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Depiction of Vertical Flight Paths for Nextgen Arrival and Departure Instrument Flight Procedures

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Charts for instrument approach procedures have a vertical profile view that pilots can refer to during the final stages of the approach to the runway. However, there is no similar view of vertical flight path on charts for arrival and departure procedures. We studied whether a depiction of vertical flight path is feasible for arrivals and departures and whether it could help pilots manage procedures such as Optimized Profile Descents (OPDs), which are becoming common in the Next Generation Air Transportation System (NextGen). We identified sample procedures with challenging features including multiple flight path transitions, multiple constraints, course reversals, and many waypoints. Then we developed low-fidelity static prototypes and gathered informal feedback from airline pilots and chart developers. Based on their feedback and prior research, we developed a list of design considerations for both static and dynamic displays of vertical flight path for arrivals and departures.

The Next Generation Air Transportation System (NextGen) relies upon Area Navigation (RNAV) and Required Navigation Performance (RNP), which allow aircraft to fly more precise lateral routes using satellite navigation and/or other aircraft navigation systems. These form the basis of Performance-Based Navigation (PBN), an important component of NextGen. NextGen leverages PBN for the design of new RNAV Standard Instrument Departures (SIDs) and RNAV Standard Terminal Arrival Routes (STARs). A SID defines a path from a specific runway to the enroute airspace, and a STAR defines a path from the enroute airspace to a termination point from which the aircraft can join an Instrument Approach Procedure (IAP) to land at a specific runway. RNAV SIDs and STARs are common at major airports in the United States, such as Denver, Dallas-Fort Worth, and Atlanta. SIDs and STARs can extend over long distances (well over 50 miles and even beyond 200 miles in some cases) and they extend well into high altitude airspace (above 18000 ft). They are developed for routes that Air Traffic Control (ATC) uses to manage flights into and out of airports. They are presented to pilots on published aeronautical charts and encoded into the navigation database of the aircraft’s Flight Management System (FMS) so that the autoflight systems can follow the route as programmed.

This paper describes an effort to identify design considerations for the depiction of vertical flight paths for SIDs and STARs. We are interested in this issue because charts for IAPs have a vertical profile view that pilots find useful, but there is no similar view of vertical flight path on charts for arrival and departure procedures. Our questions were, what is an adequate depiction of a SID/STAR vertical flight path and is this depiction feasible to implement? Could this depiction help pilots to manage compliance with vertical flight path constraints on speed and altitude? To explore these issues, we first partitioned the design problem. Our primary focus was the design of vertical flight path depictions for *static* (pre-composed) aeronautical charts (paper or Portable Document Format, PDF). Secondarily, we considered data-driven (dynamic) views of the vertical flight path for SIDs and STARs.

We begin this paper with background on SIDs and STARs and related findings from other displays of vertical flight path. Then we present the method for this effort, including the assumptions and scope. Though we prototyped several options, we present only the two that received the most favorable reviews by airline pilots and chart developers. Finally, we list design considerations for depiction of vertical flight path on arrivals and departures.

Background

RNAV SIDs and STARs have more turns and more altitude and speed constraints than older SIDs and STARs (which use conventional, line-of-sight, ground-based navigation aids). Optimized Profile Descents (OPDs) are a specific type of RNAV STAR. They have many vertical constraints (on speed and/or altitude) that allow the aircraft to descend continuously for fuel efficiency. The vertical constraints on OPDs also allow ATC to anticipate the aircraft vertical flight path, within bounds, which releases airspace for other traffic flows.

To fly RNAV SIDs and STARs, including OPDs, pilots are more dependent upon the FMS and, in particular, its Lateral Navigation (LNAV) and Vertical Navigation (VNAV) modes. Use of automated systems, such as the FMS, to manage flight path can be very effective, but introduces its own vulnerabilities (PARC/CAST, 2013). Managing automated systems can also increase pilot monitoring workload (Flight Safety Foundation, 2014).

Butchibabu, Midkiff, Kendra, Hansman, and Chandra (2010) found that problematic STARS, identified from the Aviation Safety Reporting System (ASRS), had more altitude constraints and more waypoints than baseline STARs. In other words, pilots have more difficulty managing the vertical flight path constraints on RNAV STARs with many vertical constraints, such as OPDs. Based on conversations with pilots, we found that this is more likely if the VNAV algorithms are less sophisticated or if the aircraft is not equipped with VNAV (Chandra and Markunas, 2017). For SIDs, Butchibabu et al. (2010) found that lateral deviations were more common than vertical flight path deviations. However, in discussions with industry pilots, we learned that vertical flight path constraints that do appear on SIDs are very difficult for pilots to manage, and that is why they are less common. Recent discussions with industry pilots confirmed that managing vertical flight path constraints on OPDs remains a top concern.

Vertical profile views on IAP charts graphically depict altitudes that the aircraft must meet during the last stages of the approach. It is logical to anticipate that a similar display might help pilots fly SIDs and STARs accurately, so we examined the design and use of the IAP vertical profile view. From Chandra and Markunas (2017), we learned that pilots go back and forth between the plan view on the IAP chart and the profile view; they use both. The vertical profile and the plan view are aligned in specific ways (names of waypoints, for example), and some data are duplicated (e.g., altitudes are shown in both places). The vertical profile view is less cluttered than the plan view; it simply shows less information for a shorter portion of the approach. Pilots can use the profile view for reference in flight during the final stages of the approach. However, pilots with more advanced avionics may focus on the primary flight displays and monitor other flight deck systems, such as VNAV, so they may not look at the chart’s profile view as much.

Vertical Situation Displays (VSDs) are electronic flight deck displays of vertical flight path. SAE ARP 5430 (2013) contains detailed design guidance for VSDs. Although there are many potential uses for the VSD, Boeing designed theirs primarily to mitigate controlled flight into terrain during approach (Boeing, 2002). The VSD is a strategic, real-time display, whereas pilots use the static vertical profile on an IAP for planning and reference. Also, the VSD shows ownship position; in order for pilots to correlate the view on the VSD with the view on the static IAP vertical profile, they would need to know where their own aircraft is on the static depiction.

Electronic data-driven charts are also in development and could be used to show vertical flight paths. Such charts allow pilots to access all the information from a static chart (much of which is not available on primary flight deck electronic displays) in an electronic, customizable format. For an introduction to different types of electronic charts, including data-driven charts, see Chandra, Yeh, Riley, and Mangold (2003). Additional information on data-driven charts can be found in SAE ARP 5621 (2004), and Larson (2011).

Method

Before developing our prototypes, we scoped the effort by making several assumptions to simplify the work. For example, we decided to prototype only static concepts, not data-driven electronic concepts, which would have required software development and many design choices. We also decided not to constrain the size of the depictions. Instead, we wanted to identify the best possible design, even if it did not fit on existing charts. Existing charts have very little free space, and finding any at all will be a significant problem. We also chose to make only black and white depictions. Current SID/STAR charts from the United States government are not printed in color, although that could change in the future. We did not consider how notes would be shown, the scale of the vertical axis, or symbology for speed constraints (for which we kept today's standard format, lines above and below the speed). Lastly, we did not evaluate how far along the route the vertical flight path should be depicted– whether the depiction should extend to the last waypoint with a constraint, or to the end of the whole route, up to the last waypoint.

Another key decision we made was about what pilot task(s) the display would support. To make this decision, we first brainstormed about how the depiction might be used and came up with four possibilities. After discussing these options with airline pilots and chart developers, we concluded that the most likely use for the display would be to assist with route verification during set up in FMS. This is in agreement with a finding from Chandra and Markunas (2017) that pilots do not use static charts to monitor the flight path in real time; they use static charts primarily to review and brief the route during flight preparation. The other possible uses we considered were for the depiction to (a) highlight segments with potentially steep climb or descent gradients, (b) help pilots build an internal mental representation that they could reference later in flight, and (c) help pilots understand any route amendments from ATC. Of these, only the first (highlighting steep climbs/descents) was considered to be valuable.

We also had to select specific arrival and departure procedures for our prototypes. To do this, we first created a list of challenging features. These were multiple transitions (i.e., branches in the flight path), multiple altitude or speed constraints, multiple waypoints, and course reversals. Many RNAV STARs have multiple transitions because the paths go in different directions for the different landing directions and runways at the airport. SIDs have transitions to merge paths from different runways and transitions to merge onto different airways in the enroute airspace. Although transitions can overlap to some extent, each typically has a unique vertical flight path. So, any airport with multiple runways will have more transitions (for both SIDs and STARs), and there will be more distinct vertical flight paths for those routes.

We considered five different RNAV instrument flight procedures for the prototypes and eventually used three: the FRDMM THREE STAR (an OPD) into Washington, DC (KDCA), the EDETH FIVE SID out of Salt Lake City, UT (KSLC), and the LEETZ TWO SID also from Salt Lake City. (The two Salt Lake City SIDs are no longer in use and the FRDMM has been updated.) We used these procedures to illustrate different prototype options including: four display formats, four types of altitude-constraint symbols, two types of flight path representation (line segments vs. smooth), two types of horizontal-axis scaling (equal intervals vs. notional), and different amounts of data duplication from the plan view. The four display formats include two different table views, two different 2-D graphical formats, and one 3-D format. The four different altitude constraint symbols included the standard chart convention (lines above/below the altitude), shading, the FMS convention (letters), and new triangle symbols. We did not create prototypes for all combinations of these features, just some illustrative examples for discussion and feedback.

Findings

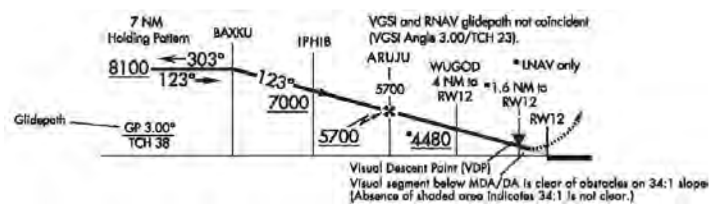
Our discussions with pilots and chart developers provided useful feedback on the design of the prototypes views. Some key points are summarized below.

Altitude-constraint symbols. The group recommendation was that we should match the symbol for altitude constraints with existing chart symbols, rather than develop a new symbol. Matching the FMS notation was not useful.

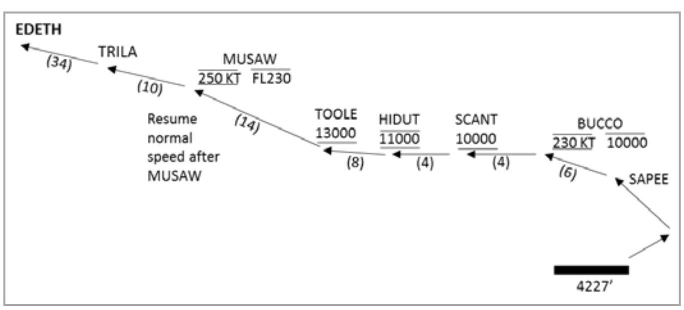
Horizontal axis. The group recommendation was that we should include a numerical value for the distance between waypoints (even if the scaling is notional). Pilots will use this along with the altitude requirements to estimate if there will be a steep descent or climb gradient. Equal intervals between waypoints along the horizontal axis were misleading, but exact scaling was unnecessary.

Display formats. The 3-D format was not effective. It produced a depiction that was difficult to interpret; turns and descents were confusable.

The two prototypes that received the most favorable feedback are shown in Figure 1, along with an IAP vertical profile view (a) for comparison. One is a graphical 2-D view (b) and the other is a table view (c), both for an RNAV SID at Salt Lake City, Utah. In Figure 1(b), the upward path (a climb) indicates either altitude increase or turns in an intuitive integrated view. This view may help pilots to identify steep or level vertical gradients and sharp turns. It uses the standard symbols for altitude constraints. However, this graphical view still requires a separate image for each transition with a unique vertical path. The pros of the table view in Figure 1(c) are that it can be used to verify the constraints quickly, its format corresponds to a familiar layout of the FMS Control and Display Unit (CDU), and it uses the standard symbols for altitude constraints. The drawbacks of the table in Figure 1(c) are that each route transition requires its own table, and the table column format will not match all CDUs.



(a)



(b)

(c)

Depart runway heading

At 4727' (500' AGL), LEFT turn

Direct **SAPEE**.
5.6 NM

BUCCO 230 KT 10000
3.7 NM

SCANT 10000
3.9 NM

HIDUT 11000
7.6 NM

TOOLE 13000
13.9 NM

MUSAW 250 KT FL230
(Resume normal speed after MUSAW)
10.4 NM

TRILA
34.2 NM

EDETH

Figure 1. Example vertical profile view from Federal Aviation Administration (FAA) chart legend (a), sample graphical format for Salt Lake City, Utah EDETH FIVE RNAV SID (b), and sample table format (c) for the same procedure, which has multiple transitions, multiple constraints, and a course reversal. The depictions in (b) and (c) end before the enroute transitions begin, after the EDETH waypoint.

In addition to receiving specific feedback on the prototypes, another important result of this effort was that, while developing the prototypes, we identified design considerations for static depictions of vertical flight path. Some of the design considerations were in-scope, in that we considered them in our prototypes. These include the display format, the symbology for altitude constraints, type of flight path representation, horizontal-axis scaling, and duplication of data between the vertical flight path depiction and the plan view. Some design considerations were not considered in our prototypes. These were space limitations, use of color, notes, how far the vertical profile should extend along the route, symbology for speed constraints, and the vertical-axis scale.

Data-driven charts have additional design considerations. These charts are presented on an electronic display and managed through a graphical user interface. As such, there are general software considerations such as user interaction with display and data elements, the physical display size, display configuration (automatic or user-controlled), and sources of data for the display. More specific considerations for data-driven vertical flight path depictions are:

- When should pilot use this depiction and why?
- What is the priority of this information relative to other available data?
- Will ownship be available?
- How is an electronic data-driven vertical profile view different from a VSD?

Summary and Conclusions

We explored design considerations related to creating vertical flight path depictions for SIDs and STARs with difficult features such as course reversals, multiple constraints, transitions, and waypoints. These procedures, which include OPDs, are being developed as part of NextGen. We selected some candidate procedures to prototype in static formats, then gathered feedback on these prototypes informally from airline pilots and chart developers. We identified several design considerations for depictions of vertical flight path for both static and electronic data-driven formats.

The most likely reason for a pilot to use a static vertical flight path depiction is to check constraints along the route during a briefing in preparation to fly the procedure. The depiction could provide an efficient way to verify the route in the FMS or help draw attention to potential challenges in segment gradients. However, static depictions of vertical flight path are not useful for in-flight monitoring because they do not provide the pilot with the necessary information at the right time.

Another problem for these depictions, which we did not address, is that they take a lot of space, even for just one transition. And, in fact, most major airports have multiple runway and enroute transitions, each with a unique vertical flight path. It would take a lot of space to show every possible transition and flight path. The operational utility of any depiction will depend on how it is integrated with other chart data. We know that depicting the vertical flight path for a SID/STAR with many flight path transitions, waypoints, and constraints is not likely to fit within the currently available space on static (paper or PDF) charts, even if we minimize the size of depictions and list only waypoints with constraints. Incorporating these depictions on static charts may be costly and of limited utility.

Even separating a SID or STAR with multiple transitions across multiple chart images (as discussed in Chandra and Markunas, 2013), may not yield sufficient free space on a chart. Vertical flight path depictions that require multiple pages will be unwieldy and are unlikely to produce sufficient benefits to make them worthwhile, given the extent of costs and resources required to update so many charts. For these reasons, we do not expect that including depictions of vertical flight path on static SID/STAR charts would provide an operational benefit. There is some hope that data-driven depictions of vertical flight paths will be helpful, but there are also many unanswered questions about how these depictions would work in practice.

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