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A Standard for Equivalent Lateral Spacing Operations

Parallel and Reduced Divergence Departures

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Abstract—**For the better part of half a century, a single 15-degree divergence requirement of the radar separation standard applies when conducting independent parallel departure operations. The origins and analytic basis of the 15-degree requirement are shrouded in history. Recent implementations of Area Navigation (RNAV) Standard Instrument Departure (SID) procedures that result in improved navigational precision and the need for more efficient operations in increasingly constrained airspace give cause to re-evaluate the divergence standard. In this paper, the current standard is reviewed, a divergence concept is presented that capitalizes on advantageous runway layout geometries as well as observed RNAV navigational precision, and an analysis of operational data is described that serves as an analytic basis for an advanced divergence concept. Depending upon runway layout geometry, the concept enables reduced divergence angles of 5 to 10 degrees in the majority of cases. Finally, the concept is applied to a RNAV departure procedure design recently proposed for The Hartsfield-Jackson Atlanta International Airport. The discussion is concerned with a key characteristic of the proposed concept: reducing divergence angles while maintaining the lateral spacing between departure paths in a manner that is defined to be equivalent to the spacing observed in diverging departure operations that meet minimum requirements of the current standard. With this characteristic, the proposed Equivalent Lateral Spacing Operation (ELSO) concept is well-suited to support the near- and mid-term development, further testing, and implementation of performance-based air traffic spacing applications that enable Next Generation Air Transportation System (NextGen) operational improvements and benefits.**

Keywords-Innovative ATM Concepts; Area Navigation (RNAV), parallel departures, divergence standard, reduced divergence, track dispersion, dispersion distribution

I. INTRODUCTION

Little data exist for evaluating the analytic basis of key separation standards, including the minimum requirement for 15-degree (deg) divergence between independent parallel departure operations [1,2]. Recent implementations of Area Navigation (RNAV) Standard Instrument Departure (SID) procedures at major airports in the United States National Airspace System (NAS) significantly improved the navigational precision in the terminal area. These advances pave the way for evolving the applicable terminal divergence standard. Such evolutions may capitalize not only on the increased navigational precision but also flexibly adapt to advantageous runway layout geometries. This paper proposes a standard that enables reduced divergence angles while maintaining the lateral spacing between departure paths provided by the minimum requirements of the currently applicable divergence standard. Key benefits include a suite of additional procedure design options not currently available to accommodate airspace and environmental constraints and to increase the efficiency of departure operations [3]. Previous investigations of non-standard departure procedures were conducted at Dallas/Fort Worth International Airport (DFW) and Charlotte Douglas International Airport (CLT) in support of operational approval programs [4,5]. Toronto/Pearson International Airport in Canada, Paris Charles de Gaulle Airport in France, and Madrid Barajas Airport in Spain also evaluated and/or implemented reduced-divergence operations. However, the scopes of these evaluations were limited to the specific airports and no attempt was made to develop a more widely applicable standard [6]. Most importantly, these evaluations only considered nominal departure trajectories and disregarded navigation and path-following errors.

This study aimed to support the Federal Aviation Administration (FAA) Next Generation Air Transportation System (NextGen) strategy and mid-term implementation goals to reduce divergence criteria for parallel departures as well as integrate arrival/departure airspace and procedures with multiple departure paths from each runway end through RNAV and Required Navigation Performance (RNP) procedures [7, 8,9].

II. CURRENT DIVERGENCE STANDARD

The standard currently applicable to diverging departure operations applies equally to conventional departures that follow Air Traffic Control (ATC)-assigned aircraft headings (i.e., radar vectors) and RNAV departures that proceed along designed routes. Conventional departure operations are used at most airports within the NAS. Departing aircraft are assigned headings that comply with local airport procedures. FAA Order JO 7110.65 and International Civil Aviation Organization (ICAO) Doc 4444-ATM define the requirements for conducting diverging departure operations [1,2]. The prime factors when implementing departure headings are generally environmental concerns or requirements and airspace design constraints.

There are three key rules pertaining to diverging departure operations from the same runway or parallel runways. In each of these cases, radar identification with the aircraft must be established within one mile of the takeoff runway end and courses must diverge by 15 degrees (deg) or more immediately after departure. Minimum separation requirements for operations conducted in the radar environment are depicted in Fig. 1. Fig. 1a refers to aircraft departing from the same runway and Fig. 1b refers to aircraft departing from the same airport or adjacent airports with parallel runways that are separated by less than 2,500 feet (ft). Wake turbulence requirements must be applied longitudinally between aircraft departing the same or departing parallel runways in these cases. Fig. 1c refers to aircraft departing parallel runways that are spaced 2,500 ft or more apart. Aircraft may depart independently and there no wake turbulence requirements apply in this case. The operational safety of diverging departures conducted at the currently authorized minimum requirements is assumed.

The primary advantage of conducting departure operations along multiple diverging departure paths is the delay reduction benefit that may result from an associated increase in operational efficiency [3]. However, a key requirement for the application of the current separation standard is the availability of the volumes of airspace needed to accommodate the diverging departure paths. When the airspace surrounding an airport is constrained or established noise footprint requirements further limit its use, associated procedure design constraints often preclude the use of diverging departure operations. In that case, divergence benefits remain unrealizable.

In Fig. 1c, dashed lines illustrate the center lines of nominal take-offs and departure tracks. The flight tracks of actual operations can be expected to display some variability resulting in departure paths of finite widths. Notional widths of departure paths are also illustrated in the figure. If the runway spacing exceeds the required minimum of 2,500 ft, the lateral spacing between the departure paths exceeds the lateral spacing associated with minimum requirements. This excess spacing may not only result from advantageous runway layout geometries but also from increased navigational precision when RNAV departure operations are conducted. The following section presents an analytic basis for a proposed standard that capitalizes on this excess spacing.

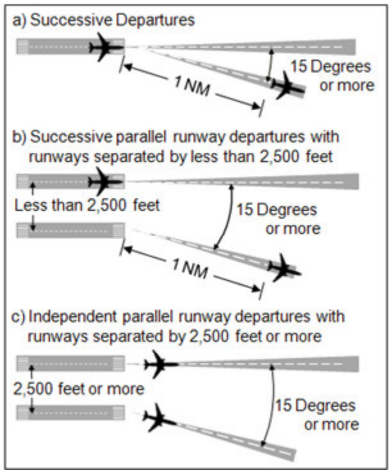

Figure 1. Current requirements for diverging departure operations.

III. EQUIVALENT SPACING STANDARD

The proposed concept that offers reduced divergence angles while maintaining established minimum lateral spacing between departure paths is subsequently referred to as Equivalent Lateral Spacing Operation, or ELSO standard. A key characteristic of the ELSO standard is that the lateral spacing between ELSO departure paths is designed to be equivalent to the minimum spacing of departure paths actually achieved in diverging departure operations based on the currently applicable divergence standard.

A. *The ELSO Concept*

The ELSO standard concept considers the widths of two categories of departure paths. The categories include (1) a path of departures that closely follow an extended center line of a departure runway and (2) a path whose center line is angled relative to a center line. The spacing between these two diverging departure paths comprising operations that meet the minimum requirements for independent parallel departures serves as the spacing baseline of the ELSO standard. In other words, the ELSO standard for diverging departure operations is defined to provide spacing between departure paths that is equivalent to the spacing observed in conventional departures at the currently applicable minimum divergence standard. The ELSO standard concept for diverging departure operations presented here takes into consideration and capitalizes on three factors:

- Parallel departure runway spacing.
- Parallel departure runway stagger.
- RNAV path following characteristics.

While this concept can be applied to both conventional and RNAV departure operations, this paper focuses on applications of the concept to RNAV departure operations [10]. Diverging departure operations, the spacing baseline, and the three factors of the ELSO standard are discussed in the following sections.

B. *Conventional Diverging Departure Operations*

Conventional departure operations generally involve ATC issuance of radar vectors to the planned route of flight. Before departure, aircraft are routinely assigned an initial heading to be flown immediately after takeoff. In the case of independent parallel departure operations, the current standard requires a minimum parallel runway spacing (r_{min}) of 2,500 ft and the assignment of headings representing nominal departure courses that differ in course angle (α_{min}) by a minimum of 15 deg.

1) *Spacing Baseline*

The minimum runway spacing r_{min} and the minimum divergence angle α_{min} currently applicable in independent parallel departure operations are illustrated in Fig. 2. In the figure, dashed lines represent nominal departure tracks. Based on the runway layout geometry, the spacing between the nominal departure tracks depends on the distance d from the runway end and is denoted as nominal spacing n(d). The nominal spacing is given by

$$n(d) = r_{min} + d \tan(\alpha_{min}). \tag{1}$$

Fig. 2 also provides a notional illustration of the scatter, or dispersion, of individual departures around the nominal departure tracks that can be expected to occur in actual operations. In this study, estimates of the angular widths of the dispersions observed in surveillance data of actual operations served to define the departure paths. It is assumed that the resulting widths of the departure paths can be adequately estimated and characterized in terms of a single or multiple standard deviations (σ) of the associated dispersion distributions.

As illustrated in Fig. 2, the width of the departure path that closely follows the extended center line of a runway is characterized by $\sigma_{STO,C}$. The subscript $_{STO,C}$ is used here to denote Straight-out Conventional departure operations. Similarly, $\sigma_{DIV,C}$ characterizes the width of the departure path whose center line is angled relative to the runway center line and the subscript $_{DIV,C}$ denotes Diverging Conventional departure operations. The only functional dependence of the widths of the departure paths and associated standard deviations considered here is the distance d from the runway end. In the figure, this functional dependence is indicated by the variable argument (d) in $\sigma_{STO,C}(d)$ and $\sigma_{DIV,C}(d)$.

Given the minimum runway spacing r_{min}, the minimum divergence angle α_{min}, and the widths of the departure paths, the spacing of the diverging departure paths is given by

$$s(d) \;=\; r_{min} \;+\; d\tan(\alpha_{min} - \sigma_{DIV,C}(d)) \\ -\; d\tan(\sigma_{STO,C}(d)). \qquad (2)$$

This spacing can be viewed to represent the minimum spacing between the dispersions that define the departure paths of diverging operations authorized by the currently applicable standard. This spacing serves as the spacing baseline for all ELSO standard application requirements reported here. In other words, all ELSO standard application requirements are defined to provide departure path spacing that is equivalent to the baseline spacing given by (2).

Two classes of ELSO standard applications are presented. The first class enables operations with parallel initial departure climb segments where the center lines of both departure paths are initially aligned with the extended center lines of their respective runways. The second class enables reduced divergence angles. Parallel application of the ELSO standard is typically limited to distances not exceeding a few miles from the runway end. Depending upon the application details, diverging application of the ELSO standard may not be subject to such range limitation. The two classes of ELSO standard applications are discussed in the following sections.

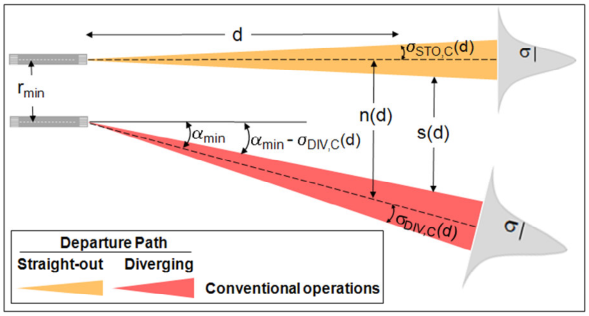

Figure 2. Spacing baseline illustrating key parameters that define the departure paths of conventional departure operations.

C. *RNAV Diverging Departure Operations*

RNAV departure operations do not typically involve ATC issuance of initial radar vectors. Instead, RNAV departure procedures provide defined course guidance from the departure end of the runway to the planned route of flight.

1) *Parallel Application*

Fig. 3 illustrates the spacing baseline s(d) and the case involving parallel application of the ELSO standard to RNAV departure operations. The width of the RNAV departure path that closely follows the extended center line of the departure runway is characterized by $\sigma_{STO,R}$. The subscript $_{STO,R}$ indicates Straight-out RNAV departure operations. Similarly, $\sigma_{DIV,R}$ characterizes the width of the departure path whose center line is angled relative to the runway center line and the subscript $_{DIV,R}$ denotes Diverging RNAV departure operations.

Given the spacing baseline s(d), the widths of the departure paths σ, and the runway stagger t as shown in Fig 3, the runway spacing is given by

$$r \;=\; s(d) + d\tan(\sigma_{STO,R}(d)) \\ +\, (d + t)\tan(\sigma_{STO,R}(d{+}t)). \qquad (3)$$

Parallel application of the ELSO standard defines the distance d from the runway end at which the lateral spacing of parallel departure paths is equivalent to the baseline spacing. Equation 3 yields

$$d = (r - s(d) - t\tan(\sigma_{STO,R}(d{+}t))) \\ /\, (\tan(\sigma_{STO,R}(d)) + \tan(\sigma_{STO,R}(d{+}t))). \qquad (4)$$

At shorter distances, the spacing of the parallel departure paths exceeds the baseline spacing. Parallel application of the ELSO standard typically assumes that conventional 15-deg divergence is established at larger distances.

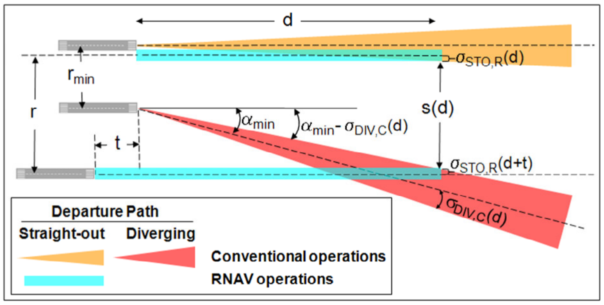

Figure 3. Spacing baseline and parallel application of the ELSO standard.

2) *Diverging Application*

Fig. 4 illustrates the spacing baseline and the case involving diverging application of the ELSO standard to RNAV departure operations.

Given the spacing baseline s(d), the widths of the departure paths, and the runway stagger, the runway spacing is given by

$$r \;=\; s(d) \;+\; d\tan(\sigma_{STO,R}(d))$$

$$- \ (d + t)\tan(\beta - \sigma_{DIV,R}(d+t)). \qquad (5)$$

The diverging application of the ELSO standard enables a reduced divergence angle β. The reduced divergence angle is defined to provide, at distance d, spacing of the departure paths that is equivalent to the baseline spacing. Equation 5 yields

$$\beta = \text{atan}\{(1/(d+t)) \\ * \ (s(d) - r + d\tan(\sigma_{STO,R}(d))\} + \sigma_{DIV,R}(d+t). \qquad (6)$$

At shorter distances, the spacing of the diverging departure paths exceeds the baseline spacing. Should 3-nautical mile (NM) lateral separation of the nominal departure tracks not already be established at distance d, diverging application of the ELSO standard assumes that conventional 15-deg divergence is established at larger distances.

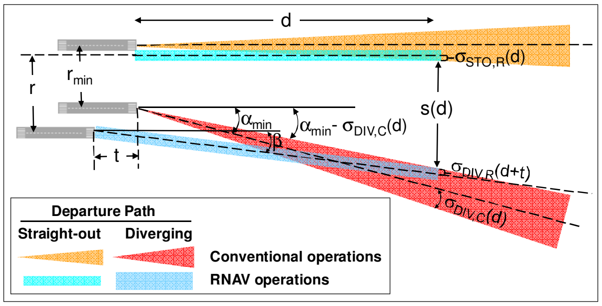

Figure 4. Spacing baseline and diverging application of the ELSO standard.

IV. DIVERGING DEPARTURE OPERATIONS

Operations at two airports were chosen to serve as models of diverging departure operations. Denver International Airport (DEN) and DFW served as models for conventional and RNAV departure operations, respectively. Key operational considerations at the two airports are discussed in this section.

Departure operations at DEN currently represent heading-based diverging operations. ATC routinely applies minimum 15-deg divergence between at least one pair of departure headings in all airport departure configurations. In routine operations the same standard headings are assigned no matter what the wind impact is on the ground track of the departures [11]. However, non-routine operations or significant weather events may require the assignment of additional and/or adjusted headings.

At DFW, almost all departures are assigned RNAV departure procedures. Each primary departure runway offers two procedures with initially diverging route segments that meet the 15-deg requirement for diverging departure operations. Diverging RNAV departure operations have been routinely conducted at the airport since 2005.

A. *Conventional Departure Operations*

The heading design at DEN is driven by airspace requirements. Due to the numerous arrival and departure runway configurations that are available at the airport, the departure headings must protect the airspace that is used to descend arrival aircraft.

Parallel runway departures can be conducted when aircraft depart in either a North or South-flow configuration. Due to DEN's geographic location and higher demand for East and West departures, aircraft departing on the North/South runways are often issued easterly or westerly on-course headings soon after their hand-off to departure control. On the other hand, East or West departures assigned to Runway 8 or Runway 25, respectively, typically maintain a departure heading for a longer time before resuming their own navigation toward a navigation fix along the planned route of flight. For this reason, the analysis of operational data focused on these departures.

1) Operational Considerations

Conventional departure operations generally provide the most flexibility for tower controllers. Ground controllers have the option of sequencing aircraft for departure in the line-up queue in such a way that the local controller can assign alternating departure headings when the aircraft reach the number one position for takeoff. This permits tower controllers to depart aircraft at minimum spacing due to the divergence rules that can be applied.

Each of the headings permitted for Runway 8 and 25 departures feed Air Route Traffic Control Center (ARTCC or Center) routes in the East and West cardinal directions, respectively. It is important that a minimum of 3-NM separation (in the case of transitional separation) or 5-NM separation is established in a manner that allows a timely hand-off to the en route departure sector.

Denver Center also requires that all Denver Tower East and West jet departures shall be established on course within 10 NM of the Center/Terminal Radar Approach Control (TRACON) common boundary [12]. This generally means that aircraft must be assigned a new heading and/or route within 15 to 20 miles after departure. If altitude separation is not applied, TRACON controllers must ensure that aircraft are always separated by a minimum of at least 3 NM prior to allowing the tower-assigned headings to be changed to less than 15-deg divergence. Differences in the track conformance of assigned headings can cause variance in the location at which the headings can be changed for adjacent departure courses.

B. *RNAV Departure Operations*

DFW operates with 16 RNAV SIDs. Aircraft capable of conducting terminal RNAV procedures at DFW are issued a clearance for a RNAV SID. This results in approximately 91 percent of aircraft departing on RNAV SIDs and a participation rate approaching 100 percent for aircraft departing the primary departure runways [13]. Departing aircraft routinely proceed toward one of four RNAV fixes located in either cardinal departure direction.

Variations in ground tracks are due to differences in the way aircraft avionics handle the transitions between legs of the RNAV departure procedure, as explained below.

1) Procedure Design Considerations

Each RNAV SID begins at the departure end of a runway (DER) and is coded in the Flight Management Computer's (FMC) 28 day navigation database with ARINC 424 leg types also known as path terminators [14]. Although ARINC coding is standardized, slight FMC variations do exist on the lateral and vertical paths. Therefore, the RNAV paths that aircraft follow are not always identical. These variations have been studied and continue to be monitored and resolved [15,16].

Fly-by waypoints are used for the runway transitions. Turn characteristics differ for both fly-by and fly-over waypoints and the difference is determined by how the path is (or is not) constructed, how the aircraft is steered, and how the Distance to Turn Anticipation (DTA) for the fly-by waypoint is computed. Consequently, different FMC/aircraft combinations will construct and fly a fly-by turn differently.

A heading-to-altitude (VA) leg is used to define the route segments at DFW that begin at a runway departure end (aircraft airborne) and terminates at a point where the aircraft altitude is at or above a specified altitude. No position is specified for the altitude termination point. Consequently, the VA track does not provide a predictable, repeatable flight path due to the unknown location of the termination point. As the V in VA denotes a heading, the aircraft ground track will be subject to prevailing winds as long as it is in heading mode.

Additionally, at DFW the VA leg is sometimes combined with a course-to-fix (CF) leg type. The CF leg type is defined as a course that terminates at a waypoint followed by a specific route segment. Since the CF leg does not have a defined starting point, it is up to the FMC to construct the starting point from which to begin the capture of the leg. The result of the above is that different FMC/aircraft combinations will capture a CF leg differently.

One other variation in RNAV departures is caused by when/where the pilot engages Lateral Navigation (LNAV) and flies the procedure using either the flight director or autopilot. This is largely driven by individual company operations policies and training guidelines. It can range from 50 ft above ground level (AGL) with automatic arming capability to 500 ft AGL when accomplished manually.

2) *Procedure Implementation Considerations*

Runways 17R-35L and 18L-36R serve as the primary departure runways at DFW and the analysis of operational data focused on departures from these runways. Examples of the two leg combinations used at DFW in RNAV SIDs are the AKUNA THREE and the DARTZ THREE RNAV DEPARURE procedures.

The DARTZ procedure represents a straight-out departure. As coded in the FMC database for runway 17R, it is heading 174 deg to 1,080 ft, direct to the first waypoint and track to the next waypoint. This leg type combination does not define a path off the runway and aircraft are simply flying a heading until the altitude constraint is satisfied. Consequently, aircraft fly the departure in a manner that is not dissimilar to the manner in which conventional departures with an assigned heading are flown. Aircraft climbing at higher rates may satisfy the altitude half way down the runway, while slower climbing aircraft may not reach the altitude until after passing the DER. The aircraft are subject to wind and may drift from the 174 deg course off the runway. Once the altitude is satisfied, the aircraft builds a path from present position to the next fix.

The AKUNA procedure represents a diverging departure that is coded in the FMC database as heading 174 deg to 1,080 ft, CF to intercept magnetic course 153 deg to the first waypoint and track to the next waypoint. The heading and altitude issues discussed above apply. However, once the altitude constraint is satisfied, the FMC begins to process the intercept to the course from present position. Because of the variations in the way FMCs compute the intercept, there are possibilities of path differences until the course is captured.

In both the cases of straight-out and diverging departures, FMCs should be expected to maintain adequate path adherence on the legs following the initial headings, satisfied altitudes, and intercepts to courses. Flight path differences along tracks will largely be limited to those that are due to varying DTAs associated with fly-by waypoints.

V. ANALYSIS OF DIVERGING DEPARTURE OPERATIONS

The objective of the data analysis was to characterize the widths of the departure paths observed in radar surveillance data of actual operations. To that end, mean values of measured radar track dispersion distributions and their widths around the means were estimated. Standard deviations from the mean values served to estimate the widths of the distributions. For each departure path under investigation, these estimates were carried out at various distances to obtain dispersion functions characterizing the widths at distances ranging from 1 to 11 NM from the runway ends.

A. *Metrics*

Two metrics were developed for measuring the dispersion functions $\sigma_{STO,C}(d)$, $\sigma_{DIV,C}(d)$, $\sigma_{STO,R}(d)$, and $\sigma_{DIV,R}(d)$ that characterized the widths of the departure paths under investigation. Although the two metrics were applied to characterize a single quantity, i.e., the width of a departure path, their complementary representations were found to highlight key differences between the navigational concepts underlying conventional and RNAV departure operations. The metrics are described in the following sections.

1) *Track Bearing Angle*

Fig. 5 illustrates the track bearing angle metric. It defines the angle γ between two lines extending from the runway end that define the origin of a departure path under evaluation. One line extends toward True North (TN) and the other extends toward the location of a point along a radar track at distance d from the runway end. In other words, for each radar track, the track bearing angle metric measures the angle γ at which a track point at distance d from the runway end is located relative to true North.

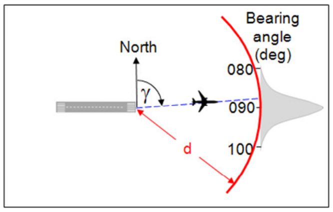

Figure 5. Track bearing angle metric.

2) *Lateral Track Offset*

Fig. 6 illustrates the track lateral offset metric. It also characterizes the location of track points at evaluation distance d from the runway end. However, the location is expressed in terms of a lateral distance ℓ from a reference point. Its location was chosen such that the dispersion distances could be measured as positive offsets from the reference point.

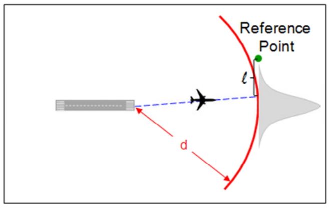

Figure 6. Lateral track offset metric.

B. *Radar Surveillance Data*

The metrics were applied to Automated Radar Terminal System (ARTS) surveillance data. The data comprised secondary radar returns recorded by single radar sensors located in close proximity to the airports. The radar tracks extracted from the data comprised both unassociated and associated tracks and allowed characterization of departure operations at altitudes ranging from approximately runway elevation to 20,000 ft AGL. The track selection and analysis methodologies are described in the following sections.

1) *Data Selection*

The data selection and analysis was carried out using MITRE's Integrated Terminal Research, Analysis, and Evaluation Capabilities (iTRAEC) [17]. For DEN, data recorded during two time periods were evaluated (1-31 July 2008 and 2-18 February 2010). For DFW, the data were recorded in February 2010 (2-28 February). In a first step, tracks of arrival and departure operations at the two airports were identified. A total of 127,355 DEN operations and 75,395 DFW operations were extracted from the data for further down-selection and analysis. Upon selection, the tracks were prepared for analysis at the various distances from a runway end under evaluation. Preparation for analysis generally involved interpolation between transponder returns to derive the locations of the tracks at the given evaluation distances.

a) *Conventional Departures*

At DEN, five departure paths were chosen for analysis and served to characterize conventional departure operations. A key consideration in this choice was the need to minimize the impact of other constraints (e.g., airspace constraints) on the operations and resulting departure paths described above.

Sample radar track data of the departure paths evaluated in this study are illustrated in Fig. 7. As indicated in the figure, Runway 8 departures are collectively referred to as East Flow (EF) departures and Runway 25 departures as West Flow (WF) departures. For the operational flows, three categories of departure paths were evaluated: straight-out departures (STO), diverging departures to the left (DIL) and diverging departures to the right (DIR). It is important to note that the evaluations were limited to distances ranging from 1 to 11 NM from the runways ends as shown in the figure.

Selection criteria were applied to select the radar tracks of jet departures associated with each departure path and evaluation distance. A selection distance range was defined for each evaluation distance. For each evaluation distance, selection criteria were applied to all transponder returns and resulting track courses within the selection range. The criteria required that all track courses measured within a selection range remained within a 15-deg window centered on the measured mean course of all tracks defining the departure path. For example, a 3 to 5-NM selection range applied to all evaluations at distances of 1, 2, 3, and 4 NM from the runway ends. The selection range was tailored and appropriately extended for larger evaluation distances. This tailored approach aimed to maximize the number of tracks available at shorter evaluation distances. For the example given above, a total of 18,579 departure tracks were selected for analysis.

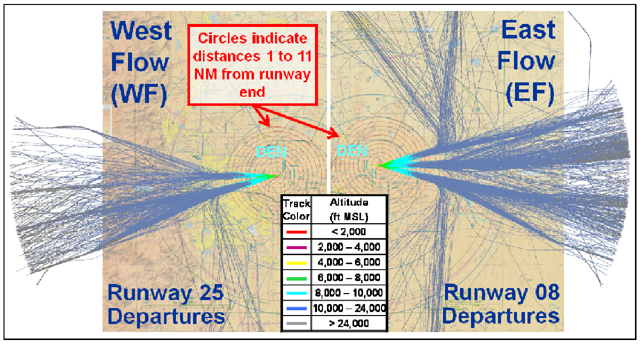

Figure 7. Radar track data of conventional departure operations.

b) *RNAV Departures*

At DFW, Runways 17R-35L and 18L-36R serve as the primary departure runways for jet departure operations. Eight departure paths originating from these runways were chosen for analysis and served to characterize RNAV departure operations. Sample radar track data of the eight departure paths are illustrated in Fig. 8. The figure shows the tracks selected to characterize the widths of departure paths at distances up to 11 NM from the runway ends.

As indicated in the figure, aircraft departing Runway 35L and Runway 36R are referred to as North Flow (NF) departures and aircraft departing Runway 17R and Runway 18L as South Flow (SF) departures. The departures were also classified by airport complex. Aircraft departing from the East Complex (EC) used Runway 17R-35L and West Complex (WC) operations departed from Runway 18L-36R. For each departure flow and airport complex, two departure paths were evaluated: straight-out (STO) and diverging departures (DIV). Similar to the analysis of DEN operations, the analysis of straight-out departure paths was limited to distances ranging from 1 to 11 NM from the runways ends. However, the RNAV route design associated with the diverging departure paths limited the evaluation of diverging operations to distances up to 5 NM from the runway ends. In the figure, the range of evaluation distances in 1-NM steps is indicated by red circles.

Selection criteria were applied to select the radar tracks of jet departures associated with each departure path. The criteria required that a track remained within 0.4 NM of the nominal route at up to five locations along the associated RNAV procedure. A key consideration in choosing the selection locations was the need to minimize the impact of RNAV course guidance characteristics (e.g., varying DTAs) on the operations and resulting departure paths. For the departure paths originating from each runway end, the track selection criteria were tailored to DFW's sixteen RNAV departure procedures. They employed multiple selection locations extending from locations prior to the first named procedure waypoint to locations in close proximity to one of the sixteen departure fixes located at the DFW TRACON airspace boundary. A total of 10,166 departure tracks were selected for analysis.

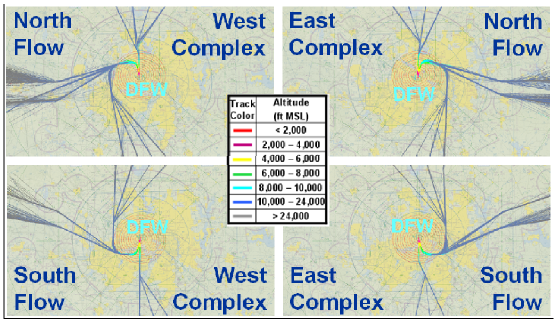

Figure 8. Radar track data of RNAV departure operations.

C. Radar Track Analysis

The track bearing angle and lateral offset metrics were applied to the radar track data selected and prepared for analysis. The analysis yielded the track dispersion distributions that served to characterize the departure paths evaluated in this study. The results of the analysis are presented in the following sections.

1) Conventional Departures

Fig. 9 illustrates the results of the analysis of DEN Runway 8 straight-out departure operations. For this example, the figure presents a plan view (top left) of the radar tracks recorded in February 2010 and the corresponding three-dimensional (3-D) view (bottom left). Also shown and based on all data evaluated in this study are the track dispersion distributions that resulted from application of the track bearing angle (top right) and lateral offset (bottom right) metrics.

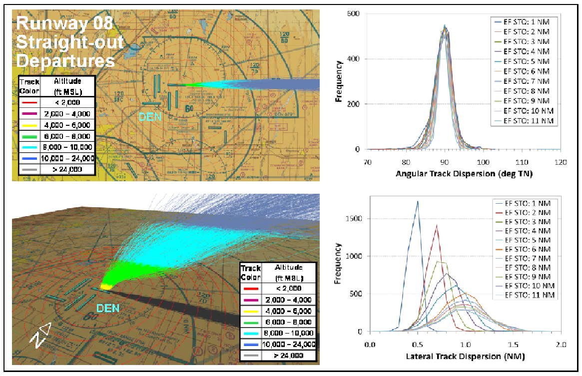

Figure 9. Conventional departure analysis.

2) RNAV Departures

Fig. 10 illustrates the results of the analysis of DFW straight-out departure operations conducted in North Flow on the East Complex of the airport and recorded in February 2010. For this example, the figure presents a plan view (top left) of the radar tracks and the corresponding 3-D view (bottom left). Also shown in the figure are the track dispersion distributions that resulted from application of the track bearing angle (top right) and lateral offset (bottom right) metrics.

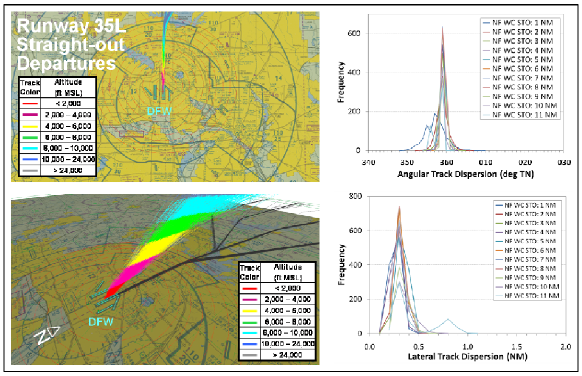

Figure 10. RNAV departure analysis.

D. Dispersion Functions

The measured angular track dispersion distributions provided the basis for estimating the angular widths of the departure paths. It is important to note that the dispersion distributions reflect the various factors that affect the ground track of conventional and RNAV departure operations including the effects of prevailing winds, the navigational performance associated with maintaining assigned headings or RNAV routes (path-following errors), as well as measurement uncertainties. In the case of departures that involved initiation of a turn to a diverging heading soon after takeoff, the distributions also reflect the variability that results from differences between the locations where the turns were initiated. Differences between departure paths especially at larger distances from the runway ends may also reflect other operational considerations outlined in Section IV.

Fig. 11 summarizes averages of angular dispersion functions of all straight-out and 15-deg diverging departure

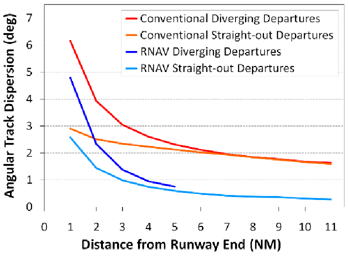

Figure 11. Angular track dispersion functions (1σ) of conventional and RNAV departure operations.

paths evaluated in this study. In the figure, the dispersion functions are presented as one standard deviation of the dispersion distributions measured at distances up to 11 NM from the runway ends. The results represent the four standard deviation functions $\sigma_{STO,C}(d)$, $\sigma_{DIV,C}(d)$, $\sigma_{STO,R}(d)$, and $\sigma_{DIV,R}(d)$ discussed in Section III.

Similar to the angular track dispersion distributions, the measured lateral track dispersion distributions served to estimate the lateral widths of the departure paths. Fig. 12 presents the resulting one standard deviation estimates of the lateral widths of all departure paths evaluated in this study. Expressing the path widths in lateral terms highlights the intrinsic differences between conventional and RNAV course guidance characteristics. Whereas conventional departure operations that employ an angular-based system and rely on the issuance of aircraft headings generally yield increasing lateral dispersions with increasing distance from the runway end, lateral dispersions display the reduced range dependence that is expected to result from procedural, RNAV-based course guidance.

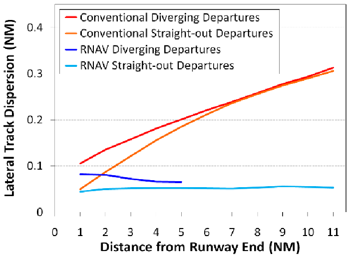

Figure 12. Lateral track dispersion functions (1σ) of conventional and RNAV departure operations.

As shown in Fig. 8, dispersion distributions of diverging RNAV departure paths were limited in the data to distances up to 5 NM from the runway end. In order to enable the application of the ELSO standard to RNAV operations at larger distances, the dispersion function was extrapolated. The extrapolation approach chosen was judged to be conservative and involved two steps. First, the width difference of straight-out and diverging RNAV departure paths was measured at the distance of 5 NM. In a second step, this difference was added to the dispersion function of straight-out departures to yield width estimates for diverging RNAV departure paths at distances from 6 to 11 NM from the runway end.

The extrapolation described above and the fits to the dispersion functions are presented in Fig. 13. As noted above, the ELSO standard concept takes into consideration and capitalizes on three factors including the stagger of parallel departure runways. In order to apply the ELSO standard to runway layout geometries that involve runway stagger values different from integer values, polynomial regression curves were fitted to the dispersion functions. The four dispersion functions $\sigma_{STO,C}(d)$, $\sigma_{DIV,C}(d)$, $\sigma_{STO,R}(d)$, and $\sigma_{DIV,R}(d)$ served as analytic basis for all applications of the ELSO standard presented in the following section.

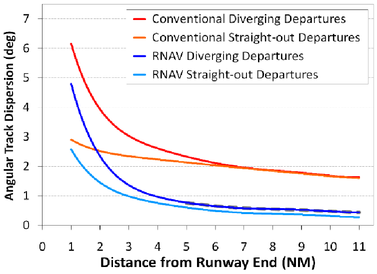

Figure 13. Angular track dispersion functions (1σ) that served as analytic basis for applications of the ELSO standard.

VI. APPLICATION REQUIREMENTS

The ELSO standard for diverging departure operations presented in Section III is defined to provide lateral spacing between departure paths that is equivalent to the spacing observed in conventional departure operations at the currently applicable minimum divergence standard (see Fig. 2). At the runway spacing of 2,500 ft and divergence angle of 15 deg currently applicable to independent parallel departure operations, the nominal spacing between the center lines of departure paths is given by (1). Also taking into consideration the dispersion functions $\sigma_{STO,C}$ and $\sigma_{DIV,C}$ presented in Section III, the baseline spacing between diverging departure paths is defined by (2). The following sections present numeric values of the nominal and baseline spacing.

A. *Nominal Spacing*

Fig. 14 presents the nominal spacing associated with 15-deg divergence and the various runway spacing values considered in this study. Taking the runway spacing of 2,500 ft as an example, a nominal lateral spacing of 3 NM between diverging departures is achieved at a distance of nearly 10 NM from the runway end. The figure also illustrates the spacing baseline applicable to successive departure operations from the same runway, i.e., same runway departures (gray curve).

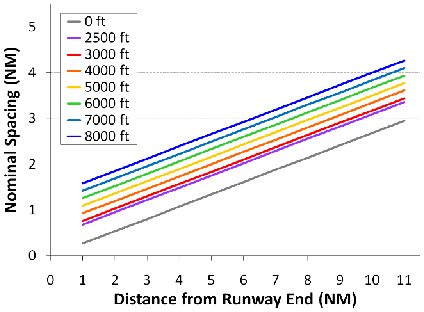

Figure 14. Nominal departure track spacing of 15-deg diverging departure operations for various runway spacing values.

B. *Spacing Baseline*

The spacing baseline illustrated in Fig. 15 (red curve) represents the minimum spacing of track dispersions that define the departure paths of operations authorized by the currently applicable divergence standard. It serves as the spacing baseline for all ELSO standard applications presented in this section. The widths of the departure paths were estimated as two standard deviations (±2σ) of the measured dispersion distributions.

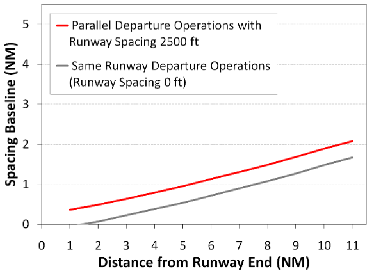

Figure 15. Departure path spacing (2σ) that served as spacing baseline for applications of the ELSO standard (see Fig. 2).

C. *Equivalence Criterion*

As stated previously, the ELSO standard is defined to provide lateral spacing between departure paths that is equivalent to the spacing observed in conventional departure operations at the currently applicable minimum divergence standard. This equivalency requirement was based on the widths of the measured dispersion distributions that were used to characterize the departure paths.

The widths of the dispersions that define the departure paths were estimated as ±2σ of the measured dispersion distributions (see Fig. 15). The same width estimation methodology applied to conventional as well as RNAV operations. This approach ensured the equal footings of the analyses of conventional and RNAV departure operations needed for the comparative evaluations presented here. The choice of ±2σ was guided by ICAO recommendations concerning the minimum protected airspace provided for RNAV routes under radar monitoring [18]. This choice primarily aimed to characterize a substantial fraction of the operations reflected in the measured dispersion distributions and to provide conservative values of ELSO standard requirements in RNAV applications. Sensitivity analyses were carried out to investigate how sensitively ELSO standard requirements for RNAV departure operations depend on the characterization of dispersion width. The choice of ±2σ necessarily provided significantly more conservative values (e.g., larger equivalent divergence angles) when compared to those based on ±3σ width estimates.

D. *RNAV Departure Operations*

The ELSO standard presented in Section III applies to independent parallel RNAV departure operations if runway layout geometries provide runway spacing of 2,500 ft or more and/or the runway ends are staggered favorably (see Fig. 3 and Fig. 4). Application requirements for the parallel and diverging applications of the ELSO standard are presented in the following sections.

1) *Parallel Application*

The ELSO standard defines the distance from the runway end at which the lateral spacing of a parallel departure path is equivalent to the baseline spacing (see Fig. 3). This equivalent parallel departure distance is given by (4). Equation 4 was solved iteratively to obtain equivalent parallel departure distances for the various runway spacing and stagger values considered in this study. Fig. 16 presents the resulting requirements for parallel applications of the ELSO standard.

Taking 0 ft runway stagger and 6,000 ft runway spacing as an example, the ELSO standard supports a parallel initial departure climb segment of up to 3.9 NM from the runway end. At shorter distances, the standard ensures that the spacing of the parallel departure paths exceeds the baseline spacing. Parallel application of the ELSO standard typically assumes that conventional 15-deg divergence is established at larger distances.

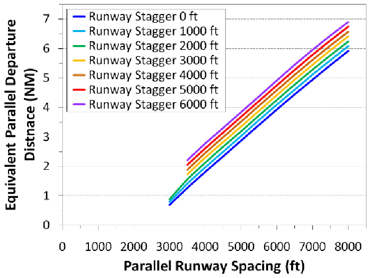

Figure 16. Equivalent parallel departure distances illustrating parallel applications of the ELSO standard to RNAV departure operations.

2) *Diverging Application*

The ELSO standard defines the reduced divergence angle that provides, at a given distance from the runway end, the spacing of the departure paths that is equivalent to the baseline spacing (see Fig. 4). The reduced divergence angle is given by (6). This equation was used to obtain equivalent divergence angles for the various runway spacing and stagger values. Table I and Fig. 17 present the resulting requirements for diverging applications of the ELSO standard to parallel

TABLE I. EQUIVALENT DIVERGENCE ANGLES

Distance from Runway End (NM)	Equivalent Divergence Angle in Degrees for Runway Stagger 2000 ft					
	RNAV Departures - Runway Spacing (ft)					
	3000	4000	5000	6000	7000	8000
1	5.5					
2	6.1	2.1				
3	6.6	3.8	1.0			
4	7.1	4.9	2.7	0.5		
5	7.5	5.7	4.0	2.2	0.4	
6	7.9	6.4	4.9	3.4	1.9	0.5
7	8.3	7.0	5.7	4.5	3.2	1.9
8	8.7	7.5	6.4	5.3	4.2	3.0
9	9.0	8.0	7.0	6.0	5.0	4.0
10	9.2	8.3	7.4	6.5	5.6	4.7
11	9.4	8.6	7.8	7.0	6.2	5.3

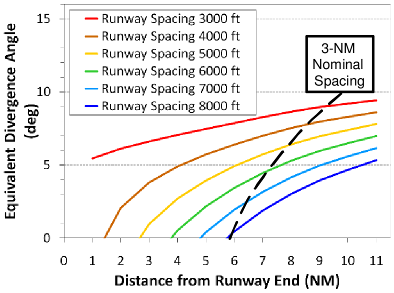

Figure 17. Equivalent divergence angles illustrating diverging applications of the ELSO standard to RNAV departure operations.

runways for the case in which the runway ends are staggered by a distance of 2,000 ft.

Taking 2,000 ft runway stagger and 3,000 ft runway spacing as an example, the ELSO standard supports an equivalent divergence angle of 8.3 deg for reduced divergence operations up to a distance of 7 NM from the runway end. At shorter distances, the standard ensures that the spacing of the diverging departure paths exceeds the baseline spacing. Should nominal lateral spacing of 3 NM not be achieved at a distance of interest (that meets given airspace or noise constraints), diverging application of the ELSO standard assumes that conventional 15-deg divergence is established at larger distances. In the above example, a nominal spacing of 2.4 NM is achieved at a distance of 7 NM from the runway end (see Fig. 14) requiring subsequent application of conventional 15-deg divergence until 3-NM nominal lateral spacing is established. Nominal lateral spacing of 3 NM is achieved at a distance of 9.3 NM from the runway end. When applied at this distance, the ELSO standard defines an equivalent divergence angle of approximately 9.1 deg. Thus, a reduced divergence angle of 9.1 deg ensures that the spacing of the diverging departure paths exceeds the baseline spacing at shorter distances (less than 9.3 NM) and that nominal lateral spacing exceeds 3 NM at larger distances.

VII. POTENTIAL APPLICATION

A recent proposal for reduced divergence departure operations at The Hartsfield-Jackson Atlanta International Airport (ATL) includes new and modified RNAV SID procedures. The procedures are scheduled for implementation in June 2011. The procedure design aims to reduce departure delay due to runway capacity constraints and increase schedule reliability at the airport [19]. This section illustrates a potential application of the ELSO standard to a real-world example and presents an initial evaluation of the proposed operations. Fig. 18 illustrates current and proposed departure paths in ATL's three-runway (or triple) East flow departure operational configuration. In this flow, the proposal calls for an additional RNAV procedure and associated departure path for Runway 8R departures.

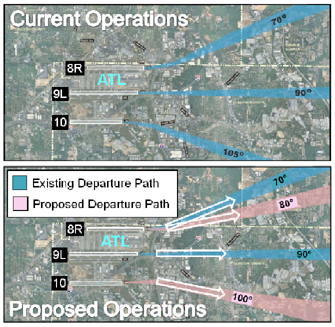

Figure 18. Departure paths proposed for ATL [19].

The procedure design features reduced 10-deg divergence between independently conducted departure operations on Runway 9L and 10. The runways are spaced 5,250 ft apart. For this runway spacing, application of the current 15-degree divergence standard results in a nominal lateral spacing of 3 NM at a distance of 8 NM from the runway end. For this distance and a runway stagger value of 2,885 ft, application of ELSO standard for RNAV departures yields an equivalent divergence angle of 6 deg. Diverging application of the ELSO standard up to this distance ensures that the spacing of the diverging departure paths exceeds the baseline spacing at shorter distances (less than 8 NM) and that nominal lateral spacing exceeds 3NM at larger distances.

The procedure design proposal also features reduced 10-deg divergence between same-runway departure operations successively conducted on Runway 8R. Application of the ELSO standard to same-runway departures necessarily involves application of 0 ft runway spacing, 0 ft runway stagger, and the use of an alternative spacing baseline. The spacing baseline applicable to same-runway departure operations is presented in Fig. 15 (gray curve). Application of the current divergence standard to same-runway departures results in a nominal lateral spacing of 3 NM at a distance of 11.2 NM from the runway end (see Fig. 14). For this distance, extrapolation of the ELSO application requirements for RNAV departures yields an equivalent divergence angle of 10 deg.

VIII. CONCLUSIONS

The current standard for independent parallel departure operations with a fixed minimum implementation requirement of 15 deg of divergence invariably inflates the lateral spacing between departure paths when runway spacing values exceed 2,500 ft or advanced course guidance is provided. The ELSO standard concept presented here not only flexibly adapts to advantageous runway layout geometries but also capitalizes on the increased navigational precision of RNAV departure operations.

The ELSO standard proposes to reduce divergence angles while maintaining the lateral spacing between departure paths in a manner that is defined to be equivalent to the minimum spacing currently achieved in diverging departure operations. Depending upon the runway geometry, parallel application of the ELSO standard enables parallel initial departure segments typically extending 3 to 5 NM for RNAV departure operations. Alternatively, diverging application of the ELSO standard enables reduced divergence angles typically ranging from 5 to 10 deg for RNAV departure operations in the majority of cases.

The standard offers a suite of additional procedure design options not currently available to better accommodate airspace and environmental constraints. Increases in the efficiency of departure operations can be expected when application of the ELSO standard enables diverging operations [3].

The ELSO standard was applied to evaluate a proposal for reduced divergence operations at ATL. Capitalizing not only on the increased navigational precision of RNAV departure operations but also on its advantageous runway layout geometry, the ELSO standard for diverging operations was found to support ATL's proposed 10-deg divergence for parallel departure operations (Runway 9L and 10) and same-runway departure departures (Runway 8R).

A key characteristic of the proposed standard is the equivalent lateral spacing between departure paths it provides.

This study assumed that departures currently conducted in accordance with minimum requirements meet the target level of safety applicable to diverging departure operations. Based on the equivalence of the lateral spacing between diverging departure operations that meet the requirements of the proposed standard, an equivalent level of safety can be expected for ELSO standard operations. While this study presented applications of the ELSO standard to departure operations that involved RNAV-based course guidance, the concept may also be extended to apply to other modes of course guidance and flight path containment such as RNP.

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NOTICE

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