

Enhanced Descent Wind Forecast for Aircraft

Facilitation of Continuous Descent Arrivals with Improved Efficiency and Predictability by
the use of Tailored Descent Wind Forecasts

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Abstract—In order to perform an efficient and predictable Continuous Descent Arrival (CDA), it is critical to accurately determine the geometric descent path that can be flown with idle thrust for the selected Cost Index. To build the geometric descent path, the aircraft's Flight Management System (FMS) needs to be aware of the forecast winds during the descent. Inaccuracies in these forecast winds can lead to a geometric path that cannot be flown as an idle-thrust CDA; (manual) energy management is required to maintain the path at the cost of loss in efficiency (fuel burn). Secondly, inaccurate forecast winds impact on predictability as they reduce the accuracy of trajectory predictions made by the FMS. This inaccuracy is caused by both the error in the forecast wind, and the deviations from the target descent speed as result of maintaining the inaccurately built geometric path at idle thrust (either too steep or too shallow).

Design constraints of current FMSs restrict the number of flight levels at which forecast data can be entered. This limits the definition of the wind profile for the complete descent path. Airservices Australia has developed a tool that tailors the wind forecast for a specific arrival using an improved resolution forecast provided by the Australian Bureau of Meteorology.

Flight trial results indicate that the tailored descent forecasts can provide the FMS with a better representation of the wind profile on descent leading to improved predictability. However, no benefits to aircraft operating efficiency were observed. The research found consistent large deviations from the target speed while performing a path managed descent (10kts slow on average); these deviations could however not be correlated to the error in the forecast. As non-idle thrust settings were often required because of these large deviations, it is believed any efficiency benefits of the tailored descent forecasts are obscured.

The large deviations from the target performance revealed in this research have major consequences for trajectory prediction initiatives which assume the aircraft will hold the target speed.

Keywords- CDA, forecast, trajectory prediction

I. INTRODUCTION

A. Background

It is promoted by aircraft operators worldwide that the preferred method of executing the arrival phase of a flight is to perform an idle-thrust Continuous Descent Arrival (CDA) ideally starting from cruise altitude and terminating at the Final Approach Fix (FAF) [1-3]. The concept of a CDA in itself is nothing new; before the introduction of advanced automation, a CDA could be performed using simple rules of thumb. Vietor [4] describes a method to fly a continuous descent profile to one nautical mile longitudinal accuracy using basic arithmetic. Later, the introduction of the Vertical Navigation (VNAV) function in aircraft avionics allowed for an automated, more accurate, and efficient profile to be flown. Calculating an accurate idle-thrust geometric path by the automation to the runway threshold is critical to perform an efficient and predictable CDA [5; 6].

From an ATM perspective, a CDA provides the pilot with more freedom to manage the descent compared to an ATC initiated step-down descent. This freedom brings with it uncertainty for ATC regarding the aircraft's performance and profile. Increased predictability of the aircraft's performance during a CDA is therefore essential to allow this procedure in dense traffic.

B. Motivation

Performing an efficient CDA is all about effective energy management; the sum of kinetic and potential energy possessed by the aircraft at Top of Descent (TOD) is to be reduced such that the final approach speed is reached at the required position and altitude (see Figure 1). A descent profile should be chosen such that the required deceleration and altitude loss are achieved ideally by solely the work done by drag forces and gravity, i.e. the engine throttle is set to idle and kept there until

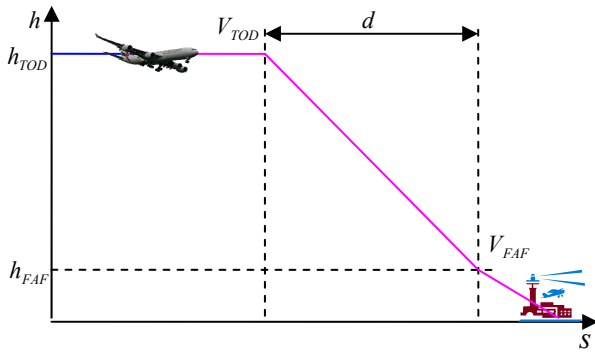


Figure 1: Energy management

the FAF¹. Equation (1) provides a simplified expression for the associated energy balance:

$$\frac{1}{2}mV_{TOD}^2 + mgh_{TOD} = \frac{1}{2}mV_{FAF}^2 + mgh_{FAF} + \int_0^d T ds - \int_0^d D ds + E_{rand}, \quad (1)$$

where V is groundspeed, T is thrust and D is drag.

It is evident that accurate estimation of the total energy for descent is essential and not only requires accurate prediction of forces involved, but also of the expected wind and temperature on descent. Any difference between predicted and experienced total energy - E_{rand} - needs to be accounted for by the application of thrust or drag reducing the efficiency of the descent.

The inaccurate representation of the wind profile on descent to the Flight Management System (FMS) is a main contributor to the error in total energy estimation [7; 8]. It is therefore hypothesized that when the FMS can contain a better representation of the wind it will encounter on descent, there will be an efficient descent with

1. demonstrable savings in fuel burn,
2. reduced application of speedbrake on descent, and
3. reduced variance in arrival time estimate error made by the FMS for points on descent.

This paper presents the research performed by Airservices Australia in conjunction with the Australian Bureau of Meteorology and Emirates Airlines, into the benefits of providing tailored descent wind forecasts to facilitate more efficient and predictable CDAs.

C. Paper Outline

This paper is organised as follows. Section II provides a detailed explanation of the forecast model available to the FMS, the associated errors, and the effect on the aircraft's performance and trajectory prediction accuracy. Section III introduces the Tailored Descent Winds forecast developed by Airservices Australia and discusses how this forecast aims to improve the wind profile representation to the FMS. Section IV

¹ Non idle thrust settings might be required for de-icing or other operational requirements.

explains the evaluation trial performed to validate the Tailored Descent Winds after which in section V the results are presented. Finally, sections VI and VII provide the conclusions and recommendations respectively.

II. FMS DESCENT WIND FORECAST MODEL

A. Weather forecast model available to FMS

To perform trajectory computations the FMS needs a model of the atmosphere the aircraft will fly through. Most relevant to trajectory computations are the wind vector in the horizontal plane (wind speed and wind direction) and (static) temperature. The World Area Forecast Centre (WAFC) supplies an aviation forecast product in a format known as GRIB (GRIdded Binary) which provides wind and temperature data for the entire world [9]. Throughout this paper this forecast product is simply referred to as GRIB.

Due to limited data storage capacity within current FMSs, only a limited forecast - extracted from the GRIB - can be loaded into the FMS. This limited forecast covers a small number of levels for climb, waypoints enroute and descent.

Depending on the FMS manufacturer, the descent forecast holds a wind direction (WD), wind speed (WS), and temperature at a limited number of levels². This design limitation requires the FMS to interpret the wind profile from cruise altitude down to the ground with limited precision.

B. Representation of descent wind profile to FMS

Figure 2 is a simplified representation of the way the FMS builds the predicted wind profile for descent. From the forecast profile above the destination, only four winds can be selected. For ease of operation, airlines generally select four standard levels, e.g. FL100, FL180, FL300 and FL390 (red arrows). The FMS subsequently interpolates between these supplied winds to form the predicted wind profile for descent (red line). The resulting predicted wind profile is used to construct the geometric path that can be flown with idle thrust for the selected Cost Index and estimate the total energy for descent.

It is reasonable to assume the interpolated profile based on four standard levels will - in general - not optimally represent

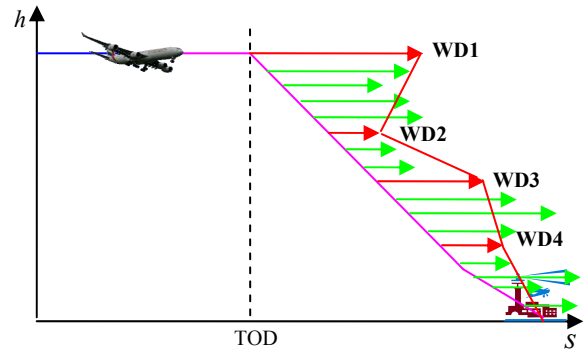


Figure 1: Predicted wind profile on descent

² The research reported in this paper involved Airbus A340 aircraft with a Honeywell FMS that accepts four descent winds. Through the remainder of this paper therefore four levels are assumed.

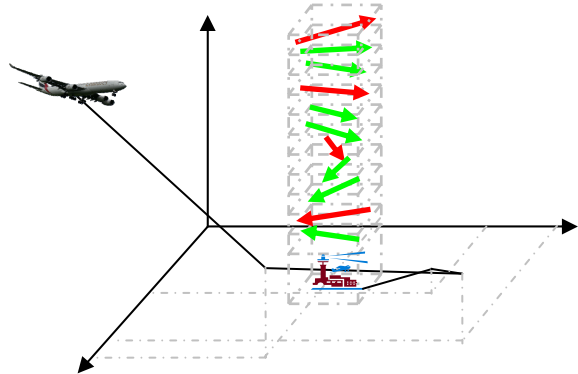


Figure 3 Limited validity of wind profile above destination

the complete forecast wind profile and therefore will lead to an inaccurate estimate for the total energy on descent.

C. Prediction error in wind profile representation

The simplified wind profile representation introduces additional errors on top of the prediction error in the GRIB base forecast. The wind profile prediction error is the sum of the base forecast error and the induced errors and is defined as the difference between the predicted wind vector \hat{w}_{FMS} - interpolated by the FMS between the four descent winds - and the observed wind vector \bar{w}_{AC} as measured by aircraft,

$$\bar{\epsilon}_{FMS}(h) = \hat{w}_{FMS}(h) - \bar{w}_{AC}(h). \quad (2)$$

Concluding, the wind profile prediction error consists of three major components:

1. *Prediction error in base forecast data.* Accuracy of the base forecast.
2. *Error due to not selected forecast grid cells corresponding to planned trajectory.* Forecast winds are currently selected from the vertical wind profile above the destination with limited spatial validity. As TOD could more than 100nm from destination, the wind profile above the destination is likely not representative for the complete descent (Figure 3).
3. *Interpolation error.* The interpolation performed by the FMS introduces additional errors.

D. Consequences on aircraft performance and trajectory prediction accuracy

When an aircraft commanded by the FMS is performing a path managed descent and encounters winds different to that expected for its descent, it will find itself tending to go either above or below its calculated geometric path. Elevator control is applied in order to maintain the path and the difference in energy - E_{rand} - is absorbed by fluctuations in the airspeed (kinetic energy). When the airspeed deviates too far from the intended target speed, either thrust is applied by the auto-throttle (add energy) or speed brake is applied manually by the crew (dissipate energy). In case the airspeed becomes too low such that non-idle thrust is required, the TOD should have been

delayed. This would have increased the cruise fuel burn; however the engines run more efficient at the higher cruise altitude. In case the airspeed becomes too high such that application of speed brake is required, the TOD should have been earlier. This would have saved some fuel in the cruise phase.

Besides affecting the efficiency of the descent, the wind prediction error affects the groundspeed and consequently the temporal accuracy of trajectory predictions. From basic aerodynamics and flight mechanics it can be derived that the effect of the wind prediction error on the groundspeed is given by [10],

$$\Delta V_g = (V_{TAS} + \Delta V_{TAS}) \cos(\gamma_{TAS} + \Delta \gamma_{TAS}) \cos(\chi_{dr} + \Delta \chi_{dr}) - V_{TAS} \cos \gamma_{TAS} \cos \chi_{dr} + \Delta w_{tl}, \quad (3)$$

where V_{TAS} is True Airspeed, γ_{TAS} the true aerodynamic path angle and χ_{dr} the angle of drift. Eq. (3) can be decomposed into the three components:

1. Δw_{tl} . Difference between experienced and predicted tailwind.
2. $\Delta V_{TAS} \cos(\gamma_{TAS} + \Delta \gamma_{TAS}) \cos(\chi_{dr} + \Delta \chi_{dr})$. Change in True Airspeed projected along the lateral path due to error in predicted wind (result of both vertical and lateral path tracking at idle thrust).
3. $V_{TAS} \cos(\gamma_{TAS} + \Delta \gamma_{TAS}) \cos(\chi_{dr} + \Delta \chi_{dr}) - V_{TAS} \cos \gamma_{TAS} \cos \chi_{dr}$. Effect of change in aerodynamic path angle and drift angle due to error in wind prediction on the True Airspeed projected along the lateral path.

The first component to consider is the direct effect of wind profile prediction error on the groundspeed. The second and third components are an indirect effect and are caused by the

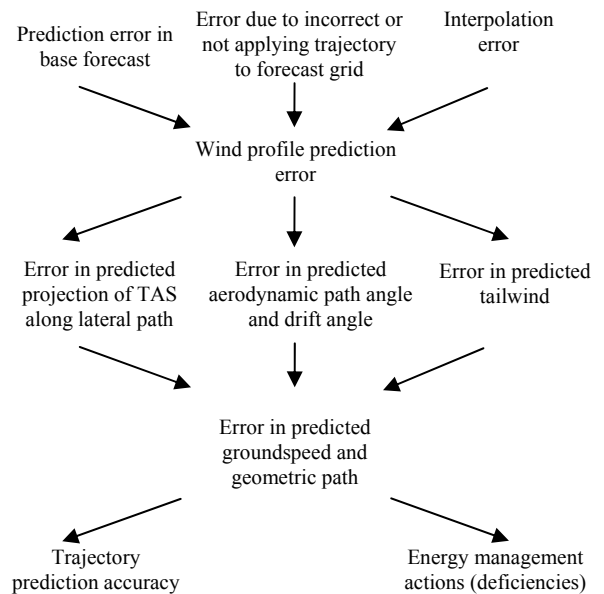


Figure 4 Schematic overview of effect of inaccurate wind profile representation to FMS on trajectory accuracy and descent efficiency

inaccuracy of the geometric descent path resulting from the wind profile prediction error (while in path managed mode). From these three components, the first two are most significant.

Estimated arrival times are in principle obtained by integrating the predicted groundspeed along the path towards the waypoint of interest. Due to the wind profile prediction error the actual groundspeed differs from the predicted groundspeed, therefore the estimate for the metering fix or any other point on descent is consequently affected;

$$\Delta T = \int \frac{1}{\Delta V_g(s)} ds. \quad (4)$$

Hence, the temporal accuracy of trajectory predictions is directly dependent on the error in predicted groundspeed and the error component of the total energy E_{rand} . As discussed, the groundspeed is affected threefold by the error in the predicted wind profile. The temporal accuracy of trajectory predictions is therefore similarly affected in threefold by the error in the predicted wind profile.

Figure 4 presents a schematic overview of the several dependencies discussed in this section and forms a roadmap for the analysis documented in this paper.

The next section describes the Tailored Descent Winds forecast developed by Airservices Australia, and discusses how it aims to provide a better representation of the forecast wind profile to the FMS.

III. TAILORED DESCENT WINDS

The Tailored Descent Winds Tool (TDWT) developed by Airservices Australia aims to decrease the wind profile prediction error in all three components:

1. *Prediction error in base forecast data.* The Australian Bureau of Meteorology has provided a high resolution forecast from the Meso- Limited Area

Prediction System (MesoLAPS) [11].

2. *Error due to not selected forecast grid cells corresponding to planned trajectory.* The TDWT computes the arrival trajectory, applies it to the MesoLAPS grid forecast, and determines the wind profile as forecast along that trajectory.
3. *Interpolation error.* From the forecast wind profile four winds are determined to most accurately describe the entire profile aiming to minimise the interpolation error.

A. Tailored Descent Winds Tool Description

Figure 5 presents a simplified view of the process in which the Tailored Descent Winds are requested, generated and delivered. At the time of this research, the tool was only configured to generate Tailored Descent Winds for aircraft arriving in Melbourne.

A request is performed through the Airservices Australia restricted access website by entering the flight’s callsign, Estimate Time of Arrival (ETA) at the destination, and final cruise level. Although this information can be derived from the flight plan, updates are required as tactical changes to the flight can cause delays and/or clearance to different final cruise level.

The request triggers the trajectory to be computed using the flight plan, the arrival information entered (TOD and ETA destination) and runway-linked Standard Terminal Arrival Route (STAR). The trajectory is subsequently applied to the MesoLAPS high resolution forecast to obtain the forecast wind profile. The trajectory is then re-computed to account for the effect of wind and temperature and re-applied to the MesoLAPS forecast. After having obtained the forecast wind profile for descent, the last step is to determine the winds most relevant to this profile - the Tailored Descent Winds.

B. MesoLAPS Base Forecast

The MesoLAPS forecast has improved spatial and temporal resolution compared to the regular WAFC GRIB forecast [11]. Using this MesoLAPS forecast the Tailored Descent Winds tool aims to decrease the prediction error in base forecast data.

The MesoLAPS forecast comprises of predictions for the wind vectors and temperatures within a volume above an area of 6 degrees latitude by 6 degrees longitude centred at Melbourne Airport with hourly forecasts up to 24 hours. This volume is designed to be sufficient to provide valid forecast from TOD to the runway threshold.

Table 1 compares the resolution of the GRIB forecast with the MesoLAPS forecast resolution. The improved resolution facilitates the application of the arrival trajectory to the forecast grid to extract the wind profile to be expected by the aircraft along that trajectory.

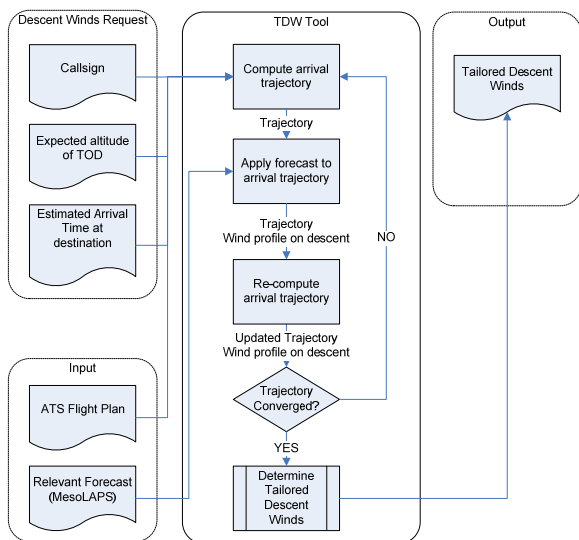


Figure 5: Tailored Descent Winds process flow chart

TABLE 1 FORECAST RESOLUTION COMPARISON

	WAFC GRIB	MesoLAPS
Lateral	1.25 deg	0.125 deg
Longitudinal	1.25 deg	0.125 deg
Vertical	9 pressure levels 850hPa–100hPa	29 pressure levels surface – 50hPa
Temporal	6 hour validity	1 hour validity

C. Application of trajectory to the forecast

The arrival trajectory computed by the TDWT is applied to the MesoLAPS forecast to extract a high resolution wind profile to be expected by the aircraft along that arrival trajectory. By applying the trajectory to the MesoLAPS forecast the TDWT aims to decrease the error due to not selecting forecast grid cells corresponding to the planned trajectory.

D. Optimisation to reduce interpolation error

After the trajectory computation process is completed the forecast wind profile $\bar{w}_{FCST}(h)$ is extracted from the trajectory and delivered to the optimization process. The optimization process in the TDWT aims to calculate four flight levels for the forecast which will minimize the profile interpolation error.

To begin the process, four initial descent winds and levels are selected from the forecast profile $\bar{w}_{FCST}(h)$. The TDWT linearly interpolates between these four winds to form the reference interpolated profile $\hat{w}_{INT_0}(h)$. For the interpolation process zero wind on the ground is assumed. The interpolated profile $\hat{w}_{INT_0}(h)$ is compared to the forecast wind profile $\bar{w}_{FCST}(h)$ to determine the Root Mean Squared Interpolation Error (RMSIE),

$$RMSIE(\hat{w}_{INT_0}) = \sqrt{E \left[\sum_{i=1}^n W(h_i) \|\bar{w}_{FCST}(h_i) - \hat{w}_{INT_0}(h_i)\|^2 \right]}, \quad (5)$$

where $W(h_i)$ are the elements of a weight vector.

The initial four winds are varied along each of their respective degrees of freedom aiming to minimise the RMSIE. Note that the TDWT handles the wind vector as a u and v (zonal and meridional wind respectively) component instead of wind direction and wind speed.

In total the Tailored Descent Winds have 11 degrees of freedom from which 3 are constrained. An overview of the degrees of freedom is given in Table 2. The lower constraint of 3000ft is to prevent the algorithm from generating a wind too close to the ground where boundary layer issues decrease the accuracy of the forecast.

The applied weight vector causes the solution to be biased to better fit those levels where the wind is most significant in relation to the True Airspeed and groundspeed. The elements

TABLE 2 DEGREES OF FREEDOM OF TAILORED DESCENT WINDS

	u	v	Level (z)
WD1	Free	Free	Fixed (LVL4 = CRL)
WD2	Free	Free	Constrained (LVL1 > LVL2 > LVL3)
WD3	Free	Free	Constrained (LVL2 > LVL3 > LVL4)
WD4	Free	Free	Constrained (LVL3 > LVL4 > A030)

of this weight vector are proportional to

$$W(h_i) \sim \frac{w_{tail}(h_i)}{V_{TAS}(h_i)} = \frac{w_{hd}(h_i)}{V_{TAS}(h_i)} - (1 - \cos \chi_{dr}(h_i)). \quad (6)$$

Note the presence of drift χ_{dr} effectively decreases the effect of a tailwind (or increases the effect of a headwind) on the groundspeed as the airspeed vector needs to be pointed off track into the crosswind in order to track a lateral path. A crosswind therefore has an indirect effect on the groundspeed.

A final note; the Tailored Descent Winds are *not* winds at four levels selected from the forecast profile along the descent trajectory; the Tailored Descent Winds are *tailored* in magnitude, direction and level such that the interpolated profile between these winds matches the weighted forecast profile most accurately.

E. Example of Tailored Descent Winds

Figure 6 shows an example of Tailored Descent Winds. The blue profile gives the predicted trajectory in latitude, longitude and altitude. The green arrows indicate the forecast wind on descent (MesoLAPS). The red arrows indicate the Tailored Descent Winds positioned along the trajectory based on the altitude levels.

IV. EVALUATION DESCRIPTION AND OPERATIONAL PROCESS

While the accuracy and benefit of the Tailored Descent Winds forecast product can be theoretically demonstrated, the purpose of the evaluation is to prove operationally if the FMS is provided with a better representation of the wind the aircraft will encounter on descent, there will be

1. demonstrable efficiency improvements (reduced fuel burn), and
2. improved accuracy of trajectory prediction.

Together with research partner Emirates Airlines, Airservices Australia evaluated the use of Tailored Descent Winds for selected arrivals into Melbourne between May 2009 and August 2009.

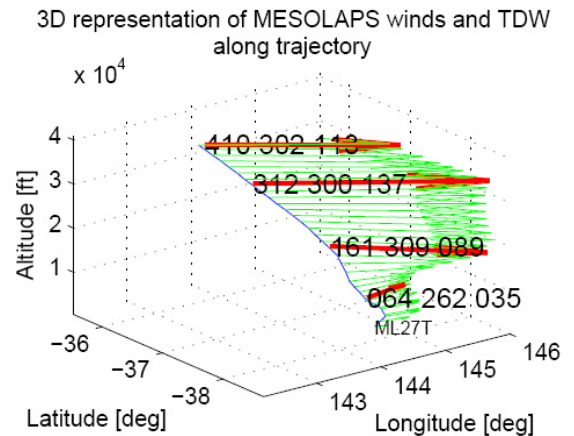


Figure 6: Example of Tailored Descent Winds

A. Evaluation and Baseline Operations

To establish benefits of the Tailored Descent Winds to the aircraft's operation over current procedures two datasets are required.

1. The first or control set contains baseline operations to analyse operations using airline provided descent winds i.e. normal operations. The airline provided descent winds will be referred to as the standard descent winds through the remainder of this paper.
2. The second or treatment set consists of a similar period of operations using the Tailored Descent Winds for comparison and evaluation.

Emirates A340-500 (A345) flights from Dubai to Melbourne were selected as suitable subject aircraft with UAE406 arriving 06:30am (local time) and UAE408 arriving 10:30pm (local time) after long transits in YMMM (Melbourne Flight Information Region) airspace. To reduce the effect of weather variations between different periods of evaluation, UAE406 provided the baseline data i.e. the current winds dataset and UAE408 provided the evaluation data using the Tailored Descent Winds. Ideally UAE406 and UAE408 should have changed role of control and treatment throughout the trial. However as an extensive manual process was involved by Emirates dispatch and flight crew to request, uplink and enter the Tailored Descent Winds, a fixed procedure was desired.

B. Collected Data

The data collected for analysis of these flights has come from two sources:

1. Automatic Dependent Surveillance – Contract (ADS-C). ADS-C intermediate projected intent data was used to determine if the use of Tailored Descent Winds resulted in more accurate arrival time predictions for points on descent [12; 13].
2. The aircraft's Quick Access Recorder (QAR). The Quick Access Recorder records among other aircraft performance data; speed (TAS, Calibrated Airspeed (CAS) and ground speed) and fuel flow. This data was used to determine if the Tailored Descent Winds resulted in operational benefits.

C. Operational Process

It was important for the validation of the Tailored Descent Winds that the aircraft systems were permitted to proceed without intervention. This was especially important in the evaluation because the benefit of the Tailored Descent Winds will be measured in terms of how the FMS controls the aircraft differently when it has more accurate and consistent information. Both Air Traffic Control and pilots were issued with instructions to ensure valid and consistent data collection.

All information concerning the arrival - (tailored) descent winds and expected STAR including duty runway - was loaded into the FMS around two hours prior to arrival at Melbourne. The Required Time of Arrival (RTA) functionality of the FMS was *not* used and the aircraft flew consistently in

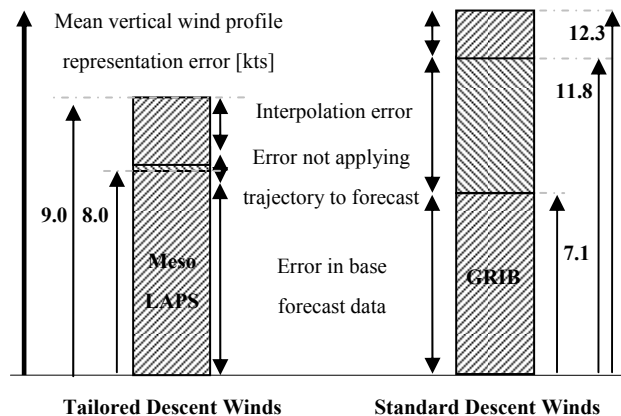


Figure 7: TDW forecast validation

LNAV/VNAV operating to a company determined Cost Index (no change in 3D geometric descent path).

V. ANALYSIS AND RESULTS

Figure 4 forms a clear roadmap of the analysis that needs to be performed to establish if the Tailored Descent Winds have provided a benefit to the accuracy of the trajectory predictions and efficiency of descent (decreased fuel burn and speed brake deflection).

First step in the analysis was to establish if the Tailored Descent Winds provided a better representation of the wind profile on descent compared to standard descent winds. Next step was to assess if the Tailored Descent Winds resulted in a demonstrably more accurate geometric path by analysing the deviation from the descent target speed from the performance data (QAR). Note that the target speed deviations provide an indication of the error component E_{rand} of the total energy as discussed earlier. Finally the effect on trajectory prediction accuracy and descent efficiency was assessed.

A. Tailored Descent Winds product validation

As discussed, the wind profile prediction error consists of three major components (top row of Figure 4). Each individual component is separately analysed to assess the effect of the Tailored Descent Winds. The Root Mean Squared Prediction Error is used to assess the wind prediction error:

$$RMSPE(\hat{w}_{FCST}) \equiv \sqrt{E \left[\sum_{i=1}^n \left\| \hat{w}_{FCST}(h_i) - \bar{w}_{AC}(h_i) \right\|^2 \right]} \quad (7)$$

For statistical significance, a large sample is preferred to validate the Tailored Descent Winds. For determination of product accuracy, it is irrelevant if the Tailored Descent Winds were actually used by the FMS, the only thing required is the wind profile observed by the aircraft and reported to the ground through ADS-C.

A sample of 91 Tailored Descent Winds forecasts is compared with the respective standard descent winds.

Figure 7 provides a summary of the results. The Tailored Descent Winds provided a reduction of 3kts in RMSPE

TABLE 3 RESULTS TARGET SPEED DEVIATION

		Sample mean	Sample Stand. Dev.
RMS Deviation	TDW	12.7	4.0
Target Speed [kts]	BASE	12.5	3.6

compared to the current standard descent winds (9.0kts vs. 12.3kts). Surprisingly, the GRIB base forecast appeared slightly more accurate than the high-resolution MesoLAPS forecast (7.1kts vs. 8.0kts).

To assess the effect of applying the trajectory to the forecast grid, the arrival trajectory is applied to the GRIB and descent winds are extracted along that trajectory at the same standard levels. These spatially selected descent winds were then compared to the normal standard descent winds. Next it was determined what improvement is gained when these winds were subsequently tailored. Clearly, the largest benefit is the application of the trajectory to the forecast grid. Note that although the interpolation error appears smaller for the standard descent winds, this is the result of interference between the error in the base forecast and interpolation error. Extensive discussion and analysis of the separate errors can be found in [10].

B. Analysis of aircraft performance

The effect of the Tailored Descent Winds on the aircraft’s performance is represented by the middle row in Figure 4. The analysis on the first component, the predicted tail wind error, is covered by the validation of the Tailored Descent Winds. The second (and third) component is analysed by evaluating the deviation from the descent target speed using the QAR data.

Of all TDW evaluation flights performed, 27 were selected to be suitable for analysis. The baseline sample consists of 56 flights.

As aircraft operate on CAS rather than TAS, the target speed given in the QAR data is a calibrated speed. The

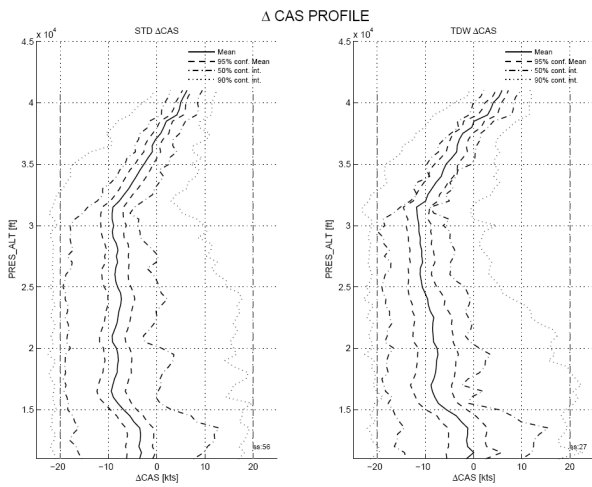


Figure 8: Profile of target speed deviation distribution

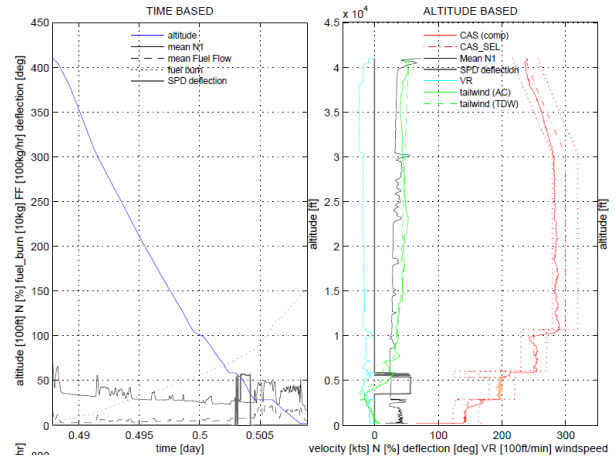


Figure 9: Example of extracted QAR data

performance indicator is therefore the root mean squared of the deviation from the target speed over the arrival,

$$RMS(\Delta V_{CAS}) = \sqrt{E[(V_{CAS_TARGET}(H_p) - V_{CAS}(H_p))^2]} \quad H_p \geq FL110, \quad (8)$$

To avoid data pollution due to manoeuvring and constraints in the terminal area, only the unconstrained arrival path above FL110 is considered.

Table 3 presents the results for the target speed deviation of both samples. There appeared to be no statistically significant difference between the two samples. Remarkably, in both samples the target speed deviation is very large. Figure 8 provides a detailed visualization of the target speed deviation for both samples as a function of altitude. On average, a descent appears to be initiated a few knots above target speed, after which it trends to an average 10 kts below target speed below FL300. Note that for the A345; the deviation is constrained to -20kts after which the throttle is activated to remain within a 20kts buffer of the target speed. From Figure 8 it can be observed that 75% of the sample operated below the target speed. No strong correlation was found between these large target speed deviations and the forecast error. The aerodynamic path appears to be built too shallow (or affected as result of other factors) to fly as an idle descent for the selected Mach/CAS. After consultation with both Emirates and Airbus, the latter confirmed the path is intentionally built a bit shallow to reduce the risk of an over-speed situation when experiencing tailwinds larger than forecasted.

Figure 9 gives an example of the QAR data extracted from one of the evaluation flights. A clear deviation from the target speed can be observed. Initially, this can be explained by the tailwind being smaller than forecast (by Tailored Descent Winds). However below FL300, the Tailored Descent Winds were shown to be accurate yet the target speed deviation remained. The deviation was that large, it triggered throttle activation resulting in a non true-idle CDA. As the aircraft flew consistently 20kts slower than the target speed upon which trajectory prediction is based, the aircraft’s estimate for the metering fix was more than 60 seconds out with less than 20 minutes to go!

Though this is just a single example, it is representative for the behaviour of the entire sample (see Figure 8). Ongoing research efforts to use aircraft derived data to enhance ground-based trajectory predictions [14; 15] relying on aircraft adhering to their target speed should be aware of this behaviour.

C. Operational Benefits

1) Average Fuel Burn

An aircraft flying an accurately calculated geometric path should have reduced need for application of thrust to account for errors in the estimation of the total energy for descent. To measure this, the average fuel flow (FF) per engine for the unconstrained descent (from cruise altitude into 10,000ft) is used as the performance indicator,

$$FF_{AVG_{FL100}} = \frac{\int_{t_{TOD}}^{t_{FL100}} FF(t)dt}{t_{FL100} - t_{TOD}} \quad (9)$$

The average fuel flow is used instead of the actual fuel used to account for difference in descent times due to different target speeds and cruise altitudes.

Table 4 provides the results for both samples. No significant difference in average fuel flow was observed. It is the authors' opinion that the large deviations of the target speed and corresponding throttle activity obscure any potential efficiency benefits of the Tailored Descent Winds.

Note that the Tailored Descent Winds should result in a more accurate determination of the TOD by the aircraft's FMS. In case the TOD resulting from the Tailored Descent Winds is before the TOD resulting from the standard descent winds, the amount of fuel saved by descending at the right time will not be measured using the proposed performance indicator. This amount of fuel saved on cruise is however not trivial to quantify.

2) Speed brake deployment

Complementary to the use of throttle is the use of speed brake. An accurately calculated geometric path should reduce the need for speedbrake deployment to prevent the aircraft accelerating through the upper limit of the allowable target speed deviation. The effect of the speed brake deployment on the aircraft's performance is best measured by calculating the work performed by the additional drag forces that cause a reduction in kinetic (and potential) energy; this is however not trivial to evaluate. Therefore, the average speed brake deployment for the unconstrained descent is used as performance indicator,

$$\delta_{AVG_{FL110}} = \frac{\int_{t_{TOD}}^{t_{FL110}} \delta_{SB}(t)dt}{t_{FL110} - t_{TOD}}, \quad (10)$$

where δ_{SB} is angle of speed brake deployment.

TABLE 4 RESULTS AVERAGE FUEL FLOW

		Sample mean	Sample Stand. Dev.
Avg. Fuel Flow into FL100 [kg/hr/eng]	TDW	577	65
	BASE	587	81

None of the evaluation flights used speed brakes during the unconstrained descent. Only one of the baseline flights used speed brakes during the unconstrained descent (12° for 16 seconds). This result is consistent with the earlier finding of an average 10kts below target speed deviation, i.e. no need for speed brake use.

3) FMS trajectory prediction accuracy

It is hypothesized the Tailored Descent Winds result in a more accurate prediction of the groundspeed on descent and hence provide a reduction in the variance of FMS trajectory prediction errors. Extensive research is being performed around the world to make use of FMS derived trajectory predictions for arrival metering purposes [16-19], therefore this paper gives special focus to the accuracy of the metering fix ETA made by the FMS.

TABLE 5 provides the ETA error (ETA minus actual time over) distribution characteristics for both samples at 10, 20 and 30min out of the metering fix. Both samples consist of 20 flights for which the metering fix ETA was extracted from the ADS-C Intermediate Projected Intent [12]. A graphical representation of the distribution versus time is given in Figure 10. The results for the baseline data are consistent with a larger sample studied by Airservices Australia [20]. It is clear that the Tailored Descent Winds resulted in decreased variance of the ETA error; maximum of 14 seconds reduction in standard deviation. Plus the bias in the data appears to have decreased, however for the small sample size it appeared not statistically significant [10]. The reduction in ETA error variance is consistent with the earlier finding that the Tailored Descent Winds improved the prediction of the tailwind component of the groundspeed on descent.

TABLE 5 RESULTS METERING FIX ETA ACCURACY

Time out		Sample mean [s]	Sample std. dev. [s]
10min	TDW	-8	19
	BASE	-13	23
20min	TDW	-9	26
	BASE	-28	36
30min	TDW	-2	30
	BASE	-17	44

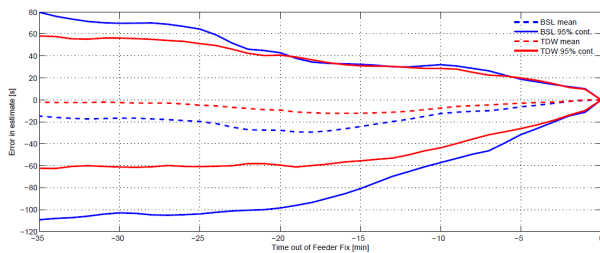


Figure 10: Metering Fix ETA error distribution over time

VI. CONCLUSION

This study evaluated the benefit of providing FMS with enhanced descent wind forecast - Tailored Descent Winds - generated by Airservices Australia's Tailored Descent Winds Tool. The tested hypothesis was that the use of an enhanced descent wind forecast leads to a more efficient CDA (demonstrated by reduced use of throttle and speedbrake on descent) and improved predictability to benefit sequencing procedures. The main conclusions found are that

1. on average the Tailored Descent Winds forecasts provided the FMS with a better representation of the wind profile on descent than the current standard descent winds forecasts,
2. the use of Tailored Descent Winds resulted in a maximum reduction of 14 seconds in the standard deviation of the estimate error for the Feeder Fix, and
3. no significant improvement to the efficiency of the descent (reduced use of throttle and speedbrake on descent) was observed due to the use of the Tailored Descent Winds. It is believed that the large deviations from the target speed obscured any efficiency benefits of the Tailored Descent Winds.

Large deviations from the target speed were observed when operating in managed descent mode for both the baseline flights and the evaluation flights. For many instances thrust was required to keep the airspeed within the buffer of the target speed, even though the predicted wind profile was accurate. The deviations from the target speed were not found to be strongly correlated to the wind profile prediction error. It is therefore believed that any efficiency benefits of the Tailored Descent Winds are obscured. It appears that the aerodynamic path is built too shallow (or affected as result of other reasons) to fly as an idle descent for the selected Mach/CAS evidenced by the 75% of the sample that operated below the target speed. After consultation with both Emirates and Airbus, the latter confirmed the path is intentionally built a bit shallow to reduce the risk of an over-speed situation when experiencing tailwinds larger than forecasted. This aircraft behaviour may have major implications for the accuracy of ground-based trajectory prediction when enhanced with aircraft derived data.

VII. RECOMMENDATIONS

Comparisons with the aircraft observational wind and temperature data received through ADS-C found that the higher resolution MesoLAPS forecast was less accurate than the regular WAFC GRIB forecast. To continue this research it

is recommended to generate Tailored Descent Winds from GRIB or other forecast product. As GRIB data is available for the entire globe, it provides the additional benefit to generate Tailored Descent Winds for any location in the world. It is noted the Bureau of Meteorology has recently implemented the Australian Community and Climate Earth-System Simulator (ACCESS) system [21] to replace previous numerical weather prediction systems and the utility of forecast data from this system will be evaluated.

This study has only used one aircraft type/ FMS combination (Airbus A340-500/ Honeywell FMS). It is therefore recommended to include other aircraft type/ FMS combinations. It would be of interest to investigate if other aircraft type/ FMS combinations also show large deviations from the target speed. It is believed that the benefits of the Tailored Descent Winds on the efficiency of the descent are obscured by the large target speed deviations. Suggestion is to include Boeing/ Honeywell (e.g. B777) and Boeing/ GE combinations (e.g. B737). Possibly, the descent forecast could be tailored per aircraft type/ FMS combination.

Finally and most importantly it is recommended to further investigate the impact of the large deviations from the target speed on the (temporal) accuracy of FMS and ground-based trajectory predictions.

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