TRAJECTORY PREDICTION PERFORMANCE COMPARISON TOWARDS EFFICIENT TIME-BASED METERING OPERATIONS

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Abstract

The performance of two Decision-Support Tools (DST) based on Trajectory Prediction (TP) technologies have been compared to demonstrate that their accuracy is influenced by the operational scenario in which they are implemented. Two sets of arrival flights into Dallas Fort-Worth (DFW), in the United States, and into Melbourne (MEL), in Australia, have been analyzed and the results are presented in this paper. The hypothesis that allowing flights to fly descent profiles managed by their Flight Management System (FMS) can significantly increase the accuracy performance of the automation systems is tested. Cross comparison data are presented and improved results are shown under these conditions. This paper demonstrates that when the FMS is able to plan the arrival trajectory based on an appropriately designed arrival procedure, and subsequently is allowed to conduct this descent in managed mode, the performance of a ground-based TP is significantly enhanced. While main focus appears on TP software improvements, this paper shows that operational concept and supporting technology are closely linked, and therefore complement one another to achieve the best result.

1 Introduction

The future evolution of the world's air transportation system heavily relies on the concept of Trajectory-Based Operations (TBOs). TBOs promise to deliver more efficient operations but most of all more predictable operations. Current operations are affected by various sources of uncertainty that cause controllers to rely on their judgment and experience to manage air traffic. This is particularly true when managing operations around busy airports. In the US and Australia, peak time arrival operations are managed using time-based metering at so-called meter fixes where air traffic controllers hand-off traffic between the en-route and the terminal airspaces.

Time-based metering is currently operated with the support of decision-support tools (DSTs) that provide controllers with a plethora of information. Among them, the most important is a schedule of the arriving traffic at the metering fix locations. The traffic schedule is built using Trajectory Prediction (TP) software that calculates the future trajectories in four dimensions, three spatial plus time. The use of TP-based DSTs is destined to increase with the forecast increase of air traffic [1].

To improve the performance of these systems the attention is often directed to software developments although the focus should also be directed to how the operations are designed to be more *predictable* by the automation. The tendency to allow more efficient type of operations, such as Continuous Descent Approaches (CDA), that are more environmentally-friendly has to be also factored in the evaluation of the performance of systems that were not designed for this operational scenario.

This paper aims at providing a different point of view in the effort to improve the performance of TP-based DSTs looking at what are the characteristics of *predictable* operations. This issue is explored looking at the arrival operations in two busy airports in two different continents, Dallas/Fort Worth (DFW) in the USA and Melbourne (MEL) in Australia. Through this comparison the additional question of how a concept developed for a specific airspace, i.e. Australia, could be extended to be applicable and successful in the USA, and vice versa is explored. The operational scenarios of the two airports are analyzed to compare how different procedures and traffic impact the trajectory prediction performance of the decision support tools that controllers use for time-based metering.

The paper starts with a description of the operations, technology and current level of performance achieved by operational and experimental TP technologies at DFW and at MEL terminal areas and airports. It continues with a comparison of the two operational scenarios and a cross-validation of the Australian experimental TP on the DFW set of flights. The paper is concluded with a discussion on the meaning of the results and on the applicability of concepts developed in one operational scenario to the other.

2 Dallas/Fort Worth TRACON Scenario

2.1 Operations: Dallas/Fort Worth TRACON

In 2012 Dallas/Fort Worth International Airport (DFW) was the fourth busiest airport in the world with more 650,000 movements per year and average more than 1,780 movements per day, within a notified daily capacity for movements of 2,938 [10]. Efficiency of arrivals calculated on a per flight average basis as 1.9 level-offs and 28.8 nautical miles of level flight between top of descent and runway threshold.

DFW terminal airspace (D10) is centered on the DFW airport consisting of a square of 60 miles on each side, and controls aircraft within its boundaries up to 17,000 feet. Dallas Love Field (DAL), the closest airport, is the next largest of more than 30 other airfields within the D10 boundaries. Super dense operations are therefore the norm around DFW airport where arrivals and departures are separated procedurally by having all arrivals enter D10 airspace from the corners of the airspace and the departures leave the airspace in the middle of the airspace edges Figure 1 [2].

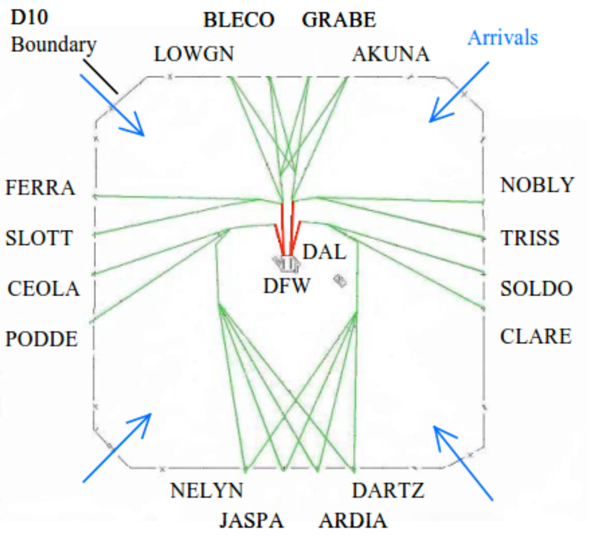

Figure 1 Departures and Arrivals in D10 in north flow situation [2].

With its seven active runways and five terminals serving mostly commercial flights (more than 67% of the total movements), DFW is a major hub for American Airlines one of the largest carriers in the United States. In order to handle the large amount of traffic wanting to land at DFW there are duplicated parallel runways generally set up to use 2 for landing and 2 for departing traffic. Arriving traffic use published Standard Terminal Arrival Routes (STAR) to descend and ATC sequence the aircraft in an arriving stream to the Terminal Radar Approach Control (TRACON) for further vectoring on to final at a minimum distance between successive arrivals.

Although the landing direction is expected, the actual landing runway is assigned by ATC to the flight crew on initial contact with the TRACON, which occurs about 35 miles from landing. The controllers keep the flight crew aware of ATC intentions however depending on circumstances the plan and sequence can change and the pilots must remain alert for that.

Vertically, without a known distance to fly along the descent path to the threshold, the FMS can only automate the descent if the crew enters their best guess of what the path will be once in the terminal area. Fortunately the vertical constraint on the STAR of 11,000 feet at either KARLA or LEMYN depending on landing direction, allows the FMS to use the

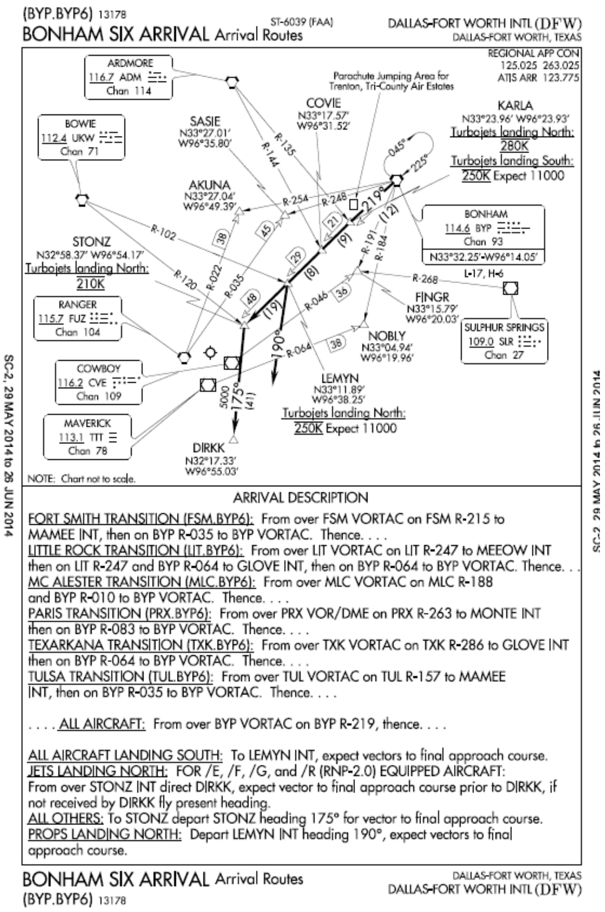

Figure 2 Bonham Six STAR for DFW, USA.

correct top of descent for an idle descent at least to the constraint point if no intervention is required from ATC. When ATC assign the aircraft descent, they also provide the expectation of the 11,000 feet vertical requirement that enables the FMS to commence descent at the appropriate location to meet the requirement. The reason ATC only issue an expectation of the requirement is that they have not yet issued descent to that level however they want the pilot to fly the aircraft as though the requirement has been issued.

During non-metering operations at DFW, traffic arriving from the North-East direction through the waypoint KARLA are handed over with at least minimum radar separation to the TRACON where up to about three minutes of delay can be absorbed. During metering operations, the TRACON traffic managers advise the center to create the required extra delay to achieve sequence times over KARLA. Techniques employed by ATC mean that with the exception of interventions for separation, in non-metering times, aircraft can fly an FMS managed descent at least to the point of the 11,000 feet requirement as it is known to the FMS prior to commencing descent. However, as a consequence of the significant traffic operating in the vicinity it is often necessary for ATC to force or even limit descent to ensure separation and thus constraining benefits of the aircraft automation.

2.2 Technology: CTAS's Traffic Management Advisor (TMA)

For TBO, Time-Based Metering is necessary to provide controllers with a consistent flow of traffic. Decision Support Tools (DSTs) are necessary to accurately predict the future trajectories of the incoming traffic. Since the 90' in the US this type of technology has been developed by NASA [4] and by MITRE [5] for the FAA. In today's operations air traffic controllers use TP-based DSTs to manage traffic into congested airport terminal areas and also to safely separate traffic in en-route airspace. An example of such a DST is the Traffic Management Advisor (TMA).

2.2.1 Description

The Traffic Management Advisor (TMA) employed at DFW was originally developed as part of the Center-TRACON Automation System (CTAS) at the NASA Ames Research Center [6], [7]. TMA was designed to provide air traffic controllers, in the transition airspace between en-route and terminal, with an accurate schedule of the incoming traffic at the meter fix and at the runway threshold.

Controllers use this schedule to manage the sequencing of incoming traffic and providing flights with delay to absorb or time to catch-up to maintain capacity. The accuracy of the information provided by TMA is paramount to provide effective time-based management of the arriving traffic into the TRACON and also to assure controller confidence in the tool.

2.2.2 Implementation

TMA has been deployed in all the centers across the US and is currently used by air traffic controllers in case when time-based metering is necessary. The FAA has a continuous program to improve the performance of TMA [3].

2.2.3 Accuracy

The data used for this analysis was recorded on May 8 2013 and comprised mainly of medium jet aircraft arrivals and over-flights (no departures) into the DFW (D10) TRACON, a total of 1,468 flights. Of this set, a small sample of 51 arriving flights through the KARLA metering fix landing south was selected. An automatic algorithm considered these descents to be not interrupted by Air Traffic Control (ATC) interventions [3]. It was important to use flights with minimal to none ATC intervention to test the performance of the system. In this case the Traffic Management Advisor (TMA) module of the Center-TRACON Automations System (CTAS) of NASA Ames, in predicting the arrival operations were consistent with the tracks actually flown.

The flights analyzed flew a consistent lateral path, entering the BYP STAR from one of two transitions: Little Rock (LIT) and Forth Smith (FSM). They were metered by TMA at KARLA where their crossing altitude was 11,000 feet and predicted speed varied by aircraft type (Figure 2). Although TMA meters flight down to the runway threshold, it is currently used by controllers to meter traffic only down to the meter fix where flights are handed from the center controllers (en-route) to the TRACON controllers in the terminal area.

The performance of TMA was evaluated using three metrics:

- The ETA error at the meter fix, calculated as the difference between the estimated time of arrival predicted by TMA at 20 minutes from crossing and the actual crossing time from recorded tracks
- The altitude error at the meter fix, calculated as the difference between the actual (flown) altitude and predicted altitude calculated at 20 minutes from crossing at the meter fix from the recorded RADAR tracks
- The Root Mean Square (RMS) error calculated at 19 minutes from the actual crossing time. This performance metric is referred as the “cone” test.

The 20 minutes time from crossing for the first two metrics was chosen to match the Australian results presented later and to make a meaningful comparison. The latter metric is presented because it is one of the performance requirements that the FAA uses to evaluate improvements in new versions of TMA [3]. This metric represents an aggregate performance of TMA in predicting the schedule of arriving flights. With little material difference, the 19 minutes represents the time before the meter fix when TMA freezes the scheduled time of arrival (STA) [6].

The mean ETA error predicted by TMA for the 51 flights arriving into DFW is 14.2 seconds with a STD of 33.6 seconds (Figure 3 and Table 1).

The mean altitude error predicted by TMA for the 51 flights arriving into DFW is 5.6 feet with a STD of 629.1 feet (Figure 4 and

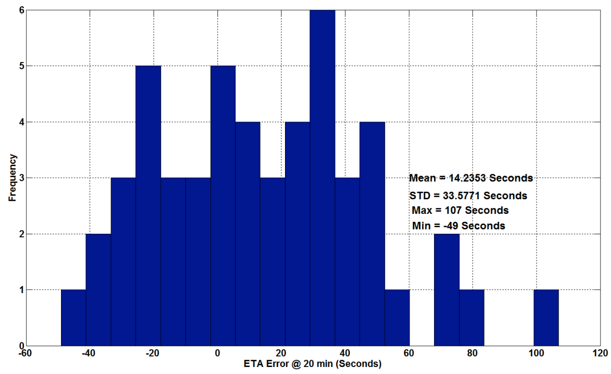

Figure 3 TMA ETA error results (DFW).

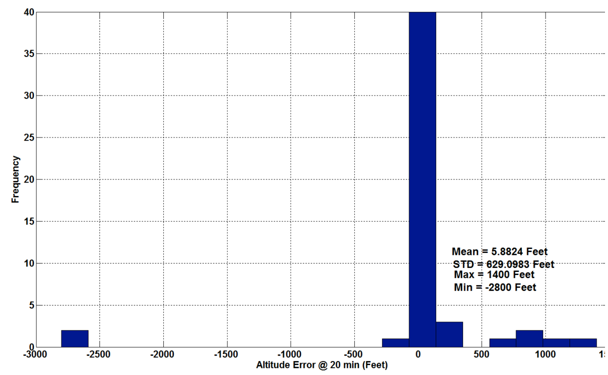

Figure 4 TMA altitude error results (DFW).

Table 1 TMA accuracy results (DFW).

TMA	DFW Sample			
Number of Flights	51			
ETA RMS Error @ 19 min (Seconds)	36			
ETA Error (Seconds)	Mean	STD	Max	Min
	14	34	107	-49
Altitude Error (Feet)	Mean	STD	Max	Min
	6	629	1,400	-2,800

Table 1). Here it needs to be noted that due to the procedural 11,000 feet altitude constraint at the metering fix KARLA for aircraft landing south, a prediction error will only occur if the constraint was tactically removed.

The RMS error predicted by TMA 19 minutes from the crossing for the 51 flights arriving into DFW is 36.2 seconds but some of the flights are outside the accuracy “cone” (Figure 5). A summary of the current accuracy results for TMA on the set of DFW flights is presented in Table 1.

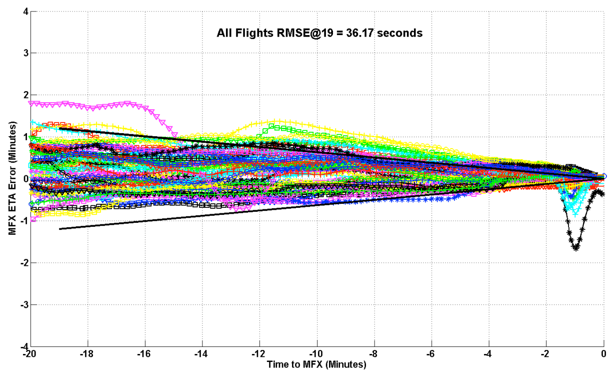

Figure 5 TMA cone test results.

3 Melbourne Terminal Area Scenario

3.1 Operations: Melbourne Terminal Area

In 2012 Melbourne Airport (MEL) was the second busiest airport in Australia with almost 280,000 movements [8], moreover the Australian city pair of Sydney-Melbourne was the 5th busiest in the world in terms of passenger movements [9]. There are two runways available at Melbourne with a third under development. Depending on the direction and strength of the wind, the landing rate using land and hold short procedures can achieve up to 44 landings per hour.

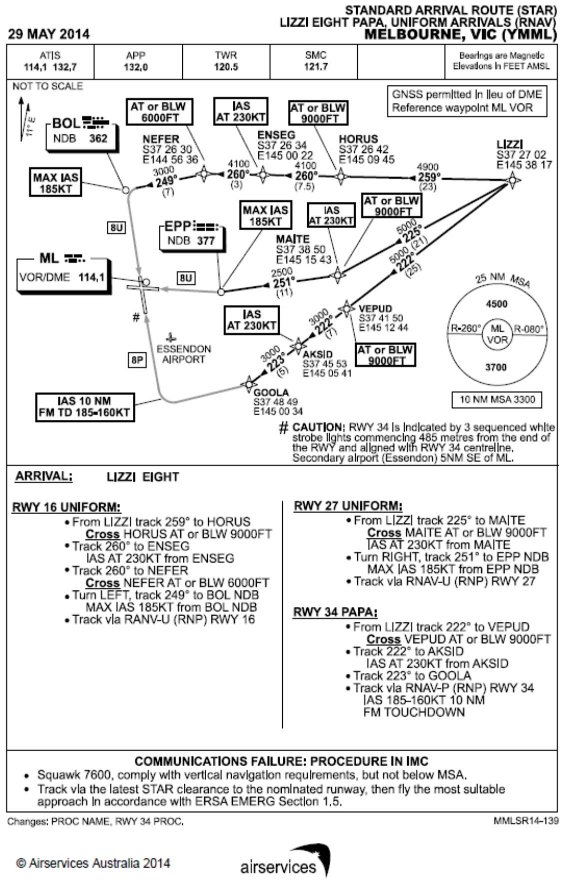

Figure 6 Example runway linked STAR for Melbourne, Australia.

The route structure surrounding Melbourne caters for arrivals from all directions by standardizing entry points to the 30 NM terminal area through a range of Feeder Fix points at approximately 30-40 NM from Melbourne. On cruise ATC assign to each arriving aircraft a Standard Terminal Arrival Procedure (STAR) providing the terminal tracking from the Feeder Fix to the landing runway in a separated structure each aircraft operates under its own navigation (i.e. departing and arriving traffic are procedurally separated through altitude constraints part of the published procedures). See the example STAR in Figure 6. The STAR and landing runway is issued and loaded to the FMS by the crew prior to top of descent allowing the FMS to plan an idle descent, and when combined with a pilot discretion descent clearance from ATC allows the aircraft to commence descent at the appropriate point. Further descent is assigned by ATC ahead of the aircraft so that normally it does not have to maintain any level on descent (Figure 7). While not specifically published as part of the STAR procedure, agreement between ATC and the major airlines operating into MEL is to descent at cruise Mach crossing over into 280KCAS. These consistent descent speeds provide ATC with improved predictability resulting in fewer interventions.

Sequencing aircraft is achieved similarly to DFW through an arrival manager calculating the time each aircraft must arrive at their specific Feeder Fix point back calculated from the sequenced original estimate for the destination. En-route ATC intervenes to adjust the Feeder Fix arrival time for each aircraft to meet the arrival manager determined time and if necessary the terminal controllers fine-tunes the spacing on final. This methodology allows coarse sequencing to occur in the cruise phase of flight with the aircraft automation allowed to commence descent appropriately to achieve an idle descent along a separated and fully defined lateral path including vertical constraints where necessary.

ATC instructions to achieve the arrival manager determined Feeder Fix time are left to the discretion of the controller and depending on the delay to absorb can vary from assigned speeds to holding. The metering to the Feeder Fix provides the terminal controller with a continuous time based sequence and each aircraft can be adjusted if necessary or allowed

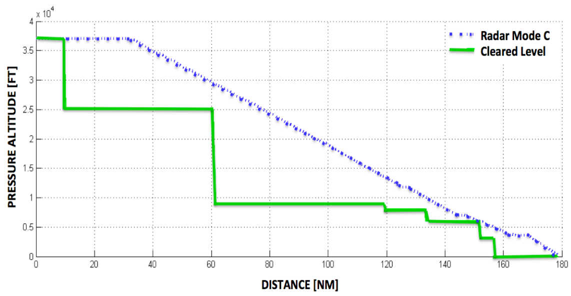

Figure 7 Continuous descent enabled by assigned altitude ahead of the aircraft.

to continue to the runway following the published procedure. Jet aircraft are issued with a different STAR to turbo props to address their different performance characteristics however the methodology and result is the same.

3.2 Technology: Dalí Trajectory Modeler

3.2.1 Description

The Dalí Trajectory Modeler tool has been developed in collaboration with Boeing Research & Technology Europe under Airservices R&D program into Trajectory Based Operations. Dalí contains a high fidelity intent generation model accurately modeling aircraft behavior, referred to as aircraft intent, including airline preferences and constraint capturing. In the model, the intent generation effectively mimics the actions of the aircraft's FMS.

Dalí has access in real-time to 6-hourly updated meteorological forecast for the entire Earth as provided by the World Area Forecast Centers (WAFCs) [11]. Dalí uses both the Base of Aircraft Data (BADA) 3 [12] and 4 [13] models, where BADA3 models are only used if no BADA4 model is available.

3.3.2 Implementation

Dalí is currently a research and development tool, and possible implementation for selected services is under investigation.

3.3.3 Accuracy

The Australian data sample consists of 438 Boeing 737-800 (B738) flights into Melbourne all performing a continuous descent fully managed by the onboard automation without ATC or crew intervention. The Dalí experimental trajectory predictor was used to generate trajectories for these flights about 15NM prior to top of descent (TOD), the resulting position and prediction horizon is comparable to the TMA results of subsection 2.2.3. While the Dalí trajectory predictor was specifically designed to integrate aircraft derived data into the ground-based prediction process, no aircraft derived data was used in the results presented in this section in order to provide a fair comparison against the TMA

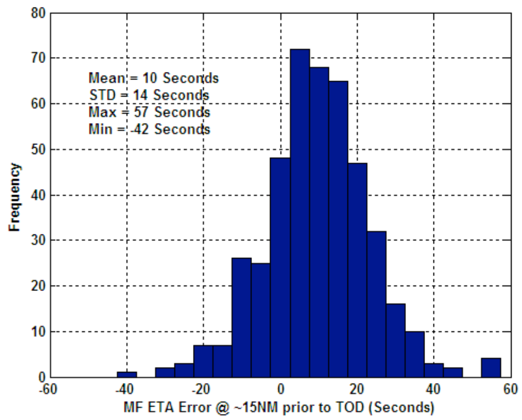

Figure 8 Dalí ETA error results (MEL).

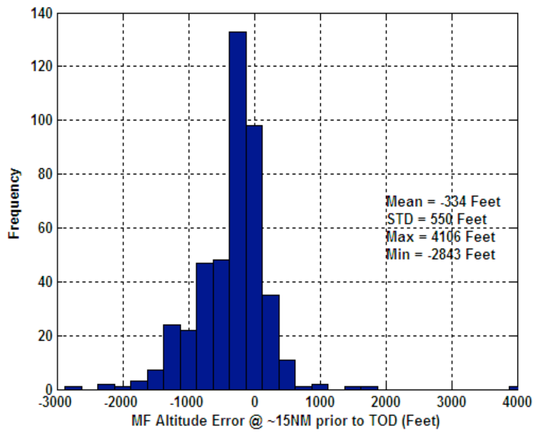

Figure 9 Dalí altitude error results (MEL).

results previously presented (for additional information please refer to Ref [14]).

While the DFW data only contains flights through a single STAR, the MEL data contains flights from all RNAV jet-aircraft STARs of which an example was provided in Figure 6. The metering fixes around MEL do not have an "AT altitude" constraint like KARLA for the DFW BONHAM STAR; the crossing altitude at the metering fix is therefore free and dependent on the FMS generated profile leading to larger prediction errors when comparing Figure 9 with Figure 4. The consistency of operations (e.g. agreed 280KIAS on descent) allows for accurate arrival time estimates when taking into account by the ground-based trajectory predictor (Figure 8 and Table 2).

Table 2 Dalí accuracy results (MEL).

Dalí	MEL Sample			
Number of Flights	438			
ETA RMS Error @ ~15NM prior TOD (Seconds)	17			
ETA Error (Seconds)	Mean	STD	Max	Min
	10	14	57	-42
Altitude Error (Feet)	Mean	STD	Max	Min
	334	550	4,106	-2,843

4 Discussion

The previous sections presented two different operational scenarios with two different supporting technologies. When comparing the experimental Dalí TP to the TMA TP, one would conclude the former TP is of higher accuracy, however what impact do the operational scenario and traffic mix have on the accuracy of the different TP systems? To answer this question, the Dalí TP was configured with adaption data for the DFW TRACON, and predictions were made for the same set of flights and initial conditions as in subsection 2.2.3. Forecast meteorological data for the DFW area was obtained from WAFC similar to the MEL predictions [11]. The results are presented in Table 3.

As can be seen from Table 3, when applied to the DFW sample, Dalí performs very similar to TMA (Table 1). If it can be assumed that the difference in accuracy between the Dalí DFW and MEL samples is independent of the

Table 3 Dalí accuracy results (DFW).

Dalí	DFW Sample			
Number of Flights	51			
ETA RMS Error @ 19 min (Seconds)	37			
ETA Error (Seconds)	Mean	STD	Max	Min
	-2	37	104	-125
Altitude Error (Feet)	Mean	STD	Max	Min
	2	629	1,392	-2,795

aircraft types (both samples consist of medium jet aircraft), the remaining major difference is the operational scenario. It therefore appears the operational scenario has a clear impact on the accuracy of supporting TP systems. Referring back to Section 2 and 3, the following clear differences between operations into DFW and MEL can be established:

- MEL has runway-linked STARs while DFW STARs end at given point after which traffic is radar vectored to final approach for final sequencing.
- For DFW an altitude constraint is present at that final point allowing to plan a FMS managed descent (i.e. LNAV/VNAV), however often tactically this constraint is relaxed as shown in the vertical accuracy results of Subsection 2.2.3.
- MEL airspace structure is less complex than the DFW metroplex and allows for less constrained terminal structures.

These differences are key to allow the aircraft to be able to plan and conduct an arrival in uninterrupted LNAV/VNAV. Both Dalí and TMA effectively assume the aircraft to fly such an automated descent; however as of tactical interferences due to traffic management strategies into DFW, often the aircraft cannot remain in managed mode and manual crew intervention is required. Such tactical intervention results in different behaviour to a standard consistent LNAV/VNAV, and therefore degraded performance of the supporting TP technology.

To investigate further, Figure 10 shows the speed profiles of two example flights into DFW in terms of calibrated airspeed (CAS). While cruising at a constant Mach number, the associated CAS should be about constant (affected by atmospheric conditions). Passing top of descent and assuming a generic managed descent, the descent is initiated at idle thrust with the cruise Mach number as target speed until crossover altitude. During this constant Mach part of the descent the CAS is increasing. Upon reaching crossover, the target speed becomes a constant CAS until a first limiting constraint is reached. When referring to Figure 10, this behaviour is somewhat recognizable, but especially closer to the metering fix significant changes in the CAS occur. During a true managed descent, such large changes

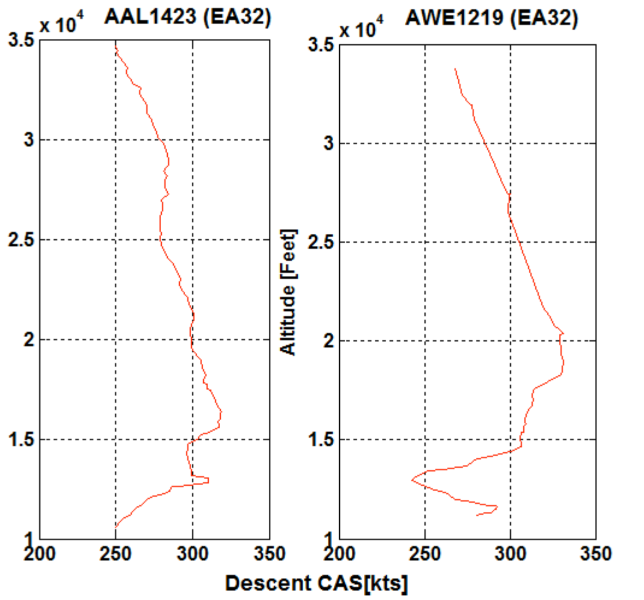

Figure 10 Example CAS profiles for DFW flights.

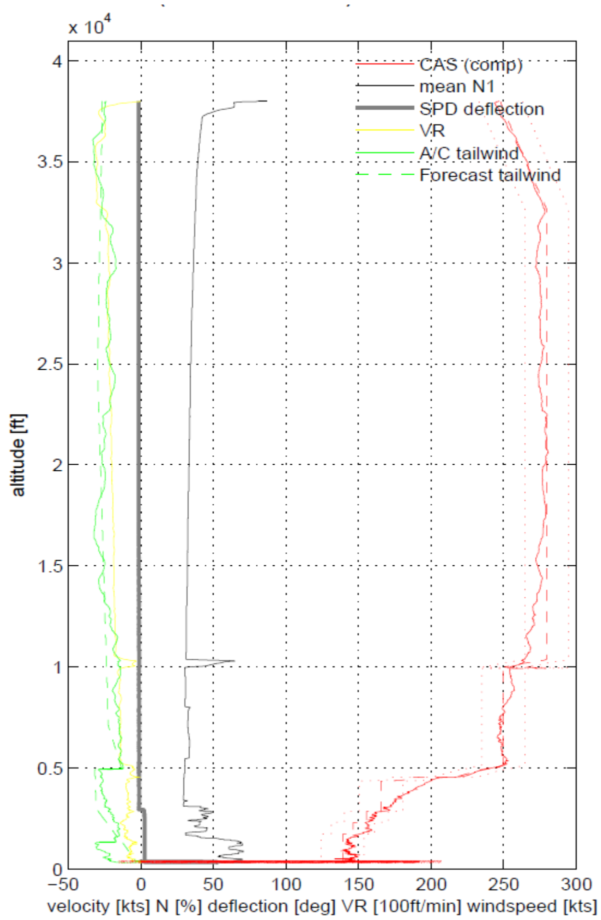

Figure 11 Example CAS profile for a MEL flight.

should not occur, and in the case of these example flights point to some crew intervention possibly to manage the descent profile in the presence of uncertain track miles to the duty runway, or uncertain ATC intent in general.

The descent speed profiles observed in DFW are often similar to the two presented in Figure 10. It is clear from the plots that, for two different aircraft types, an MD80 and an Airbus 320, the CAS in descent are not consistent, as it would be expected from a flight managed in LNAV/VNAV. This inconsistency in the descent CAS flown cause TMA (or any TP) to be inaccurate in predicting the time the aircraft cross the meter fix. This is an example of how the high-density traffic, and the structure of the STARs operational scenario in DFW affect the performance of the decision support tool (TMA) that the air traffic controllers use for metering traffic.

In contrast, Figure 11 shows a speed profile of an example flight into MEL. Because of the runway-linked STAR, the FMS is able to compute the descent profile with certainty of the amount of track miles to the duty runway. Combined with a pilot discretion descent at the FMS determined descent point, the descent can be fully conducted in managed mode, resulting in a stable speed profile close to target (dashed red line in Figure 11). As the Dalí TP is aware of the target speed through the 280KCAS agreement (see Section 3.1), it is able to predict the ETA at the metering fix with high accuracy as demonstrated in Figure 8 and Table 2.

To further support this hypothesis, the 51 flights arriving into DFW were divided to identify the cases that were (likely) flying LNAV/VNAV descents from the ones that were clearly not. Actual data on the FMS settings used by pilots were not available therefore the subdivision was performed by the authors analyzing the descent speed profiles, from recorded data, such the ones presented in Figure 10. Because the CAS data in CTAS are obtained converting the ground speed, obtained from the RADAR tracks, and the atmospheric information (temperature, wind speed and direction), this method cannot be considered completely accurate. Nonetheless the CAS profiles represent a good proxy of the guidance mode used or not used by the pilot.

The flights were therefore subdivided into "managed" and "non-managed" to verify if different performance in the TP accuracy were observed on these two categories of flights. Sixteen flights were identified to have flown "non-managed" descents and thirty-five in "managed" mode. The results for the two sub-groups of flights were analyzed for both Dalí and TMA predictions. A summary is presented in Table 4.

The accuracy results for both time predictions (ETAs) and altitude predictions are significantly better for the "managed" versus the "non-managed" flights for both TMA and Dalí. Although the sample of flights is small, it is clear how much better both TPs perform in predicting flights that are (most likely) flying in

Table 4 Results summary for Managed and Non-Managed flight, TMA and Dalí (DFW).

		DFW-Managed				DFW-Non-Managed			
Number of Flights		35				16			
ETA RMS Error @ 19 min (Seconds)	**TMA**	27				51			
	Dalí	27				53			
ETA Error (Seconds)		**Mean**	**STD**	**Max**	**Min**	**Mean**	**STD**	**Max**	**Min**
	TMA	4	27	77	-49	36	37	107	-36
	Dalí	3	28	65	-47	-15	52	104	-125
Altitude Error (Feet)		**Mean**	**STD**	**Max**	**Min**	**Mean**	**STD**	**Max**	**Min**
	TMA	77	259	1,400	-100	-150	1,062	1,100	-2,800
	Dalí	75	258	1,392	-88	-156	1,063	1,099	-2,795

a managed mode. This is not a revolutionary conclusion in fact the influence of predicted speed errors has been extensively proven in the literature. Nonetheless linking the possibility to fly in managed mode, especially for arrival operations, with the accuracy of the supporting automation has not been directly shown before.

During trial evaluations of initial versions of the NASA Efficient Descent Advisor (EDA) at Denver International Airport, Green et al. [15] established the positive effect of FMS managed flight on ground-based TP accuracy. Aircraft equipped with and without an FMS participated in the trial; the FMS-equipped aircraft performing a pilot's discretion descent arrived closer to the EDA-issued arrival time at the metering fix than those manually flown initiating descent at a controller issued top of descent. Although achieving the time more accurately, controllers were uncomfortable allowing a pilot discretion descent.

Clarke at al. [16] used appropriate altitude constraints for the design of arrival procedures aiming to allow continuous descents at Los Angeles (LAX). The altitude constraints at waypoints along the route provide a window between which the FMS is allowed to optimize its descent and provides a trade-off between flight efficiency and predictability of the vertical profile and top of descent to ATC. Most importantly, because the altitude constraints are part of the published procedure, the FMS can take them into account when computing the arrival trajectory. A subsequent managed descent respects these altitude constraints delivering a consistent and predictable result similar to as shown in Figure 11, and ultimately leading to improved accuracy of the TP in ground-based decision support tools. Such high TP accuracy was demonstrated in a different study performed for the LAX scenario, where the Dalí TP was applied to a sample of Qantas A388 flights conducting an FMS managed descent flying the BUFIE STAR into LAX [17].

5 Conclusion

The results presented in this study show that, state-of-the-art (TMA) and experimental TP technologies (Dalí), are affected by the operational scenario to which they apply. If arriving flights are not allowed to perform descents managed by their Flight Management Systems, like it often happens in peak times during current operations, at least in the US, the performance of the TP cannot be completely optimal. This affects the usability of the DST that is paradoxically designed to provide the biggest benefits during these peak traffic times. Therefore the operational scenario should be designed to allow the biggest possible number of arriving aircraft to plan and conduct managed descents flown at predictable descent speeds accurately managed by the FMS.

Having a sophisticated TP, that is accurate in the *ideal* situations in which arriving flights use their FMS to operate managed descents, would not be effective if these *ideal* conditions happen only in very limited times, such as low traffic time. Therefore the arrival procedures have to be designed to allow these *ideal* conditions to occur as often as possible and when the potential benefits are the highest. Only this double prospective in both the operational and automation scenarios can provide the total benefit that is envisioned by TBOs.

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