STUDY OF THE REQUIRED TIME OF ARRIVAL FUNCTION OF CURRENT FMS IN AN ATM CONTEXT

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Abstract

4D-trajectory-based operations (where "D" stands for Dimensional) are proposed by SESAR[1] and NGATS[2] as the fundamental cornerstones of Air Traffic Management (ATM) system improvements of the future. Various research initiatives such as PHARE[3] [1] have long described and prototyped these ideas of integrated air-ground ATM. However, because the broad implementation of this concept requires significant harmonized development of both air- and ground-based technology, progress has been limited. Nonetheless, the avionics industry has implemented initial capabilities to manage the fourth dimension, i.e. time, called Required Time of Arrival (RTA). The paper summarizes the results obtained from a EUROCONTROL study on the availability, characteristics and performance of the Required Time of Arrival (RTA) function in existing Flight Management Systems (FMS).

The RTA study is first discussed in the context of ATM, proposing some guiding premises as to how the time management function should be developed. As a consequence, the RTA study focused on performance during descent, using different FMS modes. A brief discussion of related EUROCONTROL projects has also been added. Test results from a number of sessions on Boeing 737 and Airbus A320 flight simulators are then presented. The evaluation included an assessment of the impact of wind on RTA, as well as some observations about the human machine interface aspects. Lastly, conclusions and recommendations for further development are proposed.

[1] Single European Sky ATM Research
[2] Next Generation Air Transportation System (U.S.A.)
[3] The Programme for Harmonized Air Traffic Management Research in Eurocontrol, a €90M cooperative research effort from 1989 to 1999, conducted gate-to-gate simulations with trajectory negotiation using an "Experimental FMS".

Introduction

A key aim of 4D operations is to move from the current tactical vectoring to a more strategic and predictable environment. While it is not perfectly clear how such operations will allow capacity to be maintained or increased, the idea of most flights progressing along an optimum profile is attractive both economically and environmentally. All too often, flights in high-density airspace hurry to enter an arrival holding pattern. In Europe, such competitive but counterproductive practices happen despite the good efforts of the Central Flow Management Unit (CFMU) to reduce bottlenecks by pushing back departure times. A variety of initiatives, such as improvements to the updating and sharing of flight plan data are ongoing. In contrast to the departure planning focus, however, the arrival sequence often lacks a strategic horizon. Thus, an initial step towards fully negotiated trajectory operations could be to communicate to aircrews per voice a specific RTA at a metering and sequencing fix. In case of delays due to demand exceeding capacity, this could at least permit the aircraft to slow down en-route, avoiding inefficient low altitude "sightseeing" flights in terminal airspaces. Since a significant number of aircraft are already equipped with an RTA function, the suitability of this function to support short term applications was investigated.

Operational Context

An initial RTA application in terminal airspace carries with it some implications for the development of such functionalities. Terminal airspace is far less homogeneous than the upper airspace that features the favorite airline cruise levels. Not only is each terminal airspace unique, with its particular runway configurations, traffic distribution and terrain, but the fleet mix in this airspace is often more complex than in the upper airspace. This means that even airspace users that are not FMS equipped need to be accommodated in terminal airspace. While segregated arrival and departure routes for specific user classes have been considered in the past, they are not desirable because the additional complexity introduces risks which outweigh achievable benefits. Thus, traffic with an RTA at a terminal airspace entry point needs to be compatible with non-RTA traffic. Ideally, this would be implemented in a way that makes RTA flights more predictable and easier to handle for both pilots and air traffic controllers.

RTA Compatibility with Ground ATM Tools

Trajectory fora of the past have asked whether prediction is best done in the air or on the ground. Both sides have struggled to provide good solutions, since the aircraft has the best knowledge about local wind and the current state of the aircraft (fuel / weight) to calculate the best trajectory from an individual user's point of view, while ground surveillance has the most complete picture of what is best for overall traffic flow. Despite the triviality of this observation, this separation of roles is expected to persist in the future world of 4D because even with fully automated, user-focused business trajectory sharing, some neutral arbitration and backup role will be required to handle conflicting demands in a competitive environment. Even in the short to medium term mixed-equipage environment, a complete trajectory picture is needed on both sides. But in addition to information about the predicted 4D path, the modes of operation also need to be compatible. Consequently, it is useful to briefly review what is on the horizon for arrival managers (referred to as AMAN, a controller support tool).

The widespread implementation of RNAV that is currently ongoing (called P-RNAV in Europe) presents significant opportunities for improved terminal airspace design free from the constraints of the locations of individual navigation aids. Additionally, airspace users typically strive to fly Continuous Descent Approaches (CDA) at idle power as much as possible, which is not easily accomplished when subject to radar vectoring. EUROCONTROL's TMA2010+ project is investigating the operational use of an advanced arrival manager. The basic premise is that if aircraft are flying a CDA on a fixed RNAV arrival route, the only control method left for sequencing is speed. Therefore, the new AMAN generates speed advisories that the controller forwards to the aircrew. While this has been demonstrated to work in principle even in medium-density traffic environments, actual descent strategies are still being discussed. This is necessary because a fully idle descent reduces control flexibility to a point where efficient arrival sequences can no longer be achieved. This experience is also mirrored in the PHARE implementation of RTA, which used a near-idle descent [2]. However, even at near-idle descents, there is not yet a clear consensus on operational modes, as descent path and speed are inextricably linked. Under consideration are specific foot-per-minute descent rates and constant flight path angles. The operational goals are to find near-optimal solutions in terms of track miles and fuel burn that will maintain predictable paths, both vertically and horizontally, while enabling efficient traffic flows. Whatever the final solutions will be, flights that have been assigned an RTA will need to be compatible with flights that are operating on AMAN speed advisories.

Descent Strategies Using RTA

For separation of departure and arrival traffic flows, SIDs and STARs[4] are often de-conflicted by using vertical constraints. Hence, it would be ideal if the descent can be flown with the FMS in a managed VNAV[5] path mode, where the aircraft is trying to respect both the vertical constraints of the flight plan while optimizing the descent profile between those constraints. However, this fuel optimization fixes the throttle schedule, and consequently the aircraft is controlling the descent using speed and pitch. Unfortunately, this variation in speed is in conflict with RTA performance. While current FMS do not automate flying a target speed to meet an RTA on a fixed vertical profile, this can be flown manually. Initially, the simulator trials used both managed and open descent modes (mode terminology used by Airbus – on Boeing this corresponds to path and speed descent). In the later stages of the trials, the experiments focused on

[4] SID = Standard Instrument Departure
STAR = Standard Instrument Arrival
[5] VNAV = Vertical NAVigation

using both open and managed descent modes while manually adding or removing thrust (or drag using speed-brakes) in order to maintain the target RTA speed and the vertical profile. Despite such an approach being unrealistic in day-to-day airline operations, it allowed assessing RTA performance in line with the ATC requirement to maintain a predictable vertical profile. Clearly, this will need to be simplified by automation in the future while striking a balance between aircraft, aircrew and ATC realities.

RTA Function in Current Avionics

Today, the RTA function is only available in the FMS of modern airliners. Business jets, turboprops and general aviation aircraft are not equipped with an RTA function, which requires auto-throttle.

Description of the RTA Function

The RTA function was introduced in airline FMS in the early 1990's, and used various quick estimator algorithms owing to limitations in computational power. Much of the same set of algorithms is still in use. RTA operates on the predicted trajectory of the aircraft and the associated Estimated Time of Arrival (ETA). If an RTA at a specific waypoint is entered, the FMS will attempt to eliminate the difference between RTA and ETA by either speeding up or slowing down, subject to aircraft performance limits. If the RTA – ETA difference cannot be overcome due to those limits, the FMS will announce "RTA unachievable" to the pilot.

Additionally, the RTA function is trying to minimize throttle activity by employing a "deadband". The RTA will only trigger control activity if the ETA differs from the RTA by more than a certain tolerance. On some aircraft types, this tolerance is configurable, and typically narrows as the aircraft gets closer to the RTA waypoint [3]. The RTA target speed, as well as the possible speed variations within operational limits are displayed on the speed tape of the Primary Flight Display (PFD).

RTA Equipage on Flights in Europe

Current equipage of aircraft with RTA capable FMS is shown in Table 1.

Table 1: RTA Equipage

FMS	Aircraft	Tol-erance	Flight Phase
Smiths	B737 Classic, NG	6 sec	Climb, cruise, descent
Thales - Smiths	A320, A330, A340	30 sec	Climb, cruise, descent
Honeywell Pegasus	A320, A330, A340 B757, B767, MD90	30 sec	Cruise
Honeywell	B777, B747-400, MD11	30 sec	Cruise

Based on these equipage figures, an estimation was made of the availability of RTA on IFR flights within Europe[6]. These numbers represent a regional average – percentages would be somewhat higher when considering a specific large airport. A key criterion that was added was the synchronization of the captain's clock with GPS time, since it is expected that even initial RTA applications would depend on some reliable synchronization between the aircraft and ground system reference times. This is reflected in Table 2.

[6] Based on CFMU data for flights within ECAC. ECAC is the European Civil Aviation Conference, and includes Albania, Armenia, Austria, Azerbaijan, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Moldova, Monaco, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, Ukraine, United Kingdom.

Table 2: RTA Equipped IFR Flights in Europe

Specified RTA Tolerance	GPS Time	Flight Phase	Flights in Europe [%]
±30 sec	No	Cruise	**40**
±30 sec	Yes	Cruise	**28**
±6 sec	No	Climb, cruise, descent	**21**
±6 sec	Yes	Climb, cruise, descent	**11**

While the 40% equipage figure in Table 2 is already quite impressive, it is also clearly shown that for an application in the descent phase with synchronized time, there is still a long way to go. This further underlines the need for any initial RTA application in terminal airspace to be compatible with ATC modes of operation, as equipage transition timelines will remain lengthy for the foreseeable future. Conversely, it also illustrates an opportunity to provide to equipment manufacturers a better picture of how such capabilities will need to be designed and harmonized in order to effectively complement ground based ATM tools.

Current RTA Performance in a Terminal Airspace Context

In order to perform an initial operational assessment of RTA in a terminal airpsace context, sessions were held both on Airbus A320 and Boeing B737 flight simulators. The B737 simulators were equipped with Smiths U10.6 FMS, while the A320 simulators were equipped with the Thales-Smiths FMS for Airbus. Both were capable of performing RTA control during descent. Descents were flown from cruise level to a waypoint just before the approach, under a variety of conditions. An RTA constraint applicable to this waypoint was entered a few miles before the Top of Descent (TOD). During the simulations, actual time, ETA at the RTA waypoint and the speed (Mach number or Indicated Airspeed IAS) were recorded every 5 NM. Initially, trials were flown using no wind, but in different descent modes.

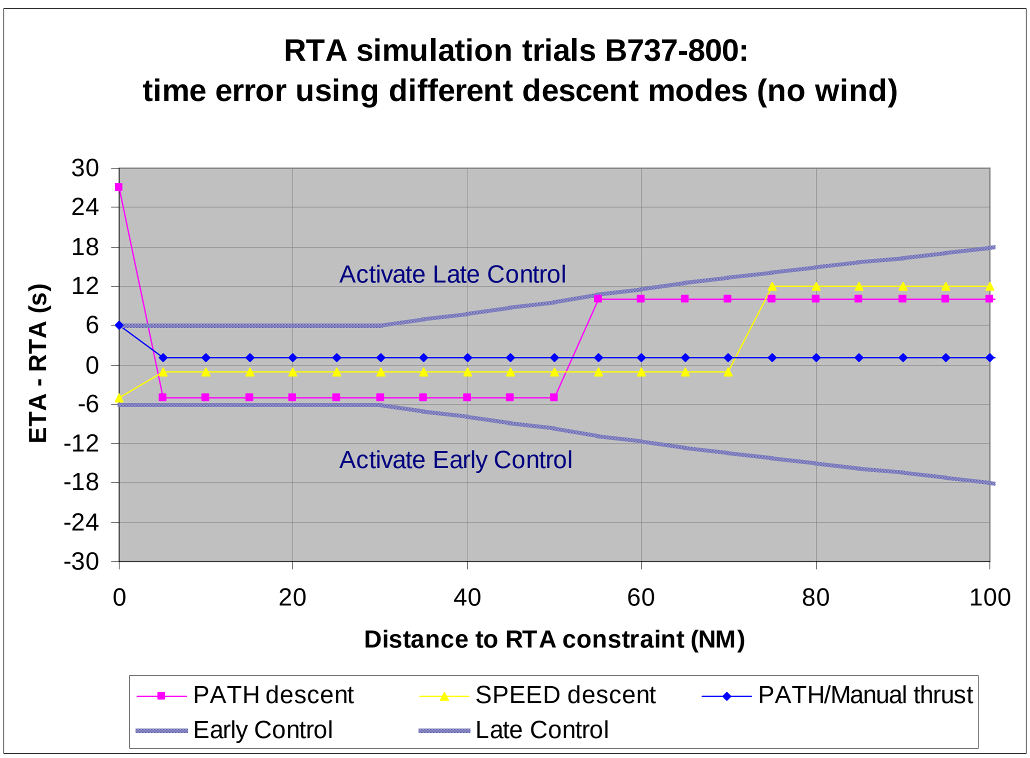

Figure 1: RTA Performance using Different Descent Strategies

RTA was set to the initial ETA in most cases. In the remaining cases, an offset was added – typically plus or minus one minute. Furthermore, while a desirable merge point before the approach would be around 5000 ft depending on the actual route structure, this was later moved up to at or above FL100[7], because current RTA is not designed to work below FL100.

Figure 1 illustrates the RTA control mechanism within the deadband as the difference between RTA and ETA, as observed during three different sessions, evolves. As alluded to earlier, the employed descent modes can be described as follows:

- **OPEN or SPEED descent:** with idle thrust, speed is held constant by changing the attitude of the aircraft (elevator control). Calculated descent path is not necessarily maintained.
- **MANAGED or PATH descent:** with nominal (close to idle) thrust, the calculated descent path is maintained by changing the attitude of the aircraft (elevator control). This leads to speed variations around the calculated target speed.
- **MANAGED or PATH descent with manual thrust input:** same as PATH descent but the speed variations are neutralised by manually adding thrust or adding drag (speedbrakes). As a result the target speed is more accurately flown.

When looking at the performance of the different modes, both the speed and path descents with manual thrust work within specified limits. Nonetheless, a jump is observed as the ETA zeroes to the Actual Time of Arrival (ATA). This appears to be due to the ETA not being updated frequently enough to correct time errors that are built up from not accurately flying the target speed. This effect is magnified in the normal path mode, which is the descent mode most commonly used by airline pilots today. Older systems are more prone to this effect than newer systems.

[7] FL = Flight Level. FL100 corresponds to 10’000 feet AMSL at standard pressure.

RTA Simulations with Tailwind

In addition to the wind-free baseline scenarios, RTA performance was also scrutinized under different wind conditions. FMSs allow manual pilot entry of winds at three to five flight levels and on the ground. The system then linearly interpolates the wind values between those altitudes. Flight simulators possess a similar capability. While such wind profiles are relatively coarse compared to actual wind profiles, it allows to evaluate how RTA performs if the encountered winds do not match the winds entered in the FMS.

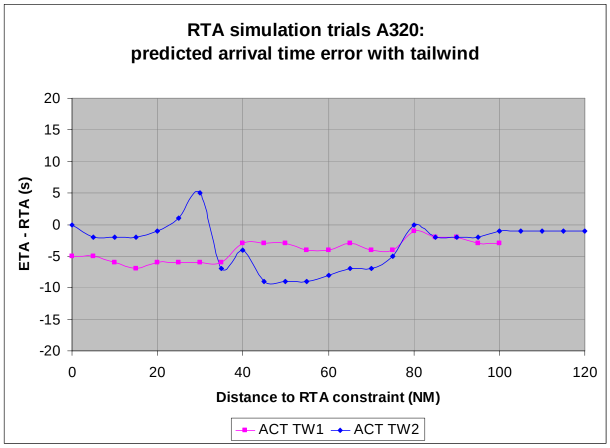

Figure 2a: RTA and Unpredicted Tailwind (Time)

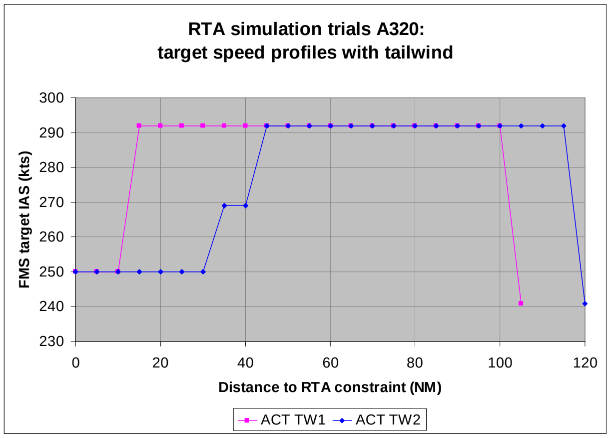

Figure 2b: RTA and Unpredicted Tailwind (Speed)

This is of interest because the PHARE Experimental FMS required accurate wind and temperature profiles in order to produce on-time guidance. Desired wind accuracies were on the order of 10 knots [2]. Such values are relevant in order to determine bandwidth requirements for future, more automated RTA operations. Figures 2a and 2b show two tailwind examples. In the first run, the actual tailwind (ACT TW) only differed from the FMS entry by a few knots. In the second run, the FMS matched the simulator at FL350 and on the ground, while at FL150, the simulator blew 30 knots harder than anticipated by the FMS. This creates a reversal in the direction of the FMS to simulator wind difference at FL150.

When looking at the blue/diamond lines of the graphs in Figures 2a and 2b, an on-time arrival over the RTA waypoint is maintained despite an impressive unpredicted tailwind. The corresponding changes in target speed are evident. While this testifies to the capability of the FMS to measure the experienced winds and blend that information into the RTA algorithm, such large, abrupt speed changes could be difficult for ATC to absorb when sequencing aircraft. Consequently, wind information is also important to ensure appropriate ATC planning, as it impacts the accuracy of the ETA and the speed profile variations, even if the RTA algorithms are robust to fairly significant inaccuracies.

Additionally, when considering the magenta /square lines of Figure 2a and 2b, it can be seen that the accurately predicted tailwind does not force any dynamic RTA updating, and thus the flight arrives five seconds early, which is still perfectly within tolerance. No target speed corrections are observed in this run besides the normal transition from constant Mach to constant IAS descent and the slow down to 250 knots below FL100. Note that this normal speed reduction occurs much later than in the case where the unpredicted tailwind was much greater.

RTA Simulations with Headwind

A number of headwind scenarios were also performed. The wind profiles are shown in Figure 3.

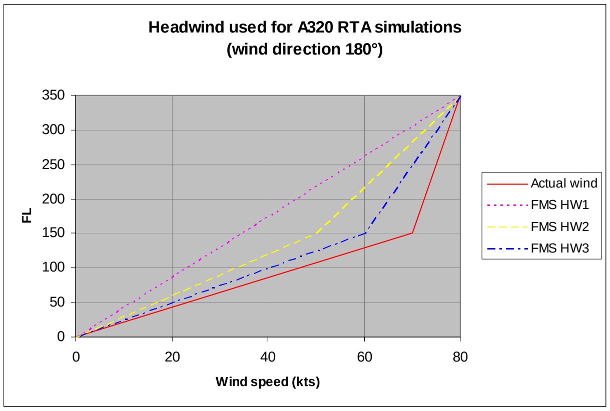

Figure 3: Unpredicted Headwind Profiles

These profiles are quite similar to the tailwind runs, but range from about 10 to 40 knots of difference at FL150. In contrast to the tailwind cases, the forecast wind entered in the FMS was varied, while the “actual” simulator wind was again stronger. The corresponding time and speed profiles are shown in Figures 4a and 4b. The blue/diamond line reflects the scenario where the forecast (FMS) best matches the actual (simulator) wind, i.e., it underestimated the true headwind the least. Thus it was the most aggressive in increasing airspeed to counter the headwind. While this led to the best RTA result, all three runs perform quite well until about 15NM prior to the RTA waypoint. A peculiar situation was encountered on the run corresponding to the magenta/square and diamond lines, which was the grossest underestimator. A little after passing 40NM to the RTA waypoint, FMS 1 and FMS 2 no longer matched in their predictions. While the Pilot Flying maintained throttle control to his FMS, it still created a discussion on the flight deck about which guidance was correct. Although still within the RTA tolerance specification of the manufacturer, all three runs arrived relatively late.

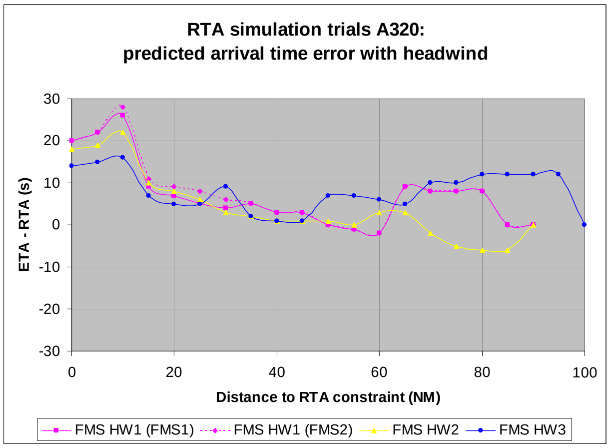

Figure 4a: RTA and Unpredicted Headwind (Time)

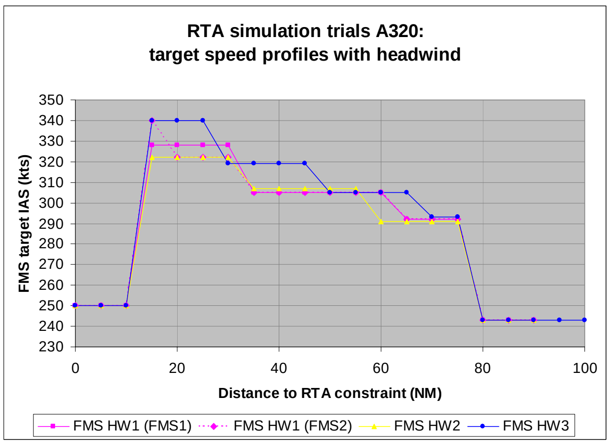

Figure 4b: RTA and Unpredicted Headwind (Speed)

It can be observed that the slow-down to 250 knots occurs at the same distance to the RTA waypoint as in one of the tailwind scenarios, except that the starting speed is much higher. These late arrivals could be due to an inaccurate estimate of the time required to decelerate to 250 knots. On the other hand, as these runs were flown in open descent mode with manual thrust control, it could also be due to the differences between the flown and predicted vertical profiles.

Summary of Observations from the Simulation Runs

While it would not be appropriate to provide all the detailed data collected during the simulator trials, the points below summarize the main observations made. The table in the appendix gives a detailed overview of all simulation runs and the associated conditions. Note that the findings are based on the specific operating scenario described herein, which in some sense extends the use of RTA outside of what it has historically been designed to do. It can also not be excluded that some of the effects are due to limitations of the simulator.

FMS Descent Mode / RTA Interaction

The most relevant observation is that, while in various cases RTA algorithms perform their intended function impressively, it is quite challenging to conduct descent scenarios that fit this function while still respecting ATC needs. It appears that for 4D-trajectory-based operations, a new FMS descent mode would be needed that maintains an efficient vertical profile while allowing accurate and flexible RTA control. Obviously, forcing the pilot to focus on manually keeping thrust at appropriate settings in a critical flight phase is not desirable.

Accommodating ATC Constraints in RTA Predictions

Deceleration to 250 knots at FL100 is a key value in terminal airspace operations today. In addition to ensuring that RTA and estimated ETA remain accurate during the deceleration, the RTA horizon also needs to be expanded below FL100. One manufacturer has just started offering its newest FMS with RTA control below FL100, which is a step in the right direction as it would be desirable to ensure a specific RTA at the start of the approach, at altitudes around 5000 feet.

Similarly, in some runs RTA did not command speeds below 250 knots at levels well above FL100, limiting the possible time to lose even if the performance envelope of the aircraft would have allowed it. It should further be noted that such key ATC values could possibly change depending on how operations evolve.

Performance and Specification of RTA

While the RTA tolerance of ±6 or ±30 seconds is a useful value, it needs to be clear under which conditions this can be achieved. These conditions would need to specify FMS descent mode, permissible inaccuracies in wind and temperature predictions, and the operating envelope. Further work would also need to consider the quality and update rate of the ETA prediction. This would be best addressed in a performance-based, commonly agreed standard.

Figure 5: RTA Page on MCDU

Human Factors and Pilot Training

Most pilots have never used RTA. Because it is provided in FMS today more as an ancillary function, it takes several keystrokes to access the RTA page. In the trials, both pilots had significant head-down time on the MCDU[8] in order to monitor RTA progress. In real operations, it would be better if pilots could monitor RTA progress in the primary field of view.

A minor but nonetheless important issue is the presentation of the RTA error. As can be seen in the MCDU screenshot of one particular FMS in Figure 5, RTA error is displayed as a numerically signed value. It would be more intuitive for pilots to sign the time error as either "early" or "late", as implemented on the B737.

ATC Interaction

Entering an RTA after the Top of Descent cannot produce reliable results, as the descent strategy has already been fixed by the aircraft prediction at that point. Consequently, any assignment of a specific RTA constraint by ATC would need to occur sufficiently well ahead of the nominal TOD to allow pilot entry and FMS predictions to take place.

Lower on the descent, currently many aircraft are instructed to fly at exactly 250 knots below FL100. This completely eliminates any speed-up capability. It would therefore be advisable to either accept the 250 knots as a nominal speed with some tolerance, or operate at a speed below 250 knots[9].

Lastly, it should be noted that ATC also depends on ETA predictions being sufficiently accurate – this would ensure that RTA speed corrections are small and monotonic enough to still enable efficient separation on the approach.

Conclusions and Further Development

The RTA simulation flights gave a good insight into the use and functioning of RTA in a terminal airspace descent context. The collected data gave an appreciation of the interaction between speed correction and ETA / RTA estimates, under a variety of operationally realistic wind scenarios. However, while a significant number of flights in Europe possess an RTA capability, functionality and operational suitability is still limited for an initial application to a sequencing fix at the start of a specific approach. On the other hand, equipage numbers and control performance to an arrival time error of ±30 seconds are encouraging, possibly enabling strategic planning to an entry point at the horizon of a ground-based arrival manager. The key result that was obtained from the simulator experience is an initial set of operational criteria that should be considered when developing trajectory-based avionics capabilities, as described in the previous section.

Required Development for an Initial RTA Application in an Arrival Sequence

When considering 3NM separation at a speed of 180 knots, the corresponding time spacing is 60 seconds. To ensure spacing using RTA constraints, FMS algorithms would need to be robust enough to consistently achieve arrival times within a small fraction of a minute – possibly less than the current state of the art of ±6 seconds (10%). Given the numerous activities on trajectory-based operations of the past and present, it appears that incremental improvements of current capabilities could yield initial benefits in terminal airspace in mixed RTA

[8] MCDU = Multifunction Control and Display Unit

[9] The B737 uses a nominal speed of 240 knots below FL100

and AMAN speed advisory traffic, even without data-link of RTA assignments and wind information. However, more operational simulations and analysis are necessary to validate whether this optimism will hold up to the scrutiny of daily operations, especially in medium to high density traffic. Because the time that can be lost or gained during descent is limited to a couple of minutes, the descent RTA may need to be preceded by an en-route RTA for some coarse pre-sequencing. On the equipment side, RTA and cockpit integration improvements will need to be complemented with GPS time input to the FMS to ensure a common time base.

From a Single RTA to 4D Operations

4D-trajectory-based operations imply that time is not controlled only at one discrete point along the trajectory, but on a continuous basis. While the RTA function provides time prediction and control along the trajectory, multiple RTA points are necessary for ATC interface purposes, especially in the arrival sequence. Judging from the crew effort to just fly a single RTA manually, it can be confirmed that a significant level of automation will be necessary which cannot be found on current flight decks. Harmonized operational concepts are critical for this development. These will need to preserve the tactical flexibility of atmospheric realities such as turbulence penetration speeds and thrust increases due to the operation of de-icing equipment. At the same time, the strategic focus from the landing backwards along the trajectory needs to ensure the original operational aim – burn less track miles at a minimum of fuel consumption while preserving an efficient and safe flow of traffic.

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Disclaimer

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Appendix: Summary of Simulator Runns

	RUN	Wind difference b/w actual and FMS	RTA	Altitude at RTA point	Descent mode	Thrust	Updates	Arrival time error
B737-800	1	None	ETA	5000ft	PATH	Auto	Auto	39s late
	2	None	ETA+60s	5000ft	PATH	Auto	Auto	38s late
	3	None	ETA+60s	5000ft	PATH	Auto	Auto	27s late
	4	None	ETA+60s	FL140	PATH	Auto	Auto	29s late
	5	None	ETA+60s	FL120	SPEED	Auto	Auto	05s early
	6	None	ETA+60s	5000ft	PATH	Manual	Auto	06s late
	7	None then 50kts tail	ETA+34s	FL120	PATH	Manual	Auto	26s early
	8	Strong headwind	ETA	4500ft	PATH	Manual	Auto	09s late
	9	Strong headwind	ETA	4500ft	PATH	Manual	Manual	02s late
	10	Strong headwind	ETA	4500ft	PATH	Manual	Manual	05s late
	11	None	ETA	4500ft	PATH	Manual	Manual	33s early
	12	Strong tailwind	ETA+60s	4500ft	PATH	Manual	Manual	79s early
	13	Strong tailwind	ETA	4500ft	PATH	Manual	Manual	11s early
A320	1	None	ETA	4500ft	Managed	Auto	Auto	13s early
	2	Light tailwind	ETA	4500ft	Managed	Auto	Auto	07s early
	3	Strong tailwind	ETA	4500ft	Managed	Auto	Auto	21s early
	4	None	ETA+60s	4500ft	Managed	Auto	Auto	09s early
	5	None	ETA	4500ft	Open	Manual	Auto	05s late
	6	None	ETA	FL100	Open	Manual	Auto	01s early
	7	Light tailwind	ETA	FL100	Open	Manual	Auto	05s early
	8	Strong tailwind	ETA	FL100	Open	Manual	Auto	0
	9	Strong headwind	ETA	FL100	Open	Manual	Auto	20s late
	10	Moderate headwind	ETA	FL100	Open	Manual	Auto	18s late
	11	Light headwind	ETA	FL100	Open	Manual	Auto	14s late