper of Session & 2nd Place Best Graduate Student Paper.

[7] Federal Aviation Administration. Advisory Circular : Aircraft Operations at Altitudes Above 25,000 Feet Mean Sea Level or Mach Numbers Greater Than .75, September 2015.

[8] *Manual of the ICAO standard atmosphere*. ICAO, 1993.

[9] Jr. John D. Anderson. *Fundamentals of Aerodynamics*. McGraw-Hill, 2011.

[10] Mondoloni,S. and Liang,D. Improving trajectory forecasting through adaptive filtering technique. In *Proceedings of* 5^{th} *USA-Europe ATM Seminar*. FAA-Eurocontrol, 2003.

[11] R.E et al. Cole. Wind prediction accuracy for air traffic management decision support tools. In *Proceedings of* 3^{th} *USA-Europe ATM Seminar*. FAA-Eurocontrol, 2000.

[12] C.M Rekkas, C.C Lefas, and N.J Krikelis. Three dimensional tracking using on-board measurements. *IEEE Transactions on Aerospace and Electronic Systems*, 27(4):617–624, 1991.

[13] D Delahaye. Wind field update using radar track data. Master's thesis, Ecole Nationale de l'Aviation Civile, 1992.

[14] Bradford. Using aircraft radar tracks to estimate winds aloft. *The Lincoln Laboratory Journal*, 2, 1989.

[15] JEPPESEN. *AIRWAY MANUAL*, 7 Jan 2016.

[16] Randy Walter. *The Avionics Handbook - Flight Management Systems*. CRC, 2001.

[17] Mike Jackson. Standards for air traffic data. communication services. an overview for e-operations workshop. In *RTCA Special Committee 214*, 2007.

[18] Laurel Stell. Prediction of top of descent location for idle-thrust descents. In *Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)*, 2011.

[19] Dengfeng Sun Li Jin, Yi Cao. Investigation of potential fuel savings due to continuous-descent approach. *JOURNAL OF AIRCRAFT*, 50(3):807–816, May-June 2013.

[20] G.L. Slater. Study on variations in vertical profile for cda descents. In *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, 21-23 september 2009.

[21] R. Sopjes and P.M.A. de Jong and C. Borst and M.M. van Paassen and M. Mulder. Continuous descent approaches with variable flight-path angles under time constraints. In *AIAA Guidance, Navigation, and Control Conference*, 08-11 August 2011.