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A Framework for Assessing and Managing the Impact of ANSP Actions on Flight Efficiency

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***Abstract* — This paper presents a framework for the assessment of Air Traffic Management (ATM) performance in relation to flight efficiency. The main philosophy behind the approach presented in this paper is to quantify the quality of the service delivered by an Air Navigation Service Provider (ANSP) to an airline in terms of meeting commonly agreed objectives. The definition is therefore aligned with the future paradigm of Trajectory Based Operations, where achieving the trajectory agreed between the ANSP and the airspace user becomes the focus. A staged approach to flight efficiency assessment is proposed to quantify the quality of the ANSP's service in terms of both "facilitating what has been agreed" and "improving what can be agreed". The framework promotes the development of more consistent efficiency performance metrics between ANSPs, as clear definitions exist for assessment references. Application of the framework was illustrated with several examples using the Airservices Dalí trajectory modeller.**

Keywords - component; ATM performance, flight efficiency.

I. INTRODUCTION

In our increasingly globalised society, aviation has become vital in facilitating the growth of international trade and connecting people; enabling them to travel practically between any populated areas in the world within 24 hours. While aviation has provided society with significant social and economic benefits we have become more conscious of the environmental consequences of air travel. The International Air Transport Association (IATA) reports that, in 2012, global airline profits were less than $3 per passenger and that airline industry returns averaged only about 4% [1]. Air Navigation Service Providers (ANSPs) play a critical role in the safety chain of the air transport system through the provision of separation services, and therefore have a significant influence on the environmental sustainability and profitability of aviation. In particular, operational actions and regulations of ANSPs have a direct impact on the efficiency at which their airline customers operate their flights.

In this paper, a framework will be presented for Air Traffic Management (ATM) performance assessment and management, aiming to quantify the impact of ANSPs actions and regulations on flight efficiency. A key challenge in this field of research has been to determine an appropriate reference (or baseline) against which to perform assessments with varying objectives. The framework proposed in this paper consists of a staged performance assessment allowing different aspects of the ANSP's impact on flight efficiency to be analysed.

This paper is organised as follows. Following the introduction in Section I, Section II will provide background information on previous work in the field of flight efficiency assessment. Section III will present the philosophy behind the proposed framework, while Sections IV and V will derive the model and subsequent high-level metrics. Sections VI and VII provide example applications of the framework to both individual flights and a multitude of flights. Finally, conclusions and future work will be discussed in Section VIII.

II. BACKGROUND

In a utopian world, an airline would be able to perform a flight free of any ATM-related constraints: the aircraft would taxi unconstrained to the preferred runway, take off, set course to its destination, perform an unrestricted climb based on selected cost-index, cruise at cost-index speed along a wind optimal trajectory with altitude slowly increasing as it burns off fuel, descend at the ideal descent point with throttles at idle, stabilise at the final approach fix for landing and taxi unimpeded to the arrival gate. This optimal trajectory would be the realisation of a true User Preferred Trajectory, as it does not include any constraints imposed by third parties (e.g. Air Traffic Control (ATC)), other than regulatory safety constraints such as circuit direction, terrain avoidance etc. However, in reality, airline scheduling means a large number of aircraft occupy the skies, and ATC has been tasked with providing separation and sequencing services. Procedures have therefore been put in place to add predictability to ATC about all trajectories that a controller must separate. Most often these procedures impact on the true optimum as represented by the User Preferred Trajectory. Reynolds (2014) [2] provides a good overview of the different causes of flight inefficiency in today's ATM system.

The field of ATM performance assessment consists of many other aspects than flight efficiency, like safety, capacity and cost. Accepting that safety is the main consideration for both ANSPs and airlines, flight efficiency - including the ground component - then becomes the main key performance area to measure quality of service delivered by the ANSP to the airline, as it inherently includes the impact of capacity (e.g. airborne delay due to arrival sequencing) and cost. Conventional methods for quantifying flight efficiency are mostly related to lateral inefficiencies, e.g. excess distance compared to flight plan or great circle, as such analysis is relatively trivial and the data required is often available.

For example EUROCONTOL and the United States Federal Aviation Administration (FAA) perform quantitative comparisons in terms of ATM performance and report on excess distance flown compared to flight plan [3]. The comparison also reports on additional time in various phases of flight. While excess time during taxi might be relatively easy to determine, this does not apply to airborne phases of flight. The problem is determining an accurate and adequate reference of what would have been the unconstrained time. Such information can be derived from trajectory predictions based on the flight plan; however trajectory predictors currently operated by ANSPs are known to be of limited accuracy [4-7].

A more sophisticated metric, known as the 3Di score, was recently introduced by UK NATS to report on its service delivery and environmental performance in terms of flight efficiency [8]. The 3Di score combines the inefficiencies associated with both the horizontal and vertical dimensions of flight. In the horizontal plane, it compares the actual radar ground track against the most direct great circle distance within the airspace network above the UK. The difference between these two distances, which describes the 'additional miles flown', defines the inefficiency in the horizontal plane. In the vertical plane, the 3Di metric compares the actual vertical profile against the airlines' preferred trajectory. Vertical inefficiency resulting from ATC interactions is (currently) simplified to periods of level flight that occur below the airlines' requested cruise level – though such levels may be a pilot request (e.g. turbulence or different loadings to flight plan). A score of zero (i.e. 'zero inefficiency', or 'optimal efficiency') is achieved when there is zero horizontal and zero vertical inefficiency. In the horizontal plane, this means a track following the great circle distance from departure to destination. There are two limitations to this metric. First, while for ANSPs covering small Flight Information Regions (FIRs), the great circle path from entry/departure to exit/destination is often the most efficient route, this does not hold true for larger FIRs like Oakland Oceanic and the Australian FIRs – where wind optimal routes regularly and deliberately take aircraft away from the great circle track. Second, a direct route from departure to destination can never be achieved due to airport runway configuration and a minimum safety and operational requirement to hold runway heading for a certain period after take-off and before landing. The 3Di score therefore includes penalties for inefficiencies the ANSP has no influence over, and highlights that the true optimum can thus never be achieved.

The approaches of EUROCONTROL/FAA and UK NATS presented before, use different references. Where the comparison study of EUROCONTROL and the FAA used the filed flight plan as the reference, the UK NATS 3Di score uses a basic definition of the User Preferred Trajectory. While both methods have their advantages and disadvantages, it highlights inconsistency in using an appropriate reference structure to assess flight efficiency. The Civil Air Navigation Services Organisation (CANSO) has called for cross-border consistent flight efficiency metrics to be adopted [9]. The following sections of this paper will propose a framework for flight efficiency assessment supporting such a vision.

III. Proposed Flight Efficiency Assessment Framework: Philosophy

The desire for operators of each flight to execute the true User Preferred Trajectory, as described in the previous section, is utopian and will never be realised, as the complex interaction of many aircraft in the skies will always require some level of compromise. In the future concept of Trajectory Based Operations (TBO), this level of compromise is reflected by the Reference Business Trajectory (RBT), and is the trajectory the airspace user agrees to fly, and ATC agrees to facilitate, optimised for known published constraints [10].

In the current ATM system, the flight plan filed by the airline is generally the only representation of the intended flight, and takes into account (most of) the constraints procedurally imposed by an ANSP through the published Aeronautical Information Package (AIP). Transposing TBO terminology to today's paradigm, the flight plan can therefore be seen as the 'contract' between the airline and an ANSP: it represents the flight the airline wants to fly within the structure and procedures that the ANSP facilitates. This is not the most optimal flight, but a compromise given the constraints present (which can include elements as ANSP charges etc). The flight plan, combined with departure and arrival procedures, can therefore be seen as a coarse definition of the Reference Business Trajectory within the current ATC paradigm; this trajectory will be further referred to as the *Procedure-Optimal Trajectory*. If the flight is pre-tactically subjected to capacity/demand balancing through Air Traffic Flow Management (ATFM) initiatives, the Procedure-Optimal Trajectory, including such constraints, becomes the *Network Optimised Trajectory*. To execute the flight, ATC delivers tactical clearances that could make the aircraft deviate from this agreed trajectory for separation and sequencing purposes, finally resulting in the *Actual Flown Trajectory*. To summarise, the following definitions apply:

- *User Preferred Trajectory.* The true User Preferred Trajectory is the trajectory without any third party constraints (other than legal) that minimises the cost of the operation or network. For a variety of reasons this trajectory is often unknown to the ANSP. It is a utopian trajectory, as it does not take into account actions required to handle other traffic, i.e. as if the aircraft flying this trajectory was the only aircraft occupying the skies (assuming advanced flight deck automation capable of computing and guiding to this trajectory).
- *Procedure-Optimal Trajectory*. This is the trajectory corresponding to the filed flight plan and contains all procedural constraints. The trajectory is supplemented with departure and arrival procedures (including associated altitude and speed constraints), but contains no tactical constraints. In summary, this trajectory would be the trajectory flown if the aircraft was able to conduct the flight free of ATC intervention, within existing procedures. In today's paradigm, this trajectory would be a basic form of the Reference Business Trajectory.
- *Network-Optimised Trajectory*. This is the Procedure-Optimal Trajectory, accounting for capacity/demand balancing actions by an ANSP. The Network Optimised Trajectory could also account for pre-tactical agreed weather diversions.
- *Actual Flown Trajectory*. This is the true trajectory flown to the objectives specified in the filed flight plan, while taking into account ground delays, tactical ATC intervention and weather diversions. These factors all contribute to the actual flown trajectory being different to what was planned.

Using these definitions of the different trajectories, the following distinctions can be made between three major concepts or 'stages' of efficiency:

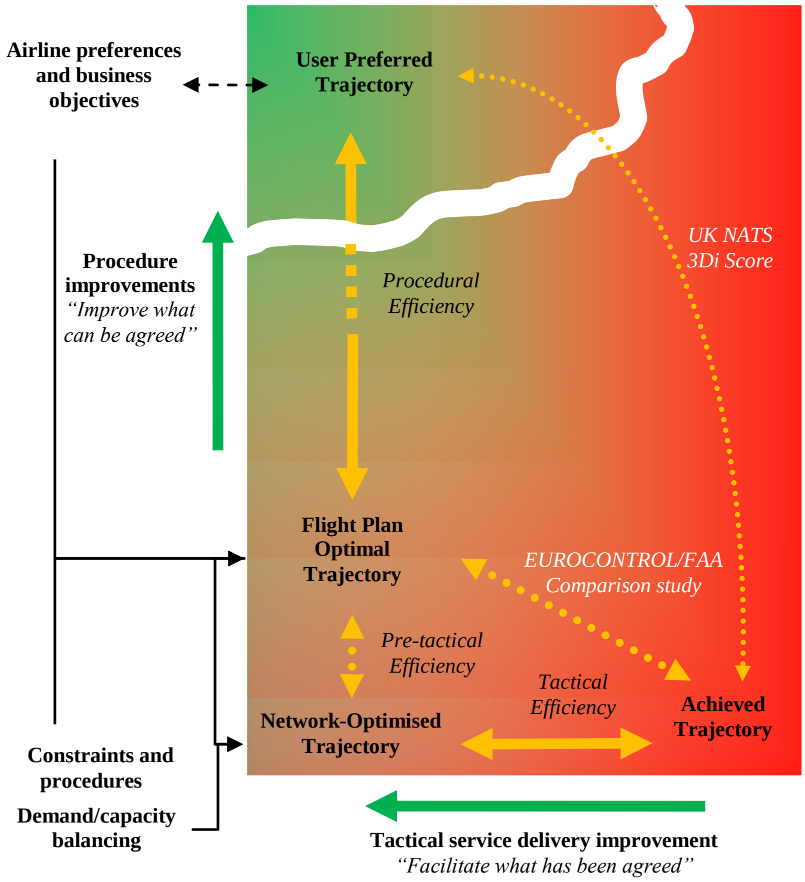

Figure 1. Levels of efficiencies associated with different conceptual trajectories. The drive for ATC is to tactically deliver a service such that the actual flown trajectory is close to the objectives of the flight plan, while the drive for ATM planning services is to improve on procedures to allow a flight plan to be closer to the true user preferred trajectory.

- *Strategic or Procedural Efficiency: Procedure-Optimal Trajectory vs. User Preferred Trajectory.* This efficiency relates to the operation as compared by the flight planning requirements versus the User Preferred Trajectory. It provides an indication of the impact that ATM procedures have on the operation. 100% efficiency would theoretically be achieved if there were no ATC procedural constraints (e.g. fixed airways, altitude constraints, speed constraints, track miles added by departure and arrival procedures, etc.).
- *Pre-tactical Efficiency: Network-Optimised Trajectory vs. Procedure-Optimal Trajectory.* This efficiency relates to the pre-tactical actions applied for capacity and demand balancing. For example, capacity and demand balancing can be performed through the use of ground delay. This ground delay effectively 'time-shifts' the Procedure-Optimal Trajectory to coincide with an allocated slot time at the destination.
- *Tactical Efficiency: Actual Flown Trajectory vs. Network-Optimised Trajectory.* This efficiency relates to the operation by comparing the actual trajectory flown to what was planned, i.e. the comparison of a flight conducting the departure procedure, the flight plan and the arrival procedure (without any ATC intervention), versus what actually happened. A 100% tactical efficiency is thus achieved whenever the flight was not intervened with by ATC, and was flown as per the flight plan filed by the airline.

In case no capacity/demand balancing actions apply, the tactical efficiency can be determined by comparing the Actual Flown Trajectory to the Procedure-Optimal Trajectory. In the rest of this paper, the intermediate step of the Network-Optimised Trajectory is left out unless stated otherwise. Figure 1 provides an overview of the different trajectories and efficiencies, and also indicates the difference in efficiencies assessed by the EUROCONTROL/FAA comparison studies and the UK NATS 3Di score. A broken line separates the User Preferred Trajectory as this trajectory is often unknown (as explained in the next section). In essence, the tactical efficiency quantifies the quality of the ANSP's service in terms of "*facilitating what has been agreed*", and the procedural efficiency in terms of "*improving what can be agreed*".

IV. Proposed Flight Efficiency Assessment Framework: Model

In this section, a model will be derived to quantify the different levels of efficiency introduced in the previous section. Starting with the procedural efficiency, a fundamental question arises: what is the true User Preferred Trajectory? As stated, this is the trajectory which is free of any constraints imposed by a third party, and is effectively the trajectory of lowest cost to the airline. However, a large number of imposed ATC constraints are safety and environmentally driven, and integrated with many dependencies – and therefore cannot be trivially eliminated. Airline operating procedures can be quite different between different airlines, resulting in different User Preferred Trajectories for the same city pair and aircraft type. The true User Preferred Trajectory may also not be supported by current flight deck automation; e.g. continuous climb during cruise is only approximated by step climbs at flight plan waypoints.

Each improvement on current procedures can be considered as progress towards the true User Preferred Trajectory. User Preferred Route (UPR) initiatives are examples of this process. By allowing off-airways flight planning, the base fuel burn (and cost) of the flight plan and of the Procedure-Optimal Trajectory is lowered, and a procedural efficiency gain is therefore achieved. Another example is Required Navigation Performance (RNP) approaches, which are often shorter than conventional instrument approaches, again resulting in procedural efficiency gains. Emphasis should be placed on identifying each incremental improvement, rather than the overall deficit to the User Preferred Trajectory. However, comparison with an ultimate 'utopian' baseline may still be desirable in order to set improvement targets and to establish trends, as is done with the UK NATS 3Di score.

An approximation of the User Preferred Trajectory for a short-haul commercial operation is proposed as a trajectory that takes-off from the preferred runway, climbs to 500ft above ground level and sets course to intercept a 2NM final approach at the destination's preferred runway, supported by RNP without any circuit requirements. This is a simplification, as different aircraft have different equipment and operating procedures, and terrain surrounding the airport could impact this trajectory. Environmental (or regulatory) elements, such as noise abatement procedures, have also been excluded: while they are important, they are third party constraints added to the trajectory. Instead of assuming a great circle between departure and destination, this trajectory accounts for some constraints that are embedded and cannot be removed. The optimal cruise levels and speeds can be taken from the filed flight plan, inherently representing the cost-index set by the airline for that flight. The fundamental rationale of the cost index is to achieve minimum cost using a trade-off between operating costs per hour and incremental fuel burn [11]. For example, if an airline chooses to fly faster and lower (less fuel efficient) levels, then this is reflected in the flight plan. Remaining unknown parameters not specified in the flight plan, such as climb and descent speed schedules, and climb strategy (e.g. derated climb), are captured by a model of the airline's standard procedures, like that provided by EUROCONTROL's Base of Aircraft Data (BADA) [12]. While for short-haul flights, the assumption can be made that the shortest path in distance is also the shortest path in time, this does not hold for long-haul operations. Deviating from the great circle path to benefit from prevailing wind conditions could significantly affect flight time and therefore fuel burn. An optimiser would be needed that finds the appropriate lateral and vertical path to accurately represent the User Preferred Trajectory for long-haul operations.

The tactical efficiency is easier to model. The actual flown trajectory can be compared to the Procedure-Optimal Trajectory as computed from the flight plan filed by the airline. If the objectives of the flight plan were met, then the tactical efficiency should be considered as optimal. The tactical efficiency could include the effects of weather deviations; realising that, while it is not trivial to clearly separate the effect of significant weather, attempts can be made to correlate this with data recording such events.

A multi-way comparison can also be made to clearly establish if a change in procedure, while leading to theoretical savings, actually leads to achieved savings. For example, the introduction of RNP arrivals may result in a more efficient Procedure-Optimal Trajectory, but if tactically this service cannot be delivered, there might not be a realised benefit.

A. The Dalí Trajectory Modeller

The key to the flight efficiency framework proposed in this paper is to accurately model the various trajectories, and infer information such as fuel burn from the Actual Flown Trajectory. To implement this performance framework, Airservices, the Australian ANSP, makes use of its in-house developed Dalí trajectory modeller. Dalí was originally developed to trial different methods of integrating aircraft-derived data in ground-based automation systems, and proved to be capable of independently computing accurate trajectories compared to those down-linked to Flight Management Systems (FMSs) [13-16]. The capability of Dalí to estimate the fuel burn of actual flown trajectories is being validated with satisfactory initial results (>96% accuracy).

Dalí is based on the concept of aircraft intent generation. Aircraft intent here refers to the basic commands, guidance modes and control strategies available to an aircraft to control its trajectory. To model aircraft intent, Dalí applies the Aircraft

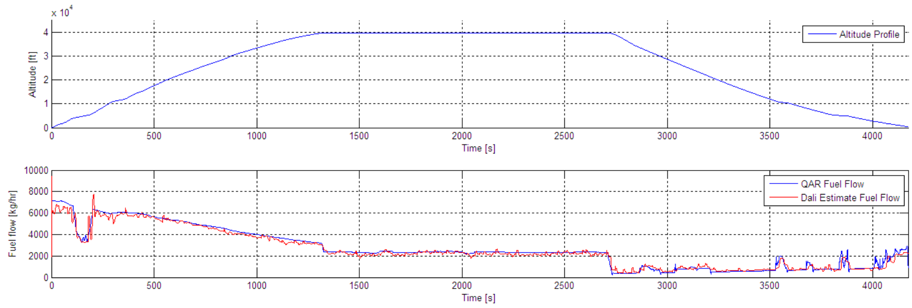

Figure 2. Altitude profile and actual (blue) and inferred (red) fuel flow by Dalí.

Intent Description Language (AIDL) framework developed by Boeing Research & Technology Europe (BR&TE) [17]. Aircraft performance data is obtained from BADA using both the BADA3 and BADA4 families [12]. The World Area Forecast Centre (WAFC) aviation forecast product is used by Dalí for wind and temperature data [18]. As the trajectory and associated fuel burn are dependent on the aircraft mass, Dalí makes an estimate of the take-off mass based on sector length and prevailing weather conditions.

Dalí can generate aircraft intent depending on the objectives of what needs to be modelled. As a first example, Dalí can take information from a filed flight plan and predict the resulting trajectory, essentially acting as the trajectory computation function within a flight planning system or FMS (prediction mode). All constraints published as part of a procedure are taken into account, consistent with generic FMS behaviour [13]. As a second example, based on provided surveillance data, Dalí can generate aircraft intent simulating the aircraft following this trajectory and perform fuel burn and emission estimation (inferring mode). An example is provided in Figure 2, where for a Boeing 737-800 flight between Sydney and Melbourne the fuel flow inferred from surveillance data is compared to the actual fuel flow for this flight which was available for analysis. The actual fuel burn for this flight was 3,080kg where the Dalí estimate was 3,050kg. As can be seen from Figure 3, the inferred fuel flow matches the actual fuel flow satisfactorily, even 'detecting' areas where increases of thrust occur. For example, while the descent appears continuous in regards to the vertical profile, increases in fuel flow can be observed. This accuracy in modelling the actual operation allows for detecting if a descent was both continuous *and* performed on idle-thrust.

Combining the inferring and prediction modes together allows for assessment of the tactical efficiency of the flight by comparing what actually happened to what was planned, as illustrated in Figure 3. Running the prediction mode for different procedures allows for assessment of differences in procedural efficiency.

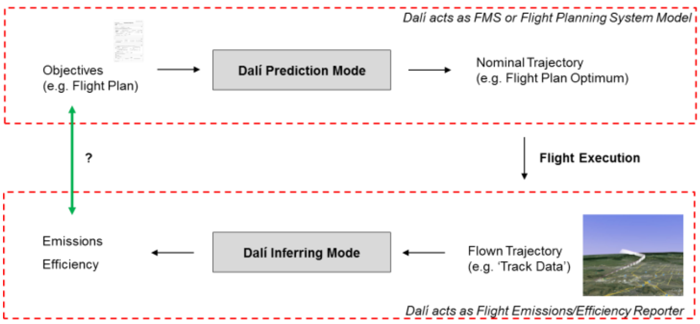

Figure 3. Inferring and prediction modes of Dalí.

V. Proposed Flight Efificiency Assessment Framework: Metrics

This section explores how to define appropriate metrics to quantify the conceptual efficiencies using the modelling capabilities described in the previous section. Traditionally, excess distance flown has been a convenient metric used by ANSPs to assess their performance and to assess the impact of procedural changes. For an airline, both fuel burn and flight time are of the greatest interest, as both directly contribute to the operational cost of the flight. In addition, pre-tactical delay and extra flight time could reduce an airline's on-time performance (a key operational performance indicator for many airlines and airports). Time and fuel have been difficult to estimate accurately in the past with the available models and data. Additional distance or flight time can be an indicator of ATC intervention (e.g. radar vectoring and/or holding), and can be related to air traffic controller workload (i.e. greater controller workload results in more vectoring and holding, which in turn results in greater distances flown). Therefore the performance of the service delivered by an ANSP to an aircraft should be measured in terms of all three quantities – additional distance, additional time and additional fuel, as shown in Figure 4.

The generic form for the efficiency metric is adopted from Reynolds (2014) [2]:

$$\text{Inefficiency} = \frac{\text{Actual - Reference}}{\text{Reference}} \text{ x } 100\% . \qquad (1)$$

The values for actual and reference change accordingly with the conceptual (in)efficiency assessed. This metric form is normalised for effects of atmospheric conditions and aircraft mass, as Dalí uses the same characteristics to derive information from the Actual Flown Trajectory as to model the Procedure-Optimal and User Preferred Trajectory. Therefore when expressing the efficiency in relative terms, biases and constant components of the error cancel, making especially the relative fuel burn metric an order of magnitude more accurate than an absolute metric. The metric can be derived for the entire flight, or a particular phase thereof.

VI. Individual Flight Efficiency Assessment

In this section the framework and metrics of the preceding sections will be illustrated by application to an example flight between Melbourne (IATA:MEL/ICAO:YMML) and Sydney (IATA:SYD/ICAO:YSSY). The example flight was a regular commercial service operated by an Airbus A330-200 in August 2014. In Figure 6, the lateral paths for the Actual Flown Trajectory (red), Procedure-Optimal Trajectory (magenta), and the User Preferred Trajectory (green) are provided. The Procedure-Optimal Trajectory includes the appropriate Standard Instrument Departure (SID) at MEL, the fixed airway system between MEL and SYD as per flight plan, and the Standard Terminal Arrival Route (STAR) at SYD. The User Preferred Trajectory has the aircraft departing MEL from runway 27, turning right at 500ft above ground level, and tracking direct to intercept via a curved approach on a 2NM final onto runway 16R at SYD. Here it is assumed that surface wind conditions dictated the runways in use though ideally varying taxi and flight distances for available runways should be taken into account in the determining the User Preferred Trajectory. The vertical profiles, speed and fuel flow for the three trajectories are given in Figure 7.

For the Actual Flown Trajectory, the departure occurred in accordance with the procedure, though the aircraft did not climb to the level requested in the flight plan; this could have been a pilot request or because conflicting traffic did not allow the planned level. A normal cruise phase at that level followed. For sequencing, the aircraft experienced one holding pattern and additional vectoring onto final approach. The effect of the ATC intervention is clear when assessing the erratic fuel flow behaviour when the aircraft was held and vectored. The efficiencies are presented in Table I for the total flight and in Table II for the area within 250NM of the destination. 250NM was chosen to ensure that the effect of all sequencing actions are taken into account and that the three trajectories are still on cruise to properly account for the impact of different descent profile on the cruise length as explained further in Figure 5. The impact of the sequencing actions on all the metrics is clear, especially when referring only to the final phase of flight. A clear difference in lateral path between the User Preferred Trajectory and the Procedure-Optimal Trajectory can be observed, noting that the User Preferred Trajectory does not account for separation with other traffic streams.

In this example, the route structure consisting of the SID, fixed airway system and STAR adds 8% to the User Preferred Trajectory. As referred to earlier, depending on prevailing wind conditions especially for long haul flights, the great circle path may not be the most optimal route. On a daily basis, the optimal route for long haul flights will vary while for short haul the optimal route is generally fixed.

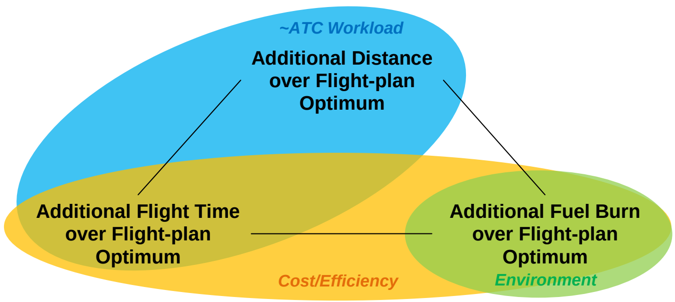

Figure 4. Three different metric quantities and their area of application. Additional flown distance and flight time can be an indication of ATC intervention and to some extent air traffic controller workload. Additional fuel burn, and thus additional emissions, results in additional environmental impacts. Finally, a combination of additional flight time and additional fuel burn result in decreased efficiency (and increased cost) of the operation.

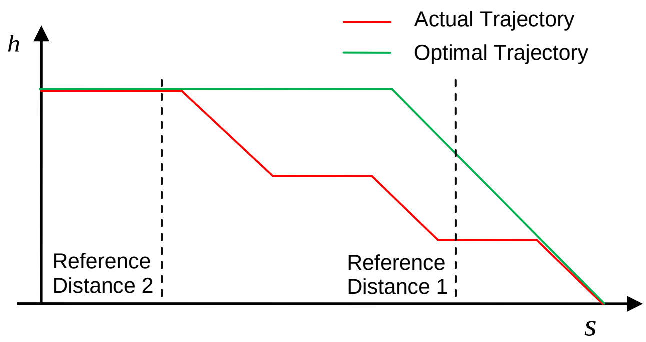

Figure 5. When comparing two descent trajectories, an appropriate reference distance must be chosen. If too close to the destination, an unfair comparison is made. In this example while the optimal trajectory experiences no level segments on descent, its cruise phase is longer. This effect should be taken into account when assessing the benefit of the optimal trajectory over the actual trajectory.

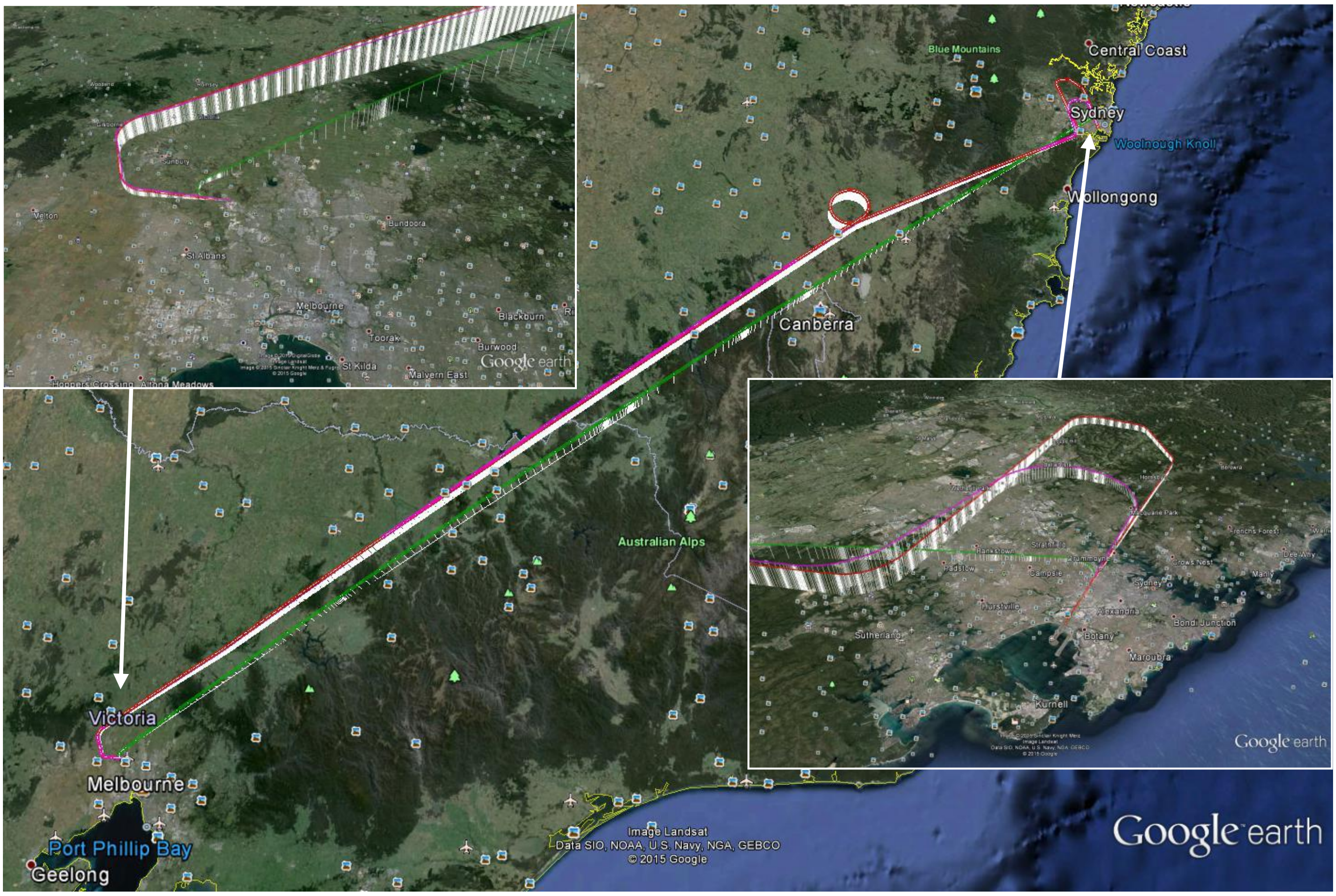

Figure 6. Lateral paths of the Actual Flown Trajectory (red), Procedure-Optimal Trajectory (magenta), and the User Preferred Trajectory (green). The Actual Flown Trajectory experiences one holding pattern and additional vectoring at Sydney resulting in 14% more miles flown over Procedure-Optimal (i.e. flight plan), or 24% over the User Preferred Trajectory. The effect of terminal area procedures is very clear with 8% aditional track miles over User Preferred.

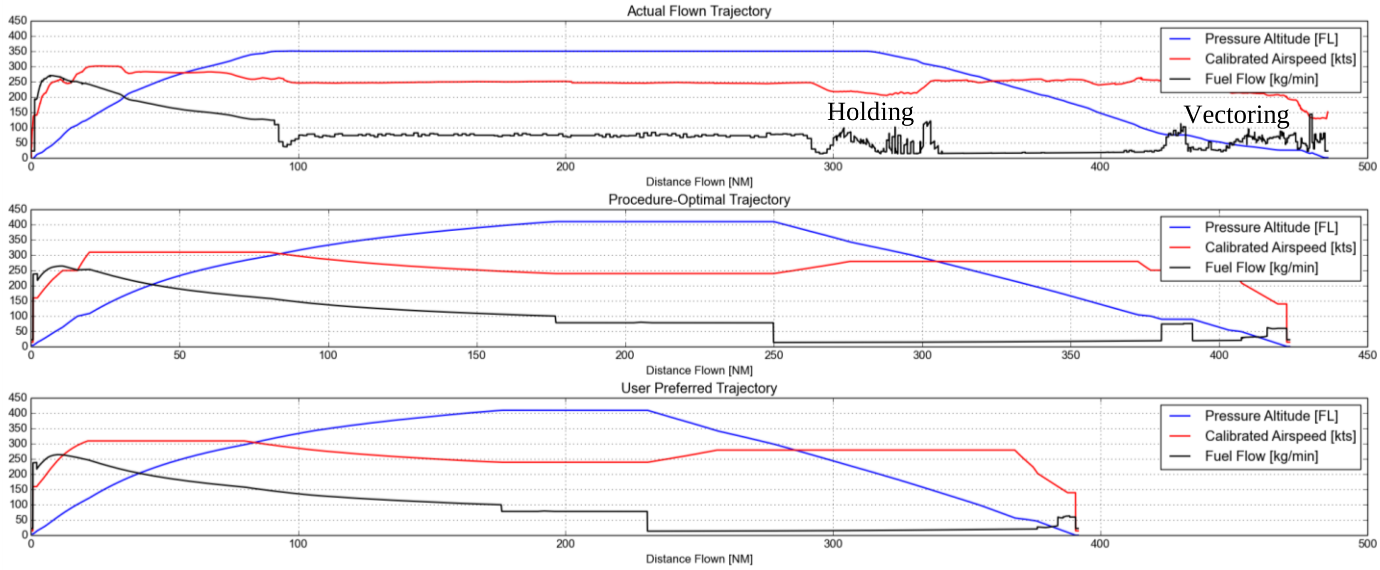

Figure 7. Vertical profiles of the Actual Flown Trajectory (top), Procedure-Optimal Trajectory (middle), and the User Preferred Trajectory (bottom). The actual Flown Trajectory did not cruise at the planned level (FL410). The effect of holding and vectoring on the fuel flow can clearly be observed when comparing to the Procedure-Optimal and User Preferred Trajectory. The User Preferred Trajectory is free from speed constraints.

ANSPs endeavour to allow airlines to take advantage of route flexibility within the rules and constraints necessary for separation. Examples of how flexible long haul routes are handled differently are the North Atlantic Track (NAT) system and the Australian Organised Track System (AUSOTS). While both are updated daily to account for prevailing wind conditions the multiple parallel NAT tracks are not individually optimal as compromises have to be made to process the large volume of traffic using these tracks. However, for a single track from the Middle East and Asia to an Australian East Coast city, AUSOTS routes can lead to significant fuel savings over the fixed airways system and are a step towards the User Preferred Trajectory.

TABLE I. EFFICIENCY METRICS TOTAL FLIGHT.

Efficiency metric	**Trajectory**					
	User Preferred Trajectory	***Procedure-Optimal Trajectory***		***Actual Flown Trajectory***		
			Proc. Ineff.		***Tact. Ineff.***	***Total Ineff.***
Distance	390 NM	424 NM	+8%	484 NM	+15%	+24%
Flight time	00:59:20	01:04:45	+9%	01:22:33	+27%	+39%
Fuel burn	5470 kg	5850 kg	+7%	6520 kg	+11%	+19%

TABLE II. EFFICIENCY METRICS 250NM FROM DESTINATION.

Efficiency metric	**Trajectory**					
	User Preferred Trajectory	***Procedure-Optimal Trajectory***		***Actual Flown Trajectory***		
			Proc. Ineff.		***Tact. Ineff.***	***Total Ineff.***
Distance	255 NM	273 NM	+7%	335 NM	+22%	+32%
Flight time	00:39:00	00:42:50	+10%	00:58:45	+37%	+50%
Fuel burn	1635 kg	1840 kg	+12%	3020 kg	+64%	+85%

When establishing the true User Preferred Trajectory for long haul flights, additional complexity includes determining the optimal cruise levels and speeds, and in particular when they change, as these are dependent not only on aircraft weight, but also on prevailing winds. As the User Preferred Trajectory for long haul flights may be more difficult to determine than for short haul flights, the concept of incremental procedural improvements can be applied as follows. Figure 8 shows the lateral paths of the AUSOTS Flextrack and the best fixed route option of the day between Singapore and Melbourne for an arbitrary day in February 2014. For one of the flights that used the Flextrack that day, Dalí was used to estimate the savings in fuel burn of the Flextrack over the fixed airways system. A first prediction was made based on the filed flight plan containing the Flextrack and the associated planned level changes (Procedure-Optimal Trajectory). Dalí was re-run with the best fixed route option for the day substituted for the Flextrack. Planned level changes remained at similar distances along the flight. While the lateral deviation between the two routes only appears small, a fuel benefit of 500kg was estimated for an Airbus A380-800. This example shows how procedural efficiency gain can be computed by comparing two Procedure-Optimal Trajectories generated for different procedures.

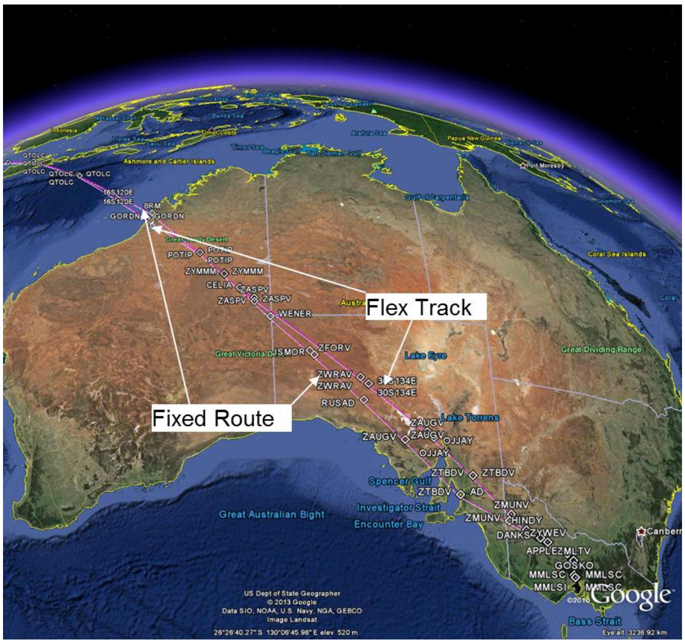

Figure 8. Lateral paths of the Flextrack and the best fixed route for the day between Singapore and Melbourne. While lateral differences are only small, a saving of about 480kg is estimated on this particular day.

Another example of the quantification of a procedural efficiency gain is provided in Figure 9. Here, a RNP approach (green) into Gold Coast International Airport, Australia is compared to a conventional non-precision approach (magenta), which provides a benefit to suitably equipped aircraft during night-time operations and low-visibility conditions (when the visual approach cannot be flown). The RNP approach is approximately 11NM shorter than the conventional non-precision approach. For a medium jet, this results in an average flight time saving of 95 seconds and 55kg of fuel [19]. Note that for both approaches, the procedure contains an at-or-below 6,000ft constraint at waypoint KERRI. When altitude constraints are present, Dalí tests if the descent profile is impacted by the constraint, and if so, a level segment is modelled until idle-descent can be resumed. In case of the non-precision approach, the vertical profile is impacted by the 6,000ft requirement as ideally a medium jet aircraft would pass this point somewhere between 7,000ft and 8,000ft. The RNP transition with less track miles to run, comfortably meets the requirement (~4500ft). Therefore in this particular case, the benefits of the RNP approach are not only reduced track miles, but also the elimination of a level segment, accounting for approximately 15% of the estimated fuel savings.

VII. AGGREGRATE FLIGHT EFFICIENCY ASSESSMENT

In this section examples are provided of how the framework can be applied to a multitude of flights. For short haul operations, the route of the User Preferred Trajectory is very static as it is normally unaffected by enroute winds, and mostly depends on the departure and arrival runway; however, the flight time and fuel can differ due to different meteorological conditions and flight objectives (e.g. cost-index). A similar concept applies to the Procedure Optimal Trajectory. With unchanging procedures the procedural efficiency is therefore a mostly static parameter. This does not apply to the tactical efficiency as operations can differ significantly from day to day due to delays and weather conditions. Figure 10 shows the daily determined median additional flown distance, flight time and fuel burn for the Melbourne – Sydney city pair over April 2014 when compared to the Procedure-Optimal Trajectory (tactical efficiency). The Melbourne – Sydney city pair ranks

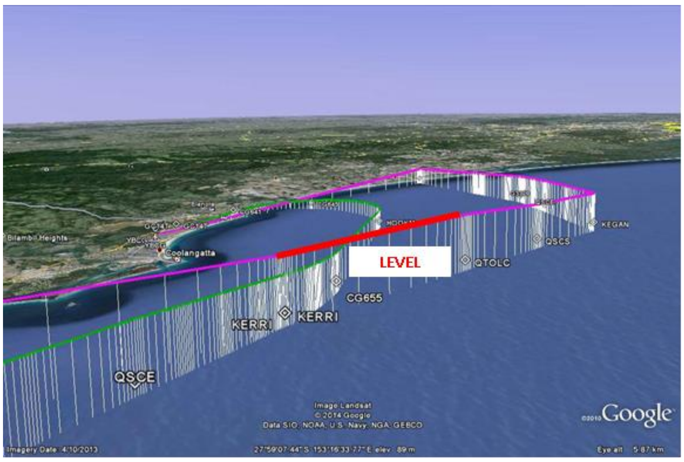

Figure 9. Lateral paths of the convetional non-precision approach and RNP approach into Gold Coast International Airport, Australia. The RNP approach provides a 11NM track mile saving, with 95 second flight time and 55 kg fuel saving for a medium jet.

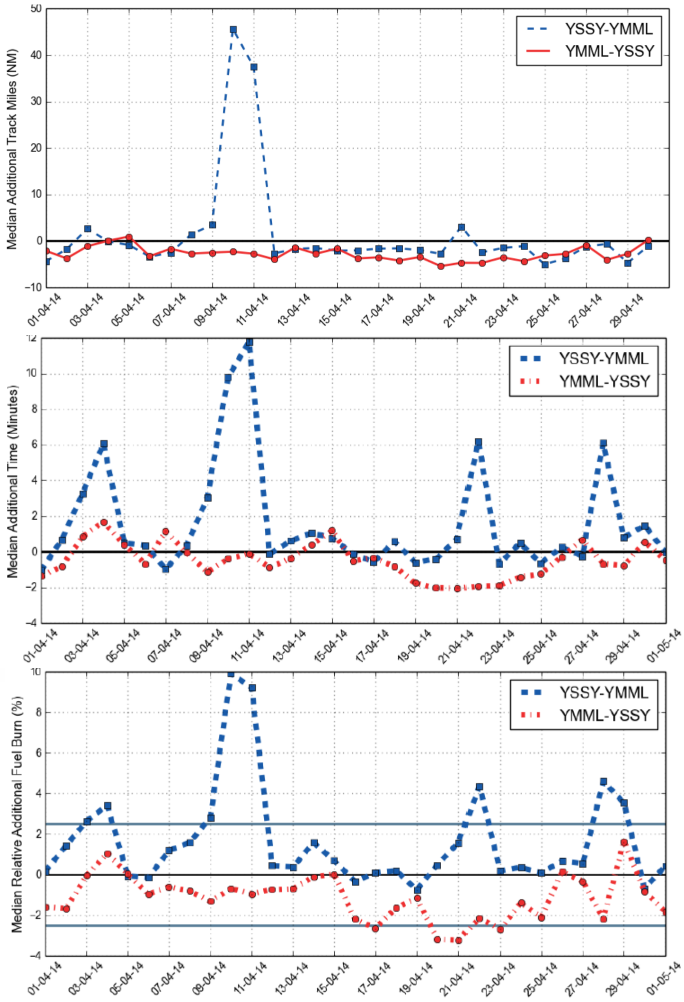

Figure 10. Plots showing median addiitonal track miles (top) , flight time (middle) and fuel burn (bottom) for the Melbourne (YMML) – Sydney (YSSY) city pair over April 2014. Melbourne experienced several occasions of severe weather during April 2014, resulting in significant disruptions.

highly in the world's top 10 busiest air routes and is therefore of specific interest to investigate. Depending on the goal of the metric, either the median, mean or third quartile of the data can be used. The mean can overestimate the contribution of long tails, while the median can underestimate the tails. Melbourne experienced several occasions of severe weather during April 2014 resulting in significant traffic disruptions, explaining the extremes observed. Another interesting observation is that the median excess distance is negative. This indicates that on average track shortening is offered, as is often the case on the SID procedures. In Sydney the STAR structure ends on down-wind legs and ATC vectors aircraft into final approach to perform final spacing. In order to compute the Procedure-Optimal Trajectory, these open-ended STARs had to be linked to the runway threshold which could have been too conservative. This also indicates another important aspect: the Procedure-Optimal Trajectory is likely to never be flown as the aircraft's FMS needs a continuous lateral path to the runway threshold. As can be seen from the data in Figure 10, besides the significant weather events, the traffic on the city pair operates on average close to maximum tactical efficiency.

It needs to be noted that the fixed airways system in Australia is mostly direct with little enroute inefficiency. In more complex areas like continental United States or core Europe, this is not the case. EUROCONTROL's Performance Review Report [20] states that in 2013 the average procedural efficiency for Europe was 4.86% (flight plan over great circle) and the tactical efficiency was 3.14% (actual over great circle). This indicates that on average air traffic control provide a tactical service more efficient than the filed flight plan by offering track directs (-1.72%). While at first thought, delivering a consistent saving over flight plan appears positive, it is not in line with the concept of TBO with an increased focus on "plan what you fly" and "fly what you plan". As explained previously, the Procedure-Optimal Trajectory – in today's paradigm based on the flight plan – can be seen as the 'contract' between the airline and an ANSP: it represents the flight the airline wants to fly within the structure and procedures that the ANSP facilitates. It is based on this structure and procedures that the operator has planned and optimised its flight. While detail and sophistication of flight planning differs between operators, the trend for mainstream commercial operators is to move to performance based flight planning in which accurate trip fuel planning and confidence in subsequent realised fuel burn is critical. This means that although if tactically track miles are being reduced, aircraft still carry the fuel as if they would fly per the longer agreed airways structure. It costs fuel to carry fuel, and while this cost may appear small, it can be significant in light of the industry's small profit margins mentioned in the introduction of this paper. It can be argued that rather than a saving, the practice of consistently offering track directs to reduce track miles over flight plan in fact leads to a penalty to industry: airlines are required to plan via the airways structure, and carry the associated fuel, but fly these as the exception rather than the rule. A negative tactical efficiency can therefore be seen as an indicator of an area in which a procedural improvement can be made such that full benefit can be realised by allowing operators to plan the way they tactically fly.

Referring back to Figure 10, the most significant outlier is for Melbourne-bound traffic on April 10th. On that day, rain and low visibility reduced the landing rate for Melbourne. Based on the Terminal Area Forecast (TAF) of the previous night, a landing rate for Melbourne was set and associated ground delays were issued. However, throughout the day conditions deteriorated further and faster, resulting in significant delays, as only a single runway could be used at a very low rate. Dalí was used to quantify the inefficiency associated with these delays. The Actual Flown Trajectory can simply be compared to the Procedure-Optimal Trajectory for each of the flights involved; however as all these flights interacted to cause the delays, they should not be assessed individually. Therefore the Procedure-Optimal Trajectory for each flight is shifted in time to make the landing time coincide with that of the actual trajectory. This time-shifted trajectory conceptually becomes the Network-Optimised Trajectory and represents the (utopian) case of a perfect ground delay program. In this scenario, the following assumptions are made:

- The actual landing times are the times assigned by the perfect ground delay program and accurately achieved.
- There are no restrictions on the departure airports to allow aircraft to remain at the gate awaiting their slot time.
- All flights absorbed the required delay on the ground, and subsequently flew the Procedure-Optimal Trajectory without any ATC intervention.
- No delay was absorbed in the air as of change in cost index, resulting in lower target speeds; i.e. the Procedure-Optimal Trajectory is based on the originally filed flight plan.

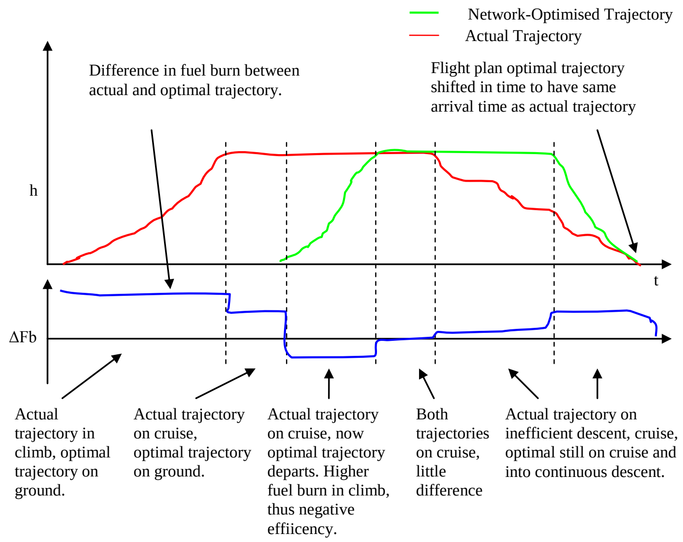

Figure 11. Stage-wise comparison of Actual Flown Trajectory and Network-Optimised Trajectory. The top plot reflects the altitude profile versus time for both profiles. The Network Optimised Trajectory is shifted in time to coincide with the actual landing time. The lower plot is the fuel burn difference between the two trajectories (ΔFb) versus time.

The difference in fuel burn per time interval is assessed between the actual scenario and the optimal scenario described above, and accumulated for all flights in the sample. For an example of the differences in fuel burn for an illustrative flight, see Figure 11 where the elapsed time of the actual trajectory is significantly longer due to airborne holding. Data was extracted for all flights inbound to Melbourne with actual departure time between 0000Z and 2400Z on the 10th of April 2014 (11:00 – 11:00(+1) Australian Eastern Standard Time (AEST)) to capture the lead-up to the evening rush hour and subsequent ease of traffic into the night. For a variety of data-related restrictions, the analysis includes only jets performing domestic sectors: about 60% of the traffic into Melbourne. Only these flights can be network-optimised as they are subjected to the ground delay program, while international flights are not.

The accumulative results for all 202 flights in the sample are presented in Figure 12. The top graph shows the accumulated excess fuel burn as a function of time (blue): excess fuel burn is the difference between the actual fuel burn and the fuel burn of the Network-Optimised Trajectory (see Figure 11) summed over all flights in the sample as a function of time. In addition, the number of aircraft airborne on their way to Melbourne is plotted against time, where the red line shows the actual number of aircraft airborne and the green line the number of airborne aircraft in case of the 'perfect' ground delay program (domestic jets only). The lower graph shows the amount of excess fuel burn discretised to 15 minute intervals relative to the optimal scenario. The height of the bars is a measure of the rate of growth of the accumulated excess fuel burn in the top graph. The excess fuel burn is plotted per given time interval rather than per flight, and therefore is not as dependent on sector length (the longer the flight, the less relevant the excess fuel burn becomes).

Between 0300Z and 0500Z there is little difference between the actual and optimal scenario indicating that the network in terms of Melbourne inbound flights, is running efficiently and near Network-Optimum. This is also evidenced by the slow growth in excess fuel burn for this time interval. Around 0500Z, and especially 0700Z (18:00 local), the inefficiency builds up as can been seen from a rapid growth in excess fuel burn due to high demand at rush hour. This rapid growth correlates with the situation around 0800Z, when double the number of aircraft are airborne and on their way to Melbourne than in the optimal scenario. Also note the strong peaks in the bar graphs of the lower plot. Around 0715Z the excess fuel burn within a 15 minute interval was in the order of 200% with respect to the optimal scenario. After 0800Z, the situation is getting better due to lower demand and the excess of airborne aircraft is slowly disappearing. At 1300Z (midnight AEST), the system has been restored and performs close to optimum again, i.e. the red and green line are on top of each other and there is a low growth rate of excess fuel burn. Of the 202 flights in the sample the mean actual flight time is 98 mins and the mean procedure-optimal flight time is 77 minutes; a difference of

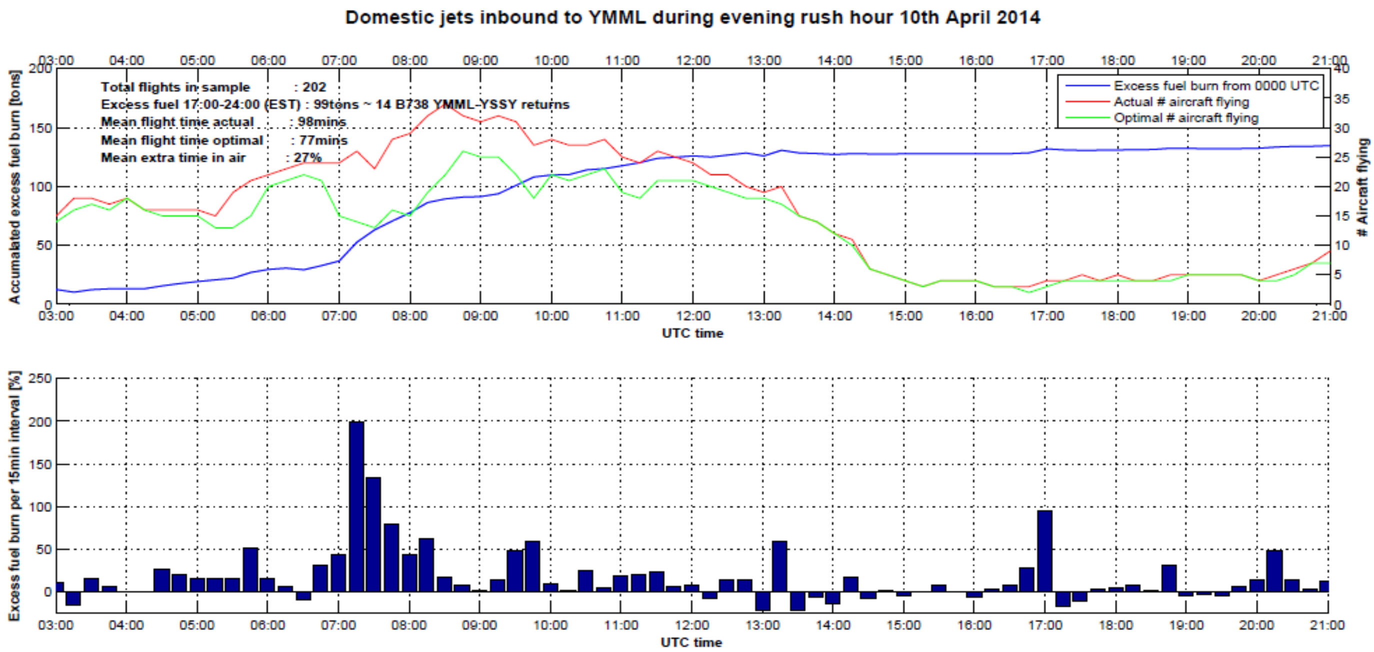

Figure 12. The top graph shows the accumulated excess fuel burn as a function of time (blue). In addition, the number of aircraft airborne on their way to Melbourne (note domestic jets only) is plotted against time (red), and the number of airborne aircraft in case of the 'perfect' ground delay program (green). The lower graph shows the amount of excess fuel burn discretised to 15 minute intervals in relative terms (relative to optimal scenario). The height of the bars can be seen as a measure of the rate of growth of the accumulated excess fuel burn in the top graph.

27%. The accumulated excess fuel burn between 0600Z-1300Z (17:00 – 24:00 AEST) is about 99 tons, or roughly 14 Melbourne – Sydney return flights for a Boeing 737-800.

As mentioned previously, significant weather events were expected for that day, but conditions deteriorated faster and earlier than forecast. As most of the domestic jets performed multiple sectors that day, the ground delay program became ineffective as aircraft started to miss arrival slots due to large delays. While such significant weather events are beyond the control of an ANSP, being able to quantify the cost of the associated delay can drive business cases to improve ATFM solutions and technology to reduce minima, etc. It also allows ANSPs to start a dialogue with airlines involved about schedule amendments, should such conditions occur again.

VIII. CONCLUSION AND FUTURE WORK

This paper presented a framework for the assessment of ATM performance in relation to flight efficiency. A staged process of references was proposed to determine different levels of efficiency. The tactical efficiency assesses the actual trajectory of the flight compared to the optimal trajectory given current procedures and published constraints. The philosophy behind the tactical efficiency is to quantify the quality of the service delivered by the ANSP to an airline, in terms of meeting the objectives stated in the flight plan. The flight plan can be seen as a basic 'contract' between the airline and an ANSP, as it represents the flight the airline wants to operate according to the structure and procedures the ANSP facilitates. This definition is therefore aligned with the future paradigm of Trajectory Based Operations, where achieving the trajectory agreed between the ANSP and the airspace user becomes the focus. As a second stage, the efficiency of the procedures in place, or 'agreement', is assessed against a best definition of the User Preferred Trajectory. If required, further intermediate stages can be defined to assess the impact of pre-tactical changes, such as ground delay programs. Applying a staged approach to flight efficiency assessment, allows for derivation of more consistent metrics between ANSPs, as clear definitions exist for references against which to perform analysis.

Application of the framework was illustrated with several examples, using the Airservices Dalí trajectory modeller to accurately estimate fuel burn for actual flights and to determine appropriate reference trajectories. Future work will involve improved definition of User Preferred Trajectories for long haul flights, including optimisation for prevailing weather conditions. Ground phases of a flight will also be considered, to provide a single framework for all flight efficiency analysis.

REFERENCES

[1] International Air Transport Association. (2013). *Profitability and the Air Transport Value Chain - IATA Economics Briefing 10*. Montreal, Canada: International Air Transport Association.

[2] Reynolds, T.G. (2014). Air traffic management performance assessment using flight inefficiency metrics. *Journal of Transport Policy, 34*, p36-74.

[3] FAA & EUROCONTROL (2014). *2013 Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe*.

[4] Bronsvoort, J., McDonald, G.N., Paglione, M.M., Garcia-Avello, C., Bayraktutar, I., & Young, C.M. (2011). *Impact of Missing Longitudinal Aircraft Intent on Descent Trajectory Prediction.* Proceedings of the 30th Digital Avionics Systems Conference, Seattle, WA, USA.

[5] Mondoloni, S. (2006). *Aircraft Trajectory Prediction Errors: Including a Summary of Error Sources and Data* (Report): CSSI Inc.

[6] Vivona, R.A., Cate, K.T., & Green, S.M. (2011). *Comparison of Aircraft Trajectory Predictor Capabilities and Impacts on Automation Interoperability.* Proceedings of the 11th AIAA Aviation Technology, Integration, and Operations (ATIO), Virginia Beach, VA, USA.

[7] Enea, G., Vivona, R., Kuo, V., Cate, K., & Eshow, M. (2013). *Automating Trajectory Prediction Performance Analyses for the FAA Traffic Management Advisor.* Proceedings of the AIAA Guidance, Navigation, and Control (GNC) Conference, Boston, MA, USA.

[8] UK NATS. (2012). *NATS Fuel Efficiency Metric.*

[9] CANSO. (2013). *Potential Air Traffic Management CO2 and Fuel Efficiency Performance Metrics for General ANSP Use*.

[10] EUROCONTROL & FAA Action Plan 16. (2009). *White Paper Common TP Structure and Terminology in support of SESAR & NextGen* (White Paper): EUROCONTROL/FAA.

[11] Airbus. (1998). *Getting to Grips with Cost Index* (Customer service brochure): Airbus Industrie.

[12] EUROCONTROL. (2012). *User Manual for the Base of Aircraft Data (BADA) Family 4*: EUROCONTROL Experimental Centre.

[13] Bronsvoort, J. (2014). *Contributions to Trajectory Prediction Theory and its Application to Arrival Management for Air Traffic Control.* Submitted to Departamento de Señales, Sistemas y Radiocomunicaciones. Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, Madrid.

[14] Bronsvoort, J., McDonald, G., Hochwarth, J, & Gallo, E. (2014). *Air to Ground Trajectory Synchronisation through Extended Predicted Profile (EPP): A Pilot Study.* Proceedings of the 14th AIAA Aviation Technology, Integration, and Operations Conference, Atlanta, GA.

[15] Bronsvoort, J., McDonald, G., Paglione, M, Young, C.M., Fabian, A., Boucquey, J., & Garcia Avello, C. (2013). Demonstration of Improved Trajectory Prediction using Future Air Navigation Systems *Air Traffic Control Quarterly, Vol. 21(4)*, p355-382.

[16] Bronsvoort, J., McDonald, G.N., Boucquey, J., Garcia Avello, C., Vilaplana, M, & Besada, J.A. (2013). *Impact of Data-Link on Ground-Based Trajectory Prediction Accuracy for Continuous Descent Arrivals.* Proceedings of the AIAA Modeling and Simulation Technologies (MST) Conference, Boston, MA, USA.

[17] López Leonés, J., Vilaplana, M.A., Gallo, E., Navarro, F.A., & Querejeta, C. (2007). *The Aircraft Intent Description Language: A key enabler for Air-Ground synchronization in Trajectory-Based Operations.* Proceedings of the 26th Digital Avionics Systems Conference, Dallas, TX, USA.

[18] U.S. National Weather Service. (2008). *NWS Instruction 10-806: World Area Forecast System*.

[19] Australia, Airservices. (2014). *Benefits of RNP Approaches at Gold Coast International Airport*. Canberra, Australia: Airservices Australia

[20] EUROCONTROL. (2014). *Performance Review Report - An Assessment of Air Traffic Management in Europe during the Calendar Year 2013*. Brussels, Belgium: EUROCONTROL.

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