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Comparison of operational wind forecasts with recorded flight data

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***Abstract*—The behaviour of an aircraft and its Flight Management System adjusting its speed in order to meet an Air Traffic Control required Time of Arrival at a given waypoint in its flight plan strongly depends on the accuracy of the predicted time of arrival at that waypoint. This is the reason why assessing the accuracy of such predictions is a key element in the research on time based operations in Air Traffic Management. The accuracy of a predicted Time of Arrival at a given waypoint will depend on the prediction performance by the aircraft but also on the weather forecast that is available in the cockpit. This study aims at assessing the accuracy of the latter. For thousands of flights over a one year period, the forecasted winds that were uplinked from an airline operational centre to the aircraft have been compared with the actual wind vectors measured by the aircraft during flight. Given the large number of flights, a statistical approach was possible and the distributions (standard deviations and mean values) of the wind speed difference, wind direction difference and resulting groundspeed difference were computed. Additionally, results have been analysed from two different perspectives. First, a waypoint-based analysis has been performed for which the statistics have been computed for all the waypoints over flown of all the flights. The impact of different elements, e.g. phase of flight, wind magnitude, waypoint altitude, season, aircraft registration and forecast latency has been assessed. It seems that the wind magnitude and the forecast latency are the main drivers in terms of accuracy. Secondly, a trajectory-based analysis has been performed for which the data along a complete descent profile has been averaged for each flight, to obtain an idea of the impact of the wind forecasts on the average ground speed uncertainty during descent. This analysis has shown that the difference in average ground speed during descent that would result from applying the measured winds instead of the forecasted winds in the trajectory computations is below 12 knots for 95% of the time.**

Keywords—meteorological data; wind forecast; aviation weather; Trajectory Based Operations

I. INTRODUCTION

The purpose of the study is to assess the wind vector forecast accuracy that is currently available in the cockpit, assuming that this wind forecast is provided by a MET service provider and used in daily operations in Europe.

This accuracy of wind data has an important influence on the quality of trajectory computations of an aircraft's Flight Management System (FMS) or ground-based trajectory predictor (TP), and especially on the computation of an Estimate Time of Arrival (ETA) over a fix in the flight plan. For example, a difference of 12 knots (kts) in ground speed can result in an ETA deviation of 5%, assuming an original ground speed of 250 kts [1]. In addition the quality of wind data plays an important role when considering the use of time control in future Air Traffic Management (ATM) applications. As the speed envelope of the aircraft is bounded, the available control range to make an aircraft arrive at a specific time over a waypoint (WPT) is also limited. Reference [2] provides detailed information of the available earliest-latest time window in which aircraft can arrive over a WPT, also called ETA_{min} – ETA_{max} window, and how this window can be further reduced to make it more reliable. This idea consists of adding an extra margin to the boundaries of the physical ETA_{min} – ETA_{max} window so that if an aircraft encounters more or less unpredicted wind along its trajectory, there is still sufficient speed control available to ensure that a predefined time within the reduced ETA_{min} – ETA_{max} window can still be met. The extent to which the ETA_{min} – ETA_{max} window should be reduced depends on the assumed magnitude of the speed correction that would be necessary to arrive on time, which itself depends on the quality and quantity of the wind data in the FMS. Reference [3] has shown that the width of the achievable time windows (ETA_{min} – ETA_{max} windows) at a metering waypoint of several aircraft arriving at an airport, has a large influence on the likelihood that an efficient arrival sequence based on primarily speed control can be found in medium to high density traffic.

The purpose of this study is not to assess the quality and accuracy of the wind forecast data itself but rather to compare the wind forecast data that is currently available for operations with actual aircraft measurements. Aircraft measurements were made available by Novair, a European airline operating a fleet of three modern A321-200 aircraft. The source of wind data and the way these data are transmitted to the aircraft depends on the airline policy. In the case of Novair, the source of the wind data is the World Area Forecast Centre (WAFC) London operated by the UK Met Office on behalf of ICAO. The ICAO

WAFC London is part of a global aviation forecast system established and specified in ICAO Annex 3 and produces wind information in a GRIdded Binary code format (GRIB) [4]. The wind forecasts are produced in 4 daily model runs, based on an analysis at 00:00, 06:00, 12:00 and 18:00 Coordinated Universal Time (UTC) respectively and valid for a period of 6, 12, 18, 24 or 30 hours after the analysis time on which the forecasts were based. The wind forecasts are available approximately 4 hours after each analysis, i.e. at 04:00, 10:00, 16:00 and 22:00 UTC to be used in airline' flight planning systems. Wind information is available for different flight levels (FL) (50, 100, 140, 180, 240, 300, 340, 390 and 450) and is based on a grid of 1.25° by 1.25°. Data from the WAFC is interpolated by the flight planning system so that a forecast is obtained tailored to a specific flight, taking into account the flight planned route. The data is made available for uplink to the aircraft through an Aircraft Communications Addressing and Reporting System (ACARS) datalink service. When an aircraft requests an uplink of MET data, the latest available data is uplinked. The MET forecast data within these wind uplink messages was compared with aircraft measured data, available through the Flight Data Recorder (FDR) exports. These exports contained, at various time intervals, the aircraft state data like altitude, position, Mach number, True Airspeed, heading as well as wind speed and wind direction.

First, this paper briefly presents the outcomes of previous studies which assessed the wind and temperature forecast accuracy and defined wind and temperature information requirements for the time based operation. Following this, section III justifies the methodology retained to compare operational wind forecasts with recorded data. Then, an overview and description of the data analyzed is given in section IV. Section V presents a waypoint-based analysis and the impact of different parameters. Section VI is focused on a trajectory based analysis and a flight by flight comparison. Concluding remarks are discussed in section VII.

II. Background

Wind and temperature information requirements for a possible future enhanced Air Traffic Management (ATM) system involving 4D-time control were already formulated in the EUROCONTROL PHARE program. Standard deviations (STD) for along track wind component of 5 kts and for temperature of 2.5° C were considered as a requirement for meteorological data to achieve accurate time of arrival control in an aircraft. MET service providers were assumed being able to comply with the temperature requirement, but not with the requirement for wind [5].

Studies have been conducted in the PHARE program showing that during winter, where the jet streams tend to be stronger in the northern hemisphere (around FL300-340), the Root Mean Square (RMS) wind vector error of aviation forecast data could exceed 20 kts in a 24 hour forecast, 15 kts in a 12 hour forecast and 10 kts in a zero hour forecast. Over Europe as a whole, where the average wind strength is weaker, the errors were found smaller, being 16 knots in a 24 hour forecast, 12 kts in a 12 hour forecast and 8 kts in a zero hour forecast. At lower levels, where winds were found to be less strong on average, the RMS errors were considerably smaller, e.g. 10 kts in a 12 hour forecast during winter. Using aircraft measured data as input to improve the forecast, also called "Nowcasting", experiments showed that errors of less than 1° C in temperature and close to or less than 5 kts in wind component were possible, results that were dependent upon a sufficient supply of aircraft data [6].

More recent studies have been conducted as well. Reference [7] assessed the quality of the MET information of an Automatic Dependent Surveillance-Contract (ADS-C) of an aircraft. MET information in the ADS-C reports of a European carrier was compared with wind and temperature forecast fields from a specific Numerical Weather Prediction (NWP) model, the European Centre for Medium-Range Weather Forecasts (ECMWF), during 76 days. For the investigated period and data sample, a STD of respectively around 5.5 kts and 10° was found for wind speed and wind direction differences.

In a study done by Air Services Australia based on aircraft measurements from 729 arrivals into Melbourne airport over a 4 month period during summer, the RMS wind vector difference between aircraft measured wind and WAFC GRIB based wind was calculated for each arrival. The average of these RMS values was 8.2 kts with a STD of 3.6 kts [8].

Finally, a study has been conducted in the U.S. comparing Aircraft Meteorological Data Relay (AMDAR) wind measurements from the aircraft with 2 hour National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) forecast data. Depending on the FL RMS wind vector differences of between 8 and 10 knots were found [9].

This brief overview indicates already that it is often difficult to compare the results of different studies, as each study has typically its own defined performance indicators (RMS vector difference of all measurements, average of RMS vector difference of each trajectory, average and STD of the ground speed difference, etc.).

III. Methodology

The measured wind reports contained in the FDR of a specific flight were compared with the wind forecasts available in the ACARS wind uplink messages which were prepared by the airline's operations centre for this flight. FDR data and wind uplink messages stored by the airline over a period of one year, between 1st of July 2011 and 30th of June 2012, were made available for analysis. During a flight, two types of wind uplink messages were available to the crew:

- Wind forecast information at a set of altitudes for climb or descent phase of flight.
- Wind forecast information for several WPTs at defined FLs for the en-route phase.

A. *En route comparison volume*

For each of the en-route WPTs defined in a wind uplink message, a comparison volume around this WPT was created (Fig. 1 and 2). This volume is defined by:

- A spatial window consisting of a cylinder centered on the WPT with a height of +/- H and a radius R.

- A time window defined as the time starting when the message has been received until the next message or the end of the flight.

The FDR data for the same flight was then retrieved and whenever the trajectory contained in this FDR data crossed the defined volume, the recorded wind measurements were averaged within the volume. A WPT for which both wind uplink information was available and measured data of the FDR had been found and averaged, is called "comparison point".

B. Climb or descent comparison volume

For each of the FLs contained in the climb or descent part of the wind uplink messages, a comparison volume around this FL was created. This volume has the same shape than the one created for the en-route comparison points except that the R of the cylinder depends on the aircraft trajectory which is illustrated in Fig. 3. In this figure it can be seen that the R is given by the aircraft's slope to ensure that all the data within the defined buffer +/- H around the FL will be considered.

C. Data processing and filtering

Directional references within the raw data were as follows:

- The wind direction in the wind uplink messages were referenced to True North.
- The wind direction recorded in the FDR data were referenced to True North.
- The aircraft heading recorded in the FDR is referenced to Magnetic North.

Therefore, to ensure that the same reference was used during the data processing, the aircraft's heading was converted to True North using a worldwide magnetic variation (declination) table.

In addition, when computing the wind direction difference, a filter was applied to only take into account the data for which the wind speed (coming from the wind uplink message) was greater than 10 kts.

D. Data analysis

For each of the comparison points, the wind speed difference WS_{diff}, the wind direction difference WD_{diff}, and a ground speed difference GS_{diff} was computed as follows:

$$WS_{diff} = WS_{FDR} - WS_{MET} . \quad (1)$$

$$WD_{diff} = WD_{FDR} - WD_{MET} . \quad (2)$$

$$GS_{diff} = GS_{FDR} - GS_{MET} . \quad (3)$$

Where:

- WS_{MET} and WD_{MET} are respectively the wind speed and the wind direction forecasted in the wind uplink message.
- WS_{FDR} and WD_{FDR} are respectively the wind speed and the wind direction recorded in the FDR.
- GS_{MET} is the aircraft ground speed computed by applying the wind forecasted in the wind uplink message to the aircraft's True Airspeed and track.
- GS_{FDR} is the aircraft ground speed computed by applying the wind recorded in the FDR to the aircraft's True Airspeed and track,

For each of these differences (wind speed, wind direction and ground speed), the statistical distribution was plotted and the mean and standard deviation of these distributions were computed. Fig. 10 in section V of the paper gives an overview of these distributions.

E. Determination of the comparison volume

Table I and II show the distribution parameters, i.e. STD and Mean, for WS_{diff}, WD_{diff} and GS_{diff} versus several comparisons volumes. The first two columns of Table I provide the definition of the comparison volume (radius R and height H). In Table II, only H is given, as the R for the descent comparison volume is computed from the aircraft's slope. The next column gives the number of analyzed comparison points. The last six columns give the STD and Mean of the wind speed difference distribution, wind direction difference distribution and ground speed difference distribution. For en route comparison points, the most important parameter is the radius of the cylinder. Indeed, when flying at cruise level, the aircraft's altitude is usually very well maintained. Therefore, the height of the cylinder has a very small impact on the results. As shown by Table I, the number of comparison points increases with the R of the comparison volume. However, the wind speed, direction and ground speed differences are not depending a lot on the volume dimensions. As a consequence, a volume which gives a high number of comparison points but which also has realistic dimensions was selected for further analysis. For the descent phase, the number of comparison points is constant whatever the height of the cylinder. In addition, the STD and the Mean of the wind speed or ground speed difference are also constant. This means that the height has very little impact on the quality of the statistical analysis. A comparison volume of 10 Nautical Miles (NM) radius and of +/-150 feet (ft) height will be used to compute the different statistics presented in this paper. Using this volume, a total of 23400 comparison points has been found (9965 comparison points for en-route, 13299 comparison points for descent and 136 comparison points for climb).

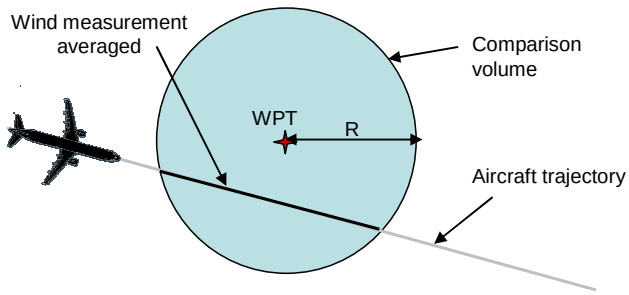

Figure 1. Plan view of an aircraft trajectory crossing an en-route comparison volume

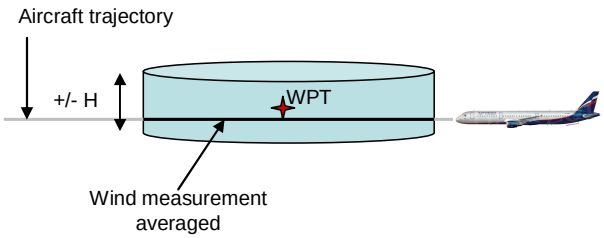

Figure 2. Side view of an aircraft trajectory crossing an en-route comparison volume

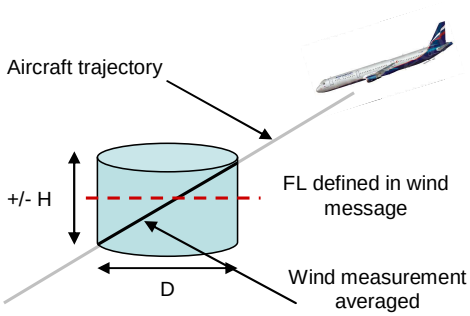

Figure 3. Climb or descent comparison volume, diameter of the cylinder (D) depends on the aircraft trajectory

TABLE I. EN.ROUTE RESULTS FOR DIFFERENT COMPARISON VOLUMES

Volume		En Route comparison points						
R (NM)	H (ft)	No. of points	WS_{diff} (kts)		WD_{diff} (°)		GS_{diff} (kts)	
			STD	*Mean*	*STD*	*Mean*	*STD*	*Mean*
3	25	4691	9.2	1.9	20.4	0.9	9.5	-0.8
3	75	6182	9.3	1.8	20.3	1.1	9.5	-0.7
5	75	7450	9.2	1.7	20.7	0.9	9.5	-0.6
10	75	9911	9.1	1.6	21.6	0.8	9.4	-0.6
10	150	9965	9.1	1.6	21.8	0.6	9.4	-0.6
20	150	13246	9.2	1.6	22.9	0.5	9.4	-0.6
20	250	13329	9.2	1.6	23	0.4	9.4	-0.6
30	250	15822	9.3	1.6	24.2	0.4	9.4	-0.8

TABLE II. DESCENT RESULTS FOR DIFFERENT COMPARISON VOLUMES

Volume	Descent comparison points						
H (ft)	No. of points	WS_{diff} (kts)		WD_{diff} (°)		GS_{diff} (kts)	
		STD	*Mean*	*STD*	*Mean*	*STD*	*Mean*
25	13296	9.2	1.4	25.5	0.7	8.4	-0.6
75	13299	9.2	1.4	26.6	0.7	8.4	-0.6
150	13299	9.2	1.4	27.5	0.7	8.4	-0.7
250	13299	9.2	1.4	28.3	0.6	8.4	-0.7

IV. OVERVIEW OF THE DATA ANALYZED

A. *Period of analysis*

A total of 2728 A321-200 flights from Novair between 1st of July 2011 and 30th of June 2012 have been considered. Fig. 4 shows the number of comparison points per month. As one may see, the number of comparison points is significantly higher during the summer (July, August and September) than during the other months, due to a more busier flight schedule in this period.

B. *Geographical coverage*

Fig. 5 shows the location of the comparison points. En-route comparison points are represented in blue while climb and descent comparison points are respectively represented in red and green. The comparison points are mainly located over Europe along a Northern Europe - Canary Island or Northern Europe - Middle East axis.

C. *Wind distribution*

The distributions of the forecasted wind speed and direction in the wind uplink messages have been plotted in Fig. 6 and 7. Fig. 6 shows that wind speeds have been forecasted from 0 to 160 kts. The average wind speed is 32 kts. The wind direction distribution plot (Fig. 7) shows that the winds are mainly coming from the North-West (from 220 to 310°). In addition, the relation between wind speed and wind direction (Fig. 8), as well as wind speed and altitude (Fig. 9) have also been plotted. These plots show that strong winds are mainly coming from the North-West and are mainly at high altitude.

V. WAYPOINT-BASED ANALYSIS

A. *Overall results*

The distribution of the wind speed difference, wind direction difference and ground speed difference are plotted in Fig. 10 for the total number of 23400 comparison points. Note that the distribution of the wind direction is based on only 20213 points which was due to the fact that wind speeds of less then 10 kts were disregarded when computing the wind direction differences. Table III provides an overview of the statistical parameters characterizing these distributions. The first column gives the number of comparison points found, the second column gives twice the STD, the third column the Mean and the last column gives the empirical 95% value of the data sample. The empirical 95% value is obtained by sorting all the values and selecting the value that bounds 95% of the values. If the data distribution is a Gaussian distribution, then the 95% value and twice the STD should be the same. It can be seen that twice the standard deviations of the ground speed and wind speed difference are very close to the 95% values, both around 18-19 kts. Twice the standard deviation for the wind direction difference is 50°, which again is close to the 95% empirical value. This indicates that the distributions can be considered as nearly Gaussian distributions.

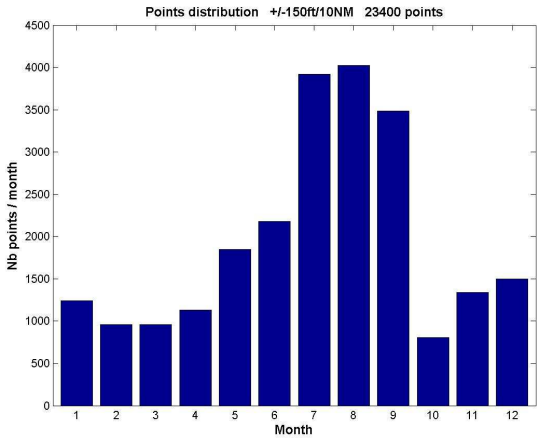

Figure 4. Number of comparison points per month

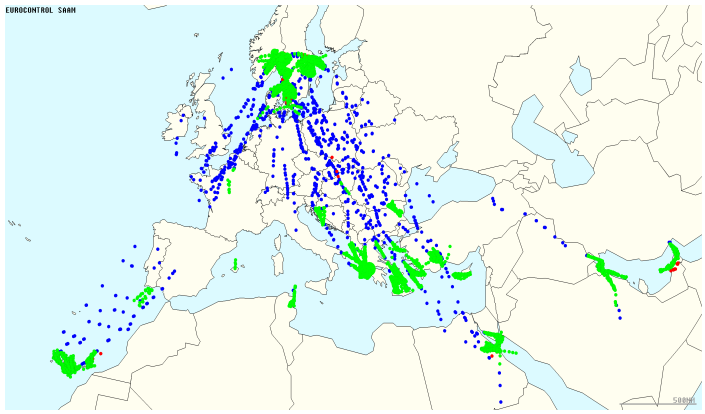

Figure 5. Plan view of en-route (blue), climb (red) and descent (green) comparison points

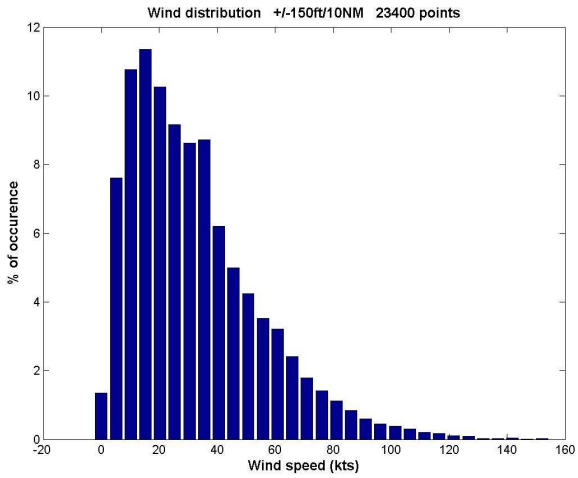

Figure 6. Wind speed distribution

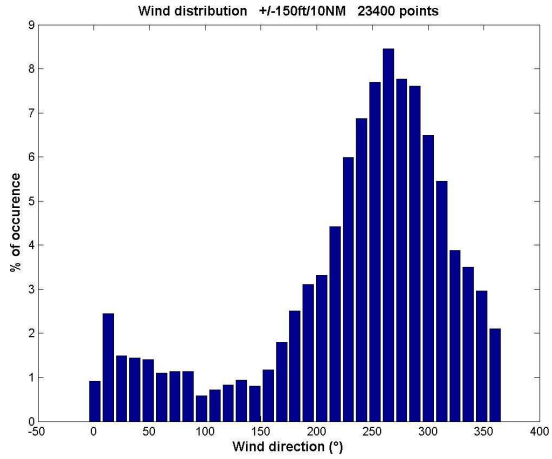

Figure 7. Wind direction distribution

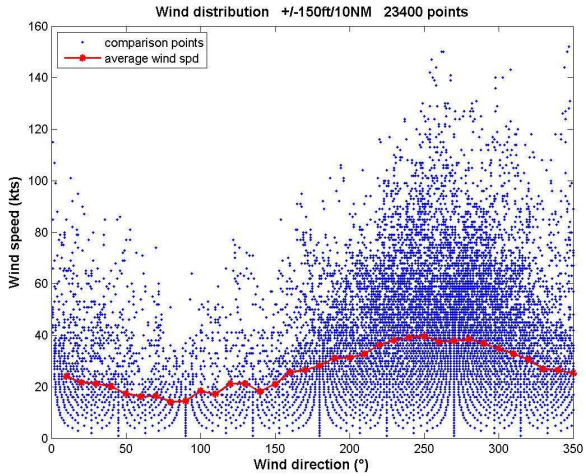

Figure 8. Wind speed versus direction

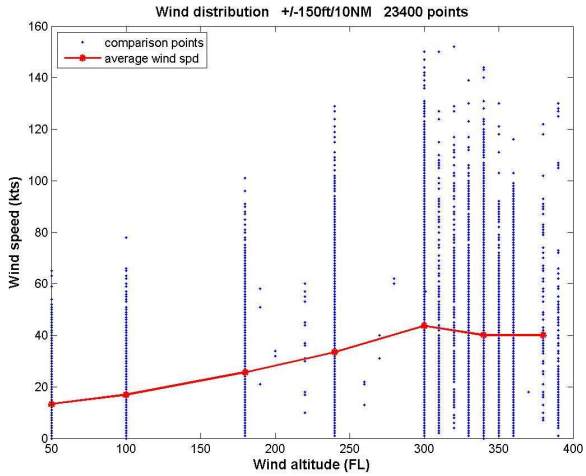

Figure 9. Wind speed versus altitude

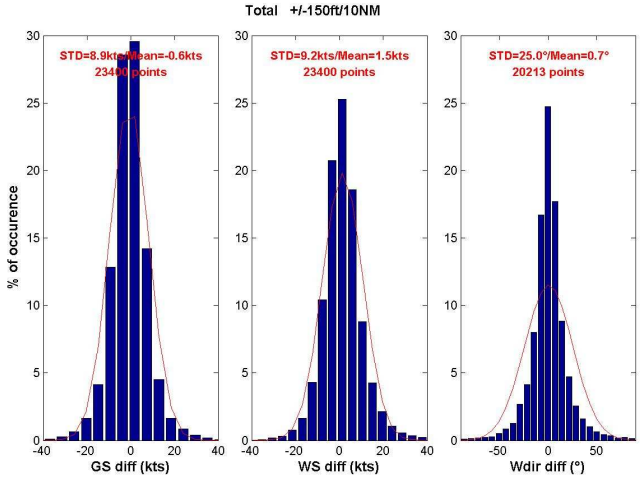

Figure 10. Ground speed (left), wind speed (centre), wind direction (right) difference distribution for the total number of comparison points

TABLE III. OVERALL RESULTS

	No. of points	2·STD	Mean	95%
GS_{diff} (kts)	23400	17.8	-0.6	18.2
WS_{diff} (kts)	23400	18.4	1.5	19.0
WD_{diff} (°)	20213	50	0.7	47.0

B. *Impact of the flight phase*

The different comparison points have been separated depending on the flight phase: en route and descent. As only the trajectory data of the last 2 hours of the flight have been considered to limit the size of the FDR exports, only 91 comparison points have been found in climb phase which is considered not enough to compute a statistical distribution. Fig. 11 shows the STD of the ground speed and wind speed difference for each flight phase. It can be observed that the STD of the ground speed and wind speed difference are both close to 9 kts, independently of the flight phase.

C. *Impact of the wind magnitude*

Another distinction has been made based on the forecasted wind speed in the ACARS datalink messages. Fig. 12 shows the STDs of the ground speed and wind speed difference for the following wind speed intervals: wind speed lower than 20 kts, between 20 kts and 40 kts, between 40 kts and 80 kts and above 80 kts. There is a clear correlation between these STDs and the wind speed: a wind speed increase induces an increase of the ground speed and wind speed difference STDs.

D. *Impact of the altitude*

The comparison points have also been separated depending on their altitude. This was done for altitudes below FL120, altitudes between FL120 and FL280, and altitudes above FL280. Fig. 13 shows the STDs of the ground speed and wind speed difference versus the wind altitude. In addition, the mean wind speed for each altitude window has been added. It seems that the ground speed and wind speed difference STDs increase with the altitude. However, this is probably related to the fact that the mean wind speed also increases with altitude.

E. *Impact of the season*

Fig. 14 shows the STDs of the ground speed and wind speed difference versus the month. In addition, the mean wind speed for each month has been added. A ground speed and wind speed difference STDs increase has been observed during fall and winter 2011/2012. However, as the mean wind speed also increases during fall and winter, and as the data sample used only covers a year of observation, it is difficult to determine whether the increase in STD is actually due to the change in season or due to the wind speed evolution.

F. *Impact of the aircraft*

Data have been retrieved from three different aircraft in the Novair fleet: SE-RDN, SE-RDP and SE-RDO. All of these aircraft are similar A321-200 types. Although it could be expected that the aircraft in which the measurements took place has no influence in the results, it makes senses to check that the ground speed and wind speed difference distributions are the same for all of the aircraft. Fig. 15 shows the STDs of the ground speed and wind speed difference for the different aircraft. As expected, no significant variation can be seen in the results from different aircraft.

G. *Impact of the forecast latency*

As previously mentioned, the wind forecast is updated every 6 hours and available for uplink at 4:00, 10:00, 16:00 and 22:00 UTC. As the wind uplink message contained the time at which this message was sent, it was possible to determine the earliest time at which the forecast information was made available to the airline. Therefore, for each comparison point, the forecast latency could be defined as the time difference between:

- The UTC time of the wind forecast availability (4:00, 10:00, 16:00 or 22:00 UTC) which is before the UTC time at which the aircraft received the wind uplink message and
- the UTC time at which the aircraft is crossing the comparison volume.

This forecast latency gives an idea about how recent the forecast was. Fig. 16 shows the STDs of the ground speed and wind speed difference for the following forecast latency intervals: 2 and 4 hours, 4 and 6 hours, 6 and 8 hours, and longer than 8 hours. It seems that overall and as could be expected, the ground speed and wind speed difference STDs increase almost linearly with the forecast latency.

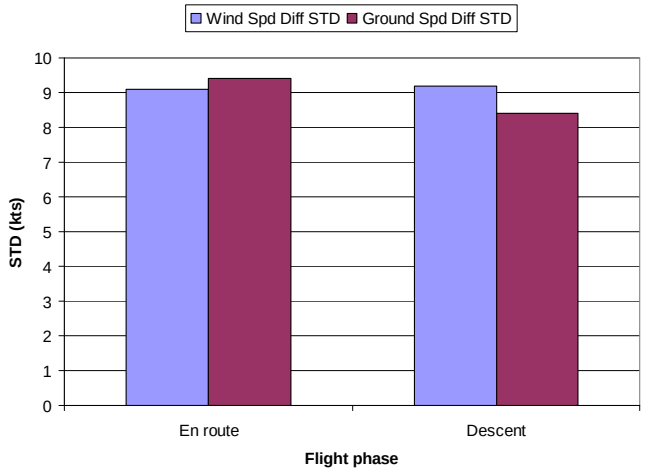

Figure 11. Wind speed and ground speed difference STD versus flight phase

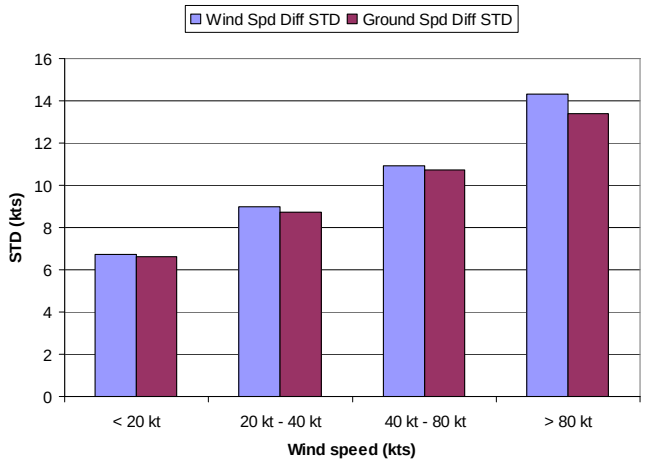

Figure 12. Wind speed and ground speed difference standard deviation versus wind speed

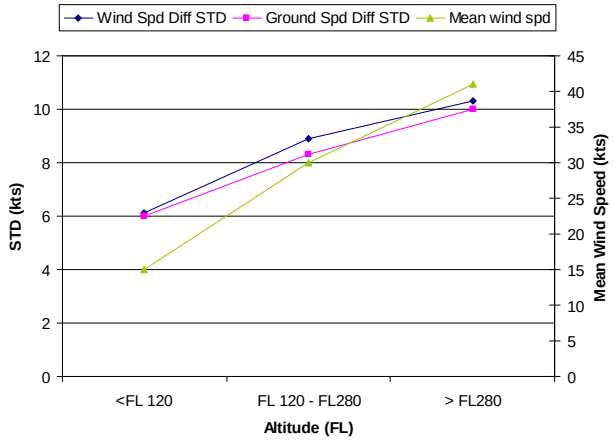

Figure 13. Ground speed and wind speed difference STDs and Mean wind speed versus altitude

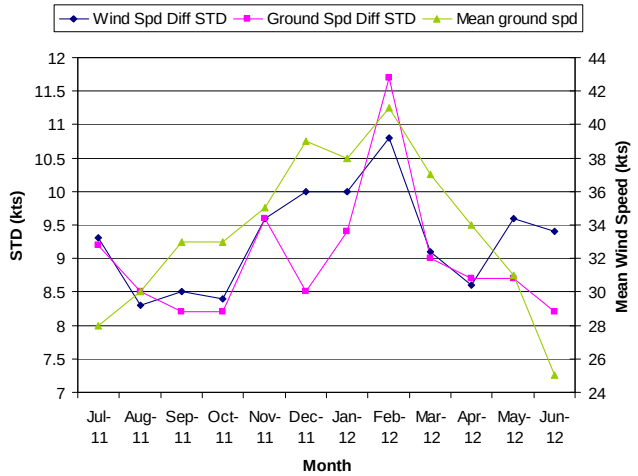

Figure 14. Ground speed and wind speed difference STDs and mean wind speed versus season

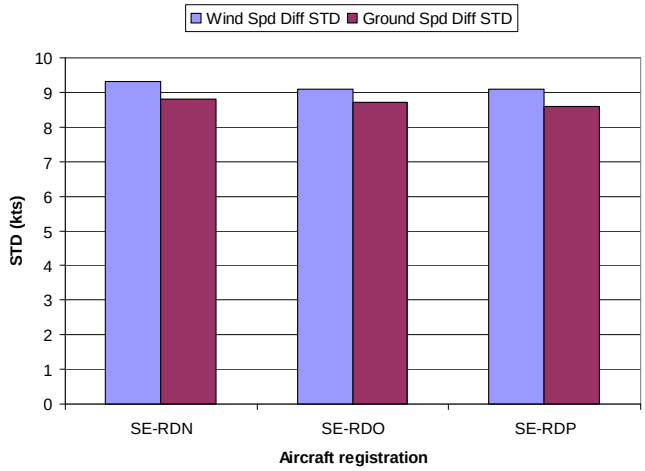

Figure 15. Ground speed and wind speed difference STDs versus aircraft

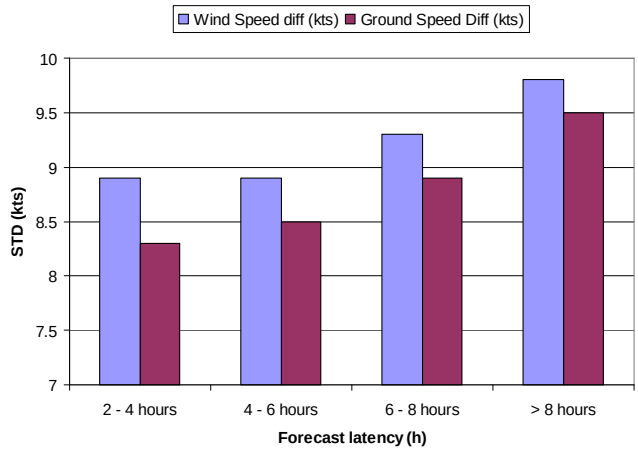

Figure 16. Ground speed and wind speed difference STDs versus forecast latency

VI. TRAJECTORY-BASED ANALYSIS

In order to assess the impact of the MET data quality on a future trajectory based operation and the capability to fly towards a Controlled Time of Arrival (CTA) in the arrival phase of flight, an analysis of the wind speed and wind direction differences at various points in the descent profile of an aircraft was undertaken and a resulting average ground speed difference during each descent profile was calculated.

The waypoint-based analysis showed that primarily the wind magnitude (and as a consequence the season and altitude as induced effects) has an impact on the ground speed and wind speed differences. Indeed, during summer and spring, the average wind magnitude is lower and so were the observed ground speed and wind speed differences. On the other hand, more comparison points were recorded during summer. To avoid any bias in the results due to this non-uniform flight distribution over the year, a subset of 433 flights was randomly selected within each season.

A. *Comparison point average along descent*

For each flight, the average of the ground speed differences, the wind speed differences, and the wind direction differences over the comparison points along the descent have been computed. Flights which had a number of descent comparison points lower than 4 were discarded. Note that in addition, the wind direction difference distribution excluded points for which the wind speed was lower than 10 kts. Fig. 17 shows the distribution of the average ground speed, wind speed and wind direction difference along the descent part of the flight while Table IV provides an overview of the statistical parameters of those distributions. The first column in Table IV gives the number of flights for which the data was calculated, the second column gives twice the STD, the third column the Mean and the last column gives the empirical 95% value. It can be observed that the STD and the 95% empirical values are much lower than the ones for the WPT based analysis. In this case, a STD of 6 kts has been computed for the ground speed and wind speed difference. In addition, twice the STD and the 95% empirical values are very close to each other, which means that the distribution can be considered as nearly Gaussian.

TABLE IV. RESULTS OF AVERAGED DATA ALONG THE DESCENT

	No. of flights	**2·STD**	**Mean**	**95%**
GS_{diff} (kts)	1732	11.8	-0.5	11.9
WS_{diff} (kts)	1732	12.2	1.3	12.9
WD_{diff} (°)	1273	29.4	1.3	31.8

B. *Interpolation of the wind profile along descent*

Another way of analyzing the effect of wind data quality on a descent operation, from a trajectory-based perspective, is to use the ACARS wind uplink message to reconstruct a descent wind profile. Then, all of the available FDR measurements along the descent profile could be compared to this descent wind profile.

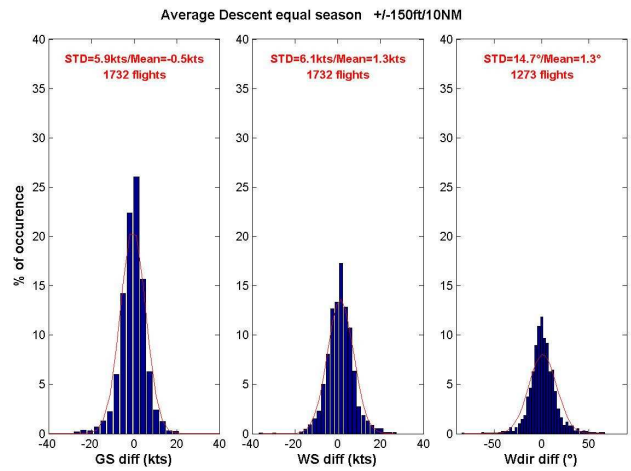

Figure 17. Average ground speed (left), wind speed (centre) and wind direction (right) difference distributions during descent phase of flight

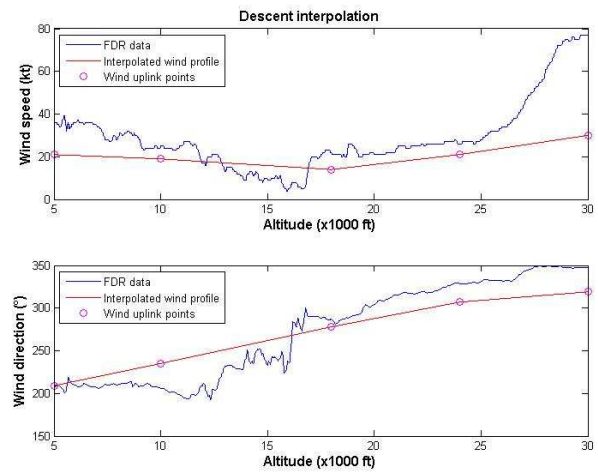

Figure 18. Wind speed (top) and direction (bottom) as defined by the FDR data (blue), the wind uplink message (magenta circle) and its linear interpolation (red)

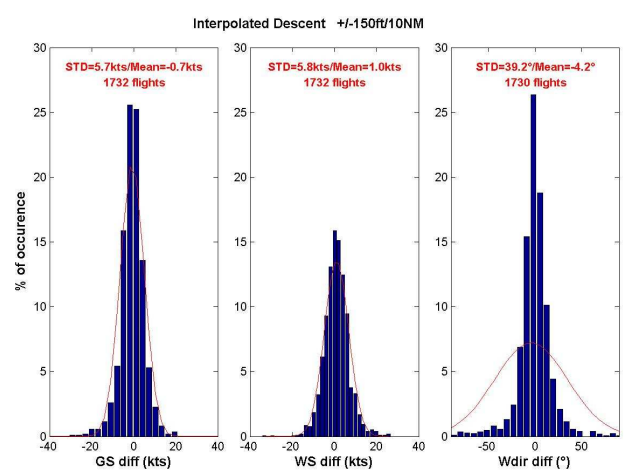

Figure 19. Average ground speed (left), wind speed (centre) and wind direction (right) differences distributions for the interpolated descent

As an example, Fig. 18 shows for one flight, the wind speed (upper figure) and wind direction (lower figure) resulting from the FDR data (blue line) as well as the same variables resulting from the wind uplink message (red line, resulting from a linear interpolation between the 5 magenta forecast points in this example).

For each flight, the descent wind profile has been determined by linearly interpolating the descent winds contained into the ACARS wind uplink message. To ensure a good quality of the analysis, any flight which had a number of descent wind points lower than 4 was discarded. In addition, the interpolated curve was bounded between the highest and lowest altitude for which a wind forecast was available in the wind uplink message. For each descent point in the FDR data, the difference between the wind speed and wind direction, resulting from the FDR data and the interpolated wind forecast, was computed and averaged along the descent profile. Also the average ground speed difference was computed using the same methodology. For the wind direction difference computation, points along the descent for which the wind speed was lower than 10 kts were discarded.

Fig. 19 shows the ground speed, wind speed and wind direction difference distributions for the interpolated wind data along the descent profiles. Table V provides an overview of the statistical parameters. The first column gives the number of flights, the second column gives twice the STD, the third column the Mean and the last column gives the empirical 95% value. The 95% empirical values and twice the STD are very close and in the order of magnitude of 12 kts.

TABLE V. INTERPOLATION ALONG THE DESCENT

	No. of flights	**2·STD**	**Mean**	**95%**
GS_{diff} (kts)	1732	11.4	-0.7	11.4
WS_{diff} (kts)	1732	11.6	1.0	11.6
WD_{diff} (°)	1730	78.4	-4.2	113.3

C. Error of the estimated time of arrival

The reconstruction of the descent wind profile allows the computation of an Estimated Time of Arrival (ETA) error at the end of the descent. This ETA error is the difference between:

- The time recorded in the FDR at which the aircraft reached the lowest descent comparison point and
- The estimated time of arrival at the lowest descent comparison point assuming that the wind is equal to the interpolated wind profile.

This ETA error can be seen as the correction to be handled by the FMS, if a Controlled Time of Arrival equal to the ETA would have been assigned at the lowest comparison point, before initiating the descent. This ETA error has been computed for each flight and divided by the altitude difference between the highest and lowest comparison point of each descent. This ratio of ETA error per altitude allows a flight to flight comparison.

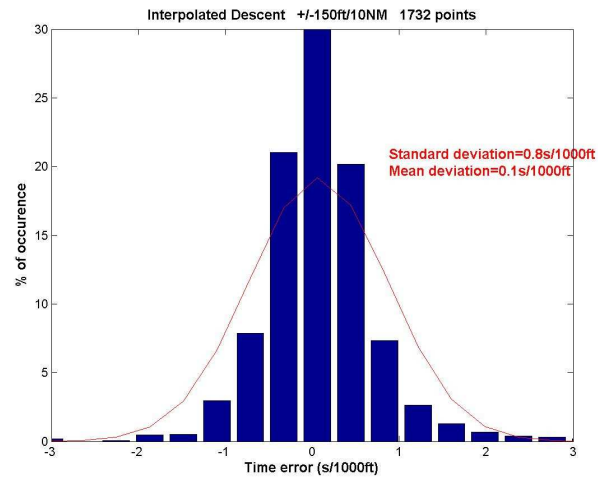

Figure 20. Arrival time error per altitude distribution for the interpolated descent

Fig. 20 shows the distribution of this ETA error. As one may see, the STD is 0.8 seconds per 1000 ft. This observation could be used to assess the arrival time error that might result from a complete descent, in the absence of active arrival time control in the aircraft FMS. Two examples can be considered:

- 95% of aircraft descending from FL300 to FL100 will arrive at FL100 with a time error of less than 32 seconds.
- 95% of aircraft descending from FL400 to the ground will arrive with a time error of less than 64 seconds.

VII. CONCLUSION

This paper has presented an analysis of the differences between operational WAFC based wind uplink data made available to an aircraft and the wind measured by the aircraft. A total of 2728 flights over a one year period have been analysed.

The first section aimed at defining the comparison volume in which the forecast and measured winds were compared. It was justified that a cylinder of 10 NM radius and 300 ft height was the most suitable. A valid time window was assigned to each comparison volume defined as the time at which the wind uplink was received until the next uplink or the end of the flight. This led to the identification of 23400 comparison points.

The second section presented the data used for the study. The distribution of the flights was not constant over the year. The number of flights was significantly higher during July, August, and September. The comparison points were not equally spread over Europe as they were mainly concentrated along the line Norway/Sweden – Canary Islands and Norway/Sweden – Greece/Turkey. The maximum forecasted wind in the wind uplink messages was 160 kts and the forecasted average wind speed over all the comparison points was 32 kts. It was concluded that winds are mainly coming from the West. The average wind speed is higher for winds at high altitude.

The waypoint-based analysis showed that the ground speed and wind speed difference standard deviations are around 9 kts which means that for 95% of the comparison points, the ground speed or speed difference is equal to or below 18 kts. The impact of different parameters has been studied. The main driver seems to be the wind speed and the forecast latency. Indeed, the STDs of the ground speed and wind speed difference increase with the wind speed and with the forecast latency. Obviously, the STD is the smallest when the winds have been uplinked less than 4 hours after the time at which the forecast data was available. As winds are stronger at high altitude and during winter, the STD of the ground speed and of the wind speed difference is higher at high altitude and during winter.

The trajectory-based analysis used a subset of flights, equally distributed in time over the year. As the wind speed is higher during winter, the use of a data set which contains more flights during summer would have lead to an over-optimistic result. Two different methods have been evaluated: the comparison point average or the average of the difference between all the descent points in the FDR and an interpolated wind forecast profile. Both methods lead to similar results. The ground speed and wind speed difference STDs along the descent were around 6 kts which means that for 95% of the flights, the average ground speed or wind speed difference along the descent would be equal to or below 12 kts. The interpolation of the wind profile allowed the computation of an ETA error at the end of the descent due to the differences in wind. This ETA error is the difference between the time of arrival estimated at the beginning of the descent and the actual time of arrival. In the absence of active time of arrival control by the aircraft FMS, the STD of this time error was estimated to be around 0.8 seconds per 1000 ft of altitude. This would mean that 95% of the aircraft descending from FL300 to FL100 would arrive at FL100 with a time error of less than 32 seconds and 95% of the aircraft descending from FL400 to the ground would arrive with a time error of less than 64 seconds.

As mentioned in the introduction, it is not straight forward to compare the results of different wind data analyses with each other, as often different performance indicators are used in each individual study. One element that seems crucial though in having reliable wind information in an aircraft is the age of the forecast data. It was observed that during some of the flights the forecast data was used more than 8 hours after the time at which it was made available to the airline operations centre, which resulted in high differences between forecast and measured data. More optimistic results were obtained when the latency of the forecast data was smaller, i.e. less than 4 hours.

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