# Flight Deck Perspectives on Departure Procedures for Multiple Airport Route Separation

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***Abstract*—This paper documents portions of a study that examined current flight deck human factors issues associated with Performance-Based Navigation (PBN) departure procedures (DPs), with a focus on issues relevant to a proposed Air Traffic Control (ATC) operational concept called Multiple Airport Route Separation (MARS). MARS aims to improve the flow of air traffic to and from nearby busy airports by reducing the separation between aircraft flying along specially approved pairs of PBN instrument flight procedures (IFPs). As long as both aircraft stay on their cleared IFPs, ATC can be confident that they will remain procedurally separated. However, past research on PBN IFPs has shown that they may add complexity to pilot tasks, potentially increasing the risk of flightpath deviations.**

**We present three components of the study. First, we met with technical airline pilots to get their insights on current operational issues with DPs. Second, we screened over 100 records from the Aviation Safety Reporting System (ASRS) with departure-related issues to curate a set of 20 records for in-depth analysis. Finally, we met with nine professional airline pilots to understand issues that occur during PBN DPs that might lead to flightpath deviations. We also employed a novel test method with the line pilots to examine how pilots might assess the threat posed by other aircraft during simulated MARS departure scenarios. In these scenarios, aircraft might appear in closer proximity and in locations that pilots would not normally expect, even as they stay on assigned routes.**

**The results confirm that pilot tasks and strategies for flying PBN DPs depend upon the use of automated systems for lateral and vertical navigation. There are many ways that pilots may become vulnerable to flightpath deviations when interacting with automated systems. Departures are highly time-sensitive; poorly-timed interruptions and time pressure can create vulnerabilities. In terms of traffic-threat assessment during the simulated MARS departures task, our results indicated that pilots might seek additional information about a traffic aircraft and/or prepare to avoid a conflict. We discuss findings with respect to PBN departure operations in general and provide some specific insights for MARS operations.**

***Keywords*—*Performance Based Navigation, instrument flight procedures, PBN, IFP, RNAV, DP, MARS.***

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## I. Introduction

The Federal Aviation Administration (FAA) has a strategic goal to expand the use of Performance Based Navigation (PBN) instrument flight procedures (IFPs) to new routes and operational concepts [1]. PBN can improve the safety and efficiency of flight operations. However, past research indicates that PBN may add complexity to flight deck tasks [2, 3].

This paper focuses on a proposed Air Traffic Control (ATC) concept called Multiple Airport Route Separation (MARS). MARS will use PBN IFPs to improve the flow of traffic in busy terminal areas with multiple nearby airports. Because MARS is an ATC initiative, prior research focuses on the ATC perspective [4], and relatively little research has been done on its impacts on pilot tasks. Previous research on flight deck perspectives of MARS studied arrivals and approaches [5]; this study considers PBN departures procedures (DPs).

We conducted this study to address research gaps related to PBN DPs, with a focus on issues relevant to MARS. A full report describes the study in detail [6]. This paper presents an overview of three key components of the full study. First, we describe the MARS concept in the next section. Next, we review what we learned from existing literature about PBN DPs. Then we provide an overview of the current study. The rest of the paper describes our methods, findings, and takeaways.

### *A. Multiple Airport Route Separation*

MARS will use PBN IFPs to de-conflict terminal-area routes between nearby airports [7]. Currently, when conflicts exist between IFP routes at different airports, only one IFP can be flown at a time and operations at one airport take priority. With MARS, the routes are de-conflicted by allowing reduced lateral separation (below the 3 nautical miles [NM] usually used for radar separation in the terminal area) between specially approved segments of the IFPs. MARS does this by relying upon the greater lateral precision and repeatability of PBN IFPs. MARS scenarios may involve all types of terminal IFPs, including arrivals, approaches, and departures.

Fig 1. shows an example of two conflicting IFPs (left) and how they could be de-conflicted under MARS (right). In the example, one of the IFPs was redesigned for MARS so that it has a parallel segment to the other IFP. The lateral separation between the aircraft on the parallel segments may be less than 3 NM. MARS may utilize existing IFPs or require the development of new IFPs. MARS can be applied as long as the

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aircraft are “established on” the assigned IFPs. ATC will only interact with the aircraft at the airport they are working, but they may see the other airport’s traffic on their displays.

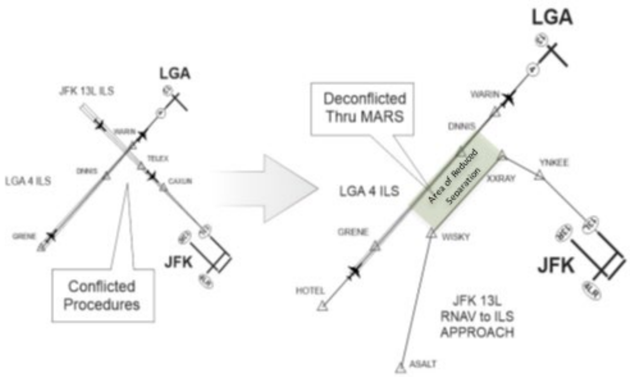


Fig. 1. Example notional MARS application (adapted from [7])

A key feature of MARS is that ATC will shift from providing radar separation to monitored procedural separation (MPS). With MPS, ATC will monitor aircraft adherence to the authorized IFPs and issue corrective instructions if the aircraft deviates from the cleared route [7]. It is important for aircraft to stay on their assigned IFP, both vertically and laterally, to assure that the aircraft are safely separated. However, previous research identified operational and human factors issues that can impact the flightcrew’s ability to stay on an IFP [2, 3]. We review related research in the next section. MARS may also put traffic in unexpected relative positions and/or in closer proximity than pilots would normally expect, which might increase the chance that pilots may choose to deviate from the assigned route to avoid the traffic.

### B. *Related Research*

Early research on PBN DPs found that lateral flightpath deviations were the most common operational issue on area navigation (RNAV) standard instrument departures (SIDs) [8]. These findings were based on an analysis of reports submitted to the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) between 2004 and 2009. Lateral deviations were most often associated with flight management system (FMS) programming and ATC route amendments. Often, FMS programming issues are precipitated by an ATC amendment.

The same study [8] found that vertical deviations were the most common operational issue on RNAV standard terminal arrival routes (STARs). At the time, RNAV STARs had more vertical constraints than RNAV SIDs. Flightpath constraints are a source of extra mental and physical workload for pilots [2]. Each constraint requires the pilot to carefully monitor whether they will meet the constraint. “At or above” altitude constraints, specifically, may be difficult to meet on a departure procedure, especially on hot days and/or in heavy aircraft.

Chandra and Markunas [2] documented aspects of IFP and chart design—such as constraints—that increase the complexity of flying PBN IFPs. Highlights from the study were published in [9]. The authors also identified other sources of complexity that cannot be controlled by IFP or chart design. These “operational complexity” factors emerge as a result of daily variations in operations, such as weather and interactions with ATC. Consistent with the earlier ASRS analysis [8], [2] found that ATC amendments can be an issue for flightcrews, especially if the amendments are given at a late stage in the departure. This puts time pressure on the flightcrew as they reprogram the FMS, verify the entry, and review and re-brief the route.

While the PBN DP literature provides some idea of the factors that might lead to flightpath deviations during MARS departure operations, most of the studies were conducted prior to 2018. We did not know whether those issues are characteristic of today’s departure operations. Some issues may have been resolved and new ones may have emerged. Moreover, MARS may produce new issues because of the higher levels of traffic density in busy airspace with multiple nearby airports.

### C. *Overview*

We had two objectives. First, we sought to update our knowledge of flightcrew issues on PBN DPs, with a focus on issues that might occur during MARS operations or that MARS would need to handle. We were specifically interested in issues that might lead to flightpath deviations. Second, we sought to understand how pilots would perceive other aircraft during MARS departure operations, when aircraft may be in closer proximity and in locations that pilots may not normally expect.

There were two primary data-related activities. First, we identified and analyzed a curated set of 20 ASRS records that described events that occurred on an RNAV SID in the past five years. The purpose of the ASRS analysis was to identify factors in the records that led to flightpath deviations and other undesirable outcomes. Second, we met with nine line pilots to elucidate pilots’ decision making when flightpath deviations occur, and to obtain pilot perceptions of traffic during simulated MARS departure operations. For the traffic perception task, we developed a novel method for presenting traffic to pilots on static images of a flight deck navigation display (ND) with traffic overlay.

We prepared for the ASRS analysis and line pilot sessions by first talking with four technical pilots. Technical pilots are specially designated pilots with knowledge of safety data and issues across an airline’s operations. The discussions gave us a sense of what has changed regarding PBN DP design and operations, and helped us to refine our methods. We briefly review what we learned from the technical pilots before going into detail on the ASRS analysis and line pilot sessions.

## II. TECHNICAL PILOT INPUT

The technical pilots provided general insights into how departure operations have changed over the past 5-10 years. We had three main takeaways from these conversations. First, today’s PBN DPs have more precise vertical profiles than they did in 2010 when [8] was published. We confirmed this with unpublished data analyzed in support of this study by the MITRE Corporation working under the auspices of their Outcome 3 efforts supporting the FAA [10]. Based on 249 RNAV SIDs with altitude constraints in 2015, and 398 such SIDs in 2023, the percent of waypoints with altitude constraints increased from about 17% to 22% between 2015 and 2023, and the percent of waypoints with "at or above" constraints increased from about 12% to 17%.

The second takeaway was that pilot-knowledge requirements and pilot techniques have changed. Nowadays, airline pilots always use the FMS to fly PBN DPs. Some airline procedures now have pilots activate the lateral navigation (LNAV) earlier than before, and pilots now routinely use the vertical navigation (called VNAV on Boeing aircraft and Managed Climb on Airbus aircraft) for initial climb. Lateral and vertical navigation systems generally reduce pilot workload, but there are potential traps. For example, pilots may choose to intervene when using VNAV if the system lags or if it will not meet an altitude constraint. Pilots need a deeper understanding of the flightpath management automated systems to be able to recognize these traps and resolve potential flightpath errors.

The third takeaway was that ATC amendments still pose a risk for pilots, especially if there are multiple amendments in sequence, or if a single amendment has multiple components (e.g., a change to the DP, runway, and/or transition. The technical pilots mentioned changes to the DP on the ground, an issue that was not specifically mentioned in [2] or [8]. Lateral deviations are associated with changes to the departure route on the ground that are not properly loaded and verified in the FMS.

Aside from the technical pilot input, we are aware that there are different types of instrument DPs in use today. The most common, earliest designs are RNAV SIDS. More recently, "Open SIDs" have come into use. These are published departure IFPs that have both vector and PBN segments. Open SIDs require pilots to manage automated systems with care as they transition between navigation methods. SIDs that use Required Navigation Performance (RNP) are rare today, but more may be developed in the future.

## III. Aviation Safety Reporting System Analysis

We first curated and then analyzed a set of 20 ASRS records to understand current issues that lead to flightpath deviations and other undesirable outcomes on PBN DPs. The method, its limitations, and results are described briefly below. Our full report provides more details on this analysis [6].

### *A. Method*

We searched the public ASRS database for records that were submitted by Title 14 Code of Federal Regulations (CFR) Part 121 or Part 135 operators between January 2019 and January 2024. We obtained over 100 records using a variety of search terms and criteria. After a preliminary review, we selected 20 records that were illustrative of the different types of issues we saw in the larger set. The records described events that presumably occurred on an RNAV SID under 18,000 ft.

We coded the 20 records using a rubric modified from past studies [3, 5]. The rubric captured basic facts as well as our interpretation of threats and outcomes. Then we generated summaries of each record from the rubric. The summaries grouped the records based on whether there was an intentional deviation, unintentional deviation, both an intentional and unintentional deviation, or undesirable outcome other than a deviation. The summaries also identified initial threats, or "triggers", that led to the event. We provide a breakdown of the event outcomes and examples of intentional and unintentional deviations later. First, we will briefly discuss the limitations of ASRS data.

### *B. Limitations*

The limitations of ASRS records are well known. The events are self-reported, subjective, and written from memory. The narratives can be incomplete and difficult to interpret. They can also be biased because of difficulty in observing one's own behavior. The records may reference IFPs that are no longer in use, and for which charts are no longer available. There is also a delay in entering the data due to processing time, typically a few months, so they may not be an early indicator of issues.

We analyzed a small set of ASRS records, but they illustrate the issues from a much larger sample of screened records, with a variety of issues that pilots might experience on PBN DPs. The dataset is not a random sample of events so the frequency of events in the dataset may not represent the frequency of occurrence in actual operations.

### *C. Results*

Consistent with [8], lateral deviations were the most common outcome in the dataset (11 records), despite the increase in vertical constraints on RNAV SIDs. As already stated, these data cannot be used to infer the frequencies of various issues in the broader population. Other common outcomes included vertical deviations (4 records), ATC vectors required (4 records), and hand-flying required (4 records). (Note that an event could have more than one outcome.) Hand-flying was an outcome when it occurred after the trigger, but there were also five records where hand-flying was in progress before the event that triggered the outcome.

We categorized the 20 records in the dataset based on the intentionality of their outcomes (i.e., intentional versus unintentional deviations) and identified the threats, or "triggers", that initiated the events. Note that two records had both unintentional and intentional deviations; these records are counted twice, once in each category. Many records had more than one trigger.

Fourteen records in the set had unintentional deviations. The most common triggers for unintentional deviations were unintentional pilot actions related to flightpath management (11 records) and unintentional pilot response to an external threat (6 records). Pilot responses to external threats involved ATC amendments in 4 of the 6 records. Pilot actions related to flightpath management involved task management in 6 of the 11 records and/or interactions with the automated systems in 4 of the 11 records. Table 1 describes a few example events to illustrate pilot issues with task management and automated systems. Note that these were not the only triggers for each of the events.

There were five records in the dataset with intentional deviations. These events were triggered by external threats including wake turbulence, an aircraft system malfunction, and traffic. In all five cases, pilots made the decision to deviate in response to the external threat.

Three records had an undesirable outcome other than a flightpath deviation. In one event, the outcomes were high workload and the need to hand-fly. In the other two events, the outcome was extra radio communications.

TABLE 1. EXAMPLE UNINTENTIONAL DEVIATIONS DUE TO TASK MANAGEMENT AND INTERACTIONS WITH AUTOMATED SYSTEMS

| Trigger | Event Description (ASRS Accession Number) |
|---|---|
| Task Management | Crew was task-saturated while hand-flying a light aircraft with the flight director; a vertical deviation resulted (1781176). |
| | Received a change to the SID at pushback. Crew unintentionally did not verify programmed route due to numerous tasks and rushed preparation, resulting in a lateral deviation (1665677). |
| | Lateral deviation resulted when ATC amended the SID altitude and gave the crew a shortcut (direct to a later waypoint). The crew was unable to complete the necessary reprogramming in time and the aircraft turned late (1783812). |
| Interactions with Automated Systems | Pilot mistakenly entered incorrect top altitude, resulting in failure to comply with a Climb Via clearance and a vertical deviation (1654249). |
| | Crew unintentionally failed to verify their route in the FMS after using auto-upload and did not notice the problem until in flight, resulting in a lateral deviation. (1877481). |

## IV. LINE PILOT DISCUSSIONS

We met with nine line pilots to understand (a) pilot perceptions of traffic during MARS departure scenarios and (b) what factors might lead to deviations on departures. The meetings were conducted individually over a virtual platform and lasted about one hour. We used a slide deck to present visual stimuli and discussion prompts.

The meetings were divided into two parts. First, we asked pilots to assess the traffic threat in two hypothetical departure scenarios shown on static images of a simulated Boeing 737 ND with a traffic overlay. Both scenarios were based on notional MARS departure applications from the New York area. (We purposely did not explain MARS to participants because pilot training for the operation is yet to be determined and may be relatively minimal.) Second, we asked pilots to describe scenarios in which they would need to deviate from their planned departure route, both intentionally and unintentionally. We recorded meeting transcripts and took notes.

We describe the participants next. Then we provide detail on the method, followed by a discussion of the limitations and the results.

### *A. Participants*

Nine line pilots from four major airlines (Title 14 CFR Part 121 operators) participated in the study. They were volunteers and were not compensated for their participation. We identified the volunteers with the help of our technical pilot contacts.

The nine participants included two first officers, four captains, and three check airmen. Their total flight hours ranged from 5,000 to 22,000 (median = 12,000). All of the participants were highly familiar with RNAV SIDs. They were all familiar with New York airspace. Eight currently flew Airbus aircraft and one flew Boeing aircraft. Eight had some familiarity with Boeing NDs, but only half of the participants considered their familiarity to be "high". All the participants were used to seeing traffic on their NDs.

### *B. Method*

*1) Traffic assessment task.* Participants talked through their perceptions of two simulated departure scenarios. Each scenario was depicted through four static images of a simulated Boeing ND. The images depicted the participant's aircraft (ownship) as the participant flew an RNAV SID, which is depicted by the magenta line. In this paper, we review only one of the two scenarios. The full report describes both scenarios [6].

Each image depicted ownship at a different location along the route. The ND had a Traffic Alert and Collision Avoidance System (TCAS) traffic overlay and traffic was present in seven of the eight images. We showed pilots an example display, shown in Fig. 2, so that they could familiarize themselves with the display and its settings. (The example display does not show any traffic.)


Fig. 2. Sample ND image shown to pilots for familiarization.

We developed the traffic scenarios with the help of subject matter experts (SMEs) who are researching and developing MARS. For one scenario, we used unusual but realistic climb rates and gradients to place the ownship aircraft and the traffic aircraft within both 3 NM and 1000 ft of each other in three of the four images. According to the SMEs, 1000 ft vertical separation is normally required between airports. The other scenario was simpler; traffic never appeared within 3 NM and 1000 ft of ownship in the same image.

Participants saw each image one at a time. For each one, they talked through their interpretation of the situation. Specifically, we asked them to describe how they would assess the threat posed by the traffic aircraft and what actions they might take if they were flying the DP in actual operations. We occasionally asked follow-up questions.

*2) Deviations*. For this task, participants described two scenarios where they might deviate from their planned departure route, one in which the deviation was intentional and one in which the deviation was unintentional. The scenarios could be real (i.e., from the pilots' own experience) or hypothetical. Participants described several factors that might lead to each deviation type. We occasionally asked follow-up questions to elicit more detail.

### C. Limitations

Before we discuss the findings from the line pilot discussions, it is important to point out several limitations. First, we only talked to nine participants, which is too few to conduct any statistical comparisons. With more participants, we could have given half of the participants a brief explanation of MARS and compared their traffic perceptions to those who did not receive information about MARS, to explore the potential effects of training. The participants were also not representative of the overall pilot population; they were from Title 14 CFR Part 121 operators and were highly experienced. Most of them were highly familiar with the New York airspace where the traffic scenarios were based. Participants from regional airlines and corporate operations, who also fly in busy airspaces, were not represented in our sample.

Most of the participants flew Airbus aircraft, whose ND does not match the ND we used for the traffic assessment task. We showed standard TCAS symbology. However, traffic displays based on Automatic Dependent Surveillance-Broadcast (ADS-B) could provide more data about the target than TCAS (e.g., its trajectory). We used static images to depict the scenarios, but a dynamic view (e.g., video or live simulation) would give the pilots more information about the movement of the traffic aircraft and might produce different results. We also told the participants to examine the threat posed by the traffic. We do not know whether participants would have noticed the traffic otherwise.

Finally, we only tested two MARS scenarios. Each presented unique issues. Additional scenarios should be evaluated.

### D. Results

We used the researchers' notes as the primary data source and referred to the meeting transcripts as needed. We present the results below. First we discuss participant perceptions of the traffic threat. Then we review information about their strategies for flying DPs; this was additional feedback that participants provided as they talked through the traffic scenarios. Finally, we summarize participants' comments about flightpath deviations.

*1) Perceived traffic threat*. Figs. 3, 4, 5, and 6 show the four images for the more extreme scenario. The participant's aircraft departs the John F. Kennedy airport (JFK) from runway 31L on the SKORR RNAV SID with a high rate of climb. The traffic aircraft departs from LaGuardia airport (LGA) on runway 13 flying the GLMDN 8 RNAV SID with a low rate of climb.

Ownship is represented by the white triangle in each figure. The traffic is represented by the cyan diamond. The diamond is unfilled, as in Fig. 3, if the traffic is non-proximate (i.e., greater than 6 NM and ±1200 ft from ownship) [11]. A filled diamond, as shown in Fig. 4, indicates a proximate target within 6 NM and ±1200 ft of ownship. The number next to the traffic indicates the relative altitude of the traffic aircraft in hundreds of feet (e.g., "25" above the diamond represents 2500 ft above ownship in Fig. 3). An upward or downward arrow (↑ or ↓) indicates that traffic is climbing or descending at a rate greater than 500 feet per minute. The traffic is climbing in both Fig. 3 and Fig. 4.

The captions for Figs. 3-6 indicate our participants' responses to traffic. We categorized the level of perceived traffic threat based on what they said they would do or think if they saw the traffic on their ND in actual operations. The levels were as follows:

1. No threat perceived
2. Aware of/paying attention to traffic
3. Gathering information about the traffic (e.g., looking for the traffic out the window; asking about the aircraft type; asking ATC about the traffic; or expecting a TCAS Traffic Advisory, or TA)
4. Planning for action (e.g., preparing for a TCAS TA or Resolution Advisory, or RA; considering asking ATC about the traffic, or possibly making an early turn)

The perceived threat level increased as the traffic got closer to ownship. Participants perceived the greatest threat when the traffic aircraft was in the 12 o'clock position in the more extreme scenario. At this point (see Fig. 5), six of the nine participants were planning for action (perceived-threat level 4). Participants said they wanted to know which way the traffic was moving, its intentions, and whether it was the same aircraft in each image. In actual operations, pilots might gather this information from other available cues (e.g., from ATC or by looking out of the window). Pilots also said that their assessment of the traffic would depend on what type of aircraft it was; helicopter traffic, which is common in the New York area, would be less threatening than another jet. The low climb rate of the aircraft departing LGA in our scenario led some pilots to ask if it was a helicopter.

*2) Pilot techniques for flying departures:* During the traffic assessment task, participants talked through their tasks and strategies for flying DPs. Several mentioned that they would set the TCAS traffic display to show traffic in the "above" mode on departure to give them a better awareness of traffic. "Above" mode shows traffic within 9900 ft above and 2700 ft below ownship, whereas the "normal" mode shows traffic within 2700 ft above and below ownship.

Participants also set their TCAS to provide both TAs and RAs on departure. They told us that RAs are rare on departure but do happen. TAs are more common. Several pilots said that they would consider taking an action in response to a TA if they could not get information about the traffic from other sources, such as ATC. This scenario may be more common in regions with dense traffic and congested radio frequencies, where MARS is more likely to be of use.

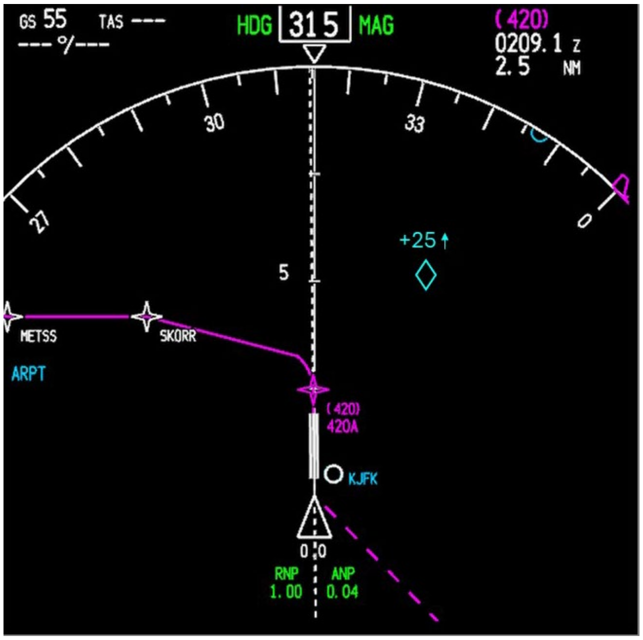


Fig. 3. Image 1 – Five pilots perceived no traffic threat, four were aware of and paying attention to traffic.


Fig. 4. Image 2 – Four pilots were aware of and paying attention to traffic, five were seeking information.


Fig. 5. Image 3 – One pilot was aware of and paying attention to traffic, two pilots were seeking information, six pilots were planning for action.

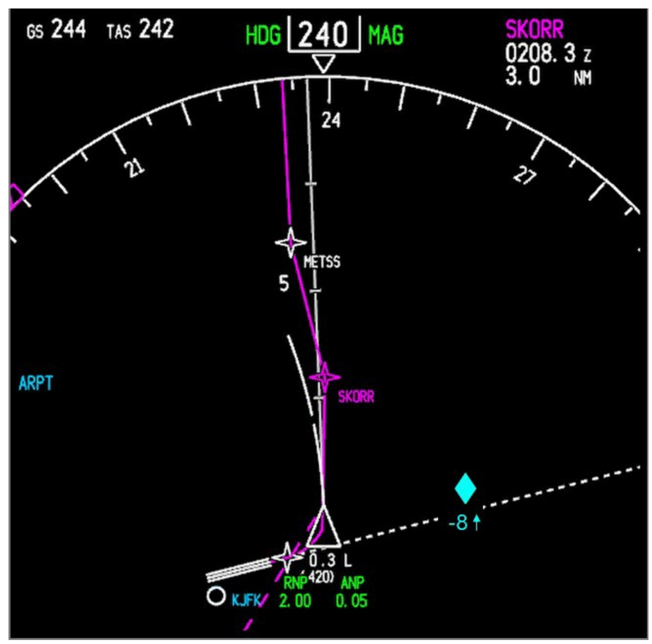


Fig. 6. Image 4 – Two pilots perceived no threat, five pilots were aware of and paying attention to traffic, two pilots were seeking information about traffic.

Finally, participants said that they prefer to hand-fly DPs, but would engage the autopilot if there was a need to reduce workload. Workload might be higher if they were unfamiliar with the DP, in solid instrument meteorological conditions (IMC), or in busy airspace with a lot of traffic. Pilots are required to turn the autopilot off if they get a TCAS RA. With MARS, pilots will be allowed to hand-fly as long as the flight director is used. However, hand-flying with the flight director might not always produce the same flightpath as the automated systems would. For example, one participant, a check airman, mentioned that when learning to fly a new aircraft type, pilots may make wider turns than an autopilot would.

*3) Flightpath deviations on departure:* The line-pilot participants described several factors that might lead to unintentional deviations and a select few that might lead to intentional deviations.

The examples of unintentional deviations involved situations where pilots might be vulnerable to making mistakes when interacting with flight deck automated systems. Participants mentioned the possibility of making FMS programming errors after ATC amends the clearance. Changes on the ground can be particularly challenging due to time pressure. Participants also described how route amendments received while in flight can lead to FMS programming errors. For example, pilots might make mistakes when entering a new waypoint into the FMS after ATC gives a “direct to” clearance. If the flightcrew is task saturated, they might select “go direct” without confirming that the new waypoint is correctly entered in the FMS. They are also vulnerable to entering the wrong waypoint when there are waypoints with similar-sounding names. Another case where an unintentional deviation might occur is if the flightcrew selects the incorrect automation mode at takeoff. For example, flightcrews might select HDG (heading) mode instead of LNAV, or FLCH (flight level change, as it is called in Boeing aircraft) or Open Climb (in Airbus) mode instead of VNAV or Managed Climb.

Participants provided fewer examples of intended deviations, and several examples were mentioned by more than one participant. Examples of unintended deviations were commonly associated with an outside disturbance, such as weather, traffic, or equipment problems. Pilots may decide to deviate to avoid severe weather such as thunderstorms, heavy precipitation, microbursts, or wind shear. Flight deck displays may show small pop-up storms that are not visible on ATC displays. Pilots may also deviate to avoid wake turbulence, either by adjusting their vertical rate or making an early turn. If the flightcrew receives a TCAS RA, they are required to hand-fly the aircraft and follow the RA vertical command. Deviations may also be necessary in response to an aircraft equipment malfunction or non-normal procedure. For example, a caution message might require the flightcrew to return to the airport. If there is an engine failure, pilots must fly their company’s engine-out procedure, which typically requires the flightcrew to fly straight on runway heading initially. Other, less common, issues such as a bird or wildlife strike that affect aircraft controllability could also lead to the decision to deviate.

## V. Discussion

This study provides insights about flightcrew perspectives related to PBN DPs and MARS. The study specifically addressed two research gaps:

1. PBN DPs have become more complex in the vertical domain over the past 10 years, but little was known about the impacts of these changes on flightcrew tasks. This study updated our knowledge of flightcrew issues on PBN DPs that can lead to flightpath deviations and other undesirable outcomes.
2. Relatively little is known about potential pilot perspectives on MARS departure operations. This study takes a step forward in understanding what pilots might see, think, and do when MARS is active. Specifically, this study provides insights into pilot perceptions of traffic during MARS departure scenarios, when traffic may be closer and in unexpected locations.

Below, we discuss our findings and contributions to each of these topics in more detail.

### *A. Current Operational Issues on Departures*

Pilot tasks and strategies for PBN DPs have changed as the use of aircraft automated systems for PBN DPs has increased. There is a greater need for pilots to understand the automated systems to recognize potential traps and avoid errors. Both the ASRS and line pilot data indicated that unintentional flightpath deviations are often associated with interactions with the automated systems and task management issues. Line pilots described numerous ways that pilots could be task saturated and make a mistake when entering or verifying DP routes in the FMS. The participants provided multiple examples, and we expect to find even more examples if we talked to more pilots.

Flightpath deviations do occur. This is not a new insight. The types of deviations we found were consistent with the earlier literature [2, 8]. It is not possible to guarantee there will be no errors associated with unintentional deviations, and some of the external factors that lead to intentional deviations (e.g., weather) cannot be controlled. Even those that can be controlled, such as ATC amendments, may be necessary to optimize the safety and efficiency of operations. We know from our earlier work that controllers prefer to have the flexibility to change routes, especially at busy airports [5].

Timing is very important for flight deck departure tasks. Pilots are highly sensitive to the timing of disruptions. We saw this in the ASRS data, where pilots made unintentional deviations when they were task saturated and/or rushed. On departure, pilots have a lot to do in a very short time period, and they must complete those tasks in the right sequence and at exactly the right time.

Pilots may decide to hand-fly the aircraft on departure. We found instances of hand-flying in the ASRS reports; in some cases, pilots were hand-flying when the triggering event occurred and in others, hand-flying was an outcome of the event. Several line pilots said that they prefer to hand-fly the aircraft on departure. Sometimes, hand-flying can be more efficient (e.g., make a tighter turn) than the automated system. However, less experienced pilots who are hand-flying might make wider turns than they would with the automated system. MARS allows hand-flying with the flight director.

### B. *Flightcrew Perspectives on Traffic in Multiple Airport Route Separation Departure Operations*

We developed a novel method to ascertain how pilots might perceive traffic that is paired with their aircraft during MARS departure operations. We presented MARS DP scenarios to participants on simulated images of an ND with traffic. The method worked well; participants understood the task and we gathered data that contributed to our understanding of MARS. The method is relatively easy to develop, implement, and scale, making it a good option for future research.

Developing the traffic scenarios was particularly informative. First, we learned that MARS applications may only put aircraft within reduced lateral separation for a short period of time. It is possible that pilots may not notice the traffic or that the perceived threat goes away before the pilot acts. Second, we learned that MARS applications will almost always be separated by at least 3 NM or 1000 ft (i.e., the aircraft are unlikely to be in reduced lateral *and* vertical separation at any given point). We manipulated the climb rates and gradients in one of the scenarios to put the traffic and ownship aircraft within the region of reduced lateral and vertical separation. This was actually hard to do. In fact, we found that it was not possible to produce the same situation with our second scenario due to the altitude constraints on the IFPs. Despite this, it is still possible for aircraft to adhere to their published IFPs during MARS operations and enter the region of reduced lateral and vertical separation. This study examined this uncommon but plausible case.

The main takeaway from the traffic assessment task was that pilots might prepare for action or seek additional information about traffic during MARS operations. This might increase pilot workload during an already busy time. Interestingly, the study's participants were highly experienced and accustomed to operations at busy airports. Pilots with less experience might be less comfortable with the traffic and respond differently. Several pilots said they would ask ATC about the traffic, which may also add to the controller's workload.

## VI. Insights for Multiple Airport Route Separation

Results of this study provide insights for stakeholders involved in the development of MARS, outlined below.

### A. *Planning for MARS*

MARS designers may need to develop ATC procedures to manage situations that might disrupt MARS operations. MARS operations will need a way to be turned on and off quickly. This may be important, for example, if an aircraft experiences a malfunction that requires it to return to the airport from which it just departed. Aircraft malfunctions can require pilots to conduct non-normal flight deck procedures, which may require alternate flightpaths (e.g., flying a single-engine procedure). MARS may also need procedures for handling unintended flightpath deviations. There are many causes for unintended deviations. ATC may not be able to predict when these types of deviations might occur.

IFP designs that are difficult to fly in operations could have an increased risk of deviations. While this is not a new finding (e.g., see [5]), it is important to reiterate that new or revised IFP designs, for MARS or otherwise, should minimize factors that have been found to increase the complexity of pilot tasks. Reference [2] details these factors in a full report and [9] summarizes them in a conference paper.

### B. *MARS Operations*

MARS designers and users (e.g., ATC) should be aware that ATC amendments may increase the risk of flightpath deviations. Deviations would interfere with MARS operations and could pose a risk if they occur under reduced separation.

Operationally, hand-flying with the flight director may not produce the exact same flightpath as an autopilot. While pilots will be allowed to hand-fly with the flight director during MARS operations, it may produce slightly different flightpaths depending on pilot technique. If those differences are noticeable to ATC, they could affect MARS operations.

ATC should be prepared for pilots to ask them about the traffic during MARS operations. While ATC will know that MARS operations are in use, they will not be in communication with traffic at other airports and may not know the traffic aircraft's intentions. Designers should consider what, if anything, pilots should know about MARS.

Pilots may perceive MARS traffic differently with flight deck traffic displays based on ADS-B. Traffic displays that show ADS-B data might be more widely used by the time MARS is implemented. Pilots may use these data in lieu of contacting ATC for more information about the traffic.

## VII. Plans

While there are no immediate plans to gather additional data, this study is a first step in identifying considerations for MARS departure operations. Additional research could expand on our novel method for the traffic assessment task. We suggest many ways to improve the traffic-threat assessment method to gather more robust data to address our research questions. These include, for example, testing more pilots with more diverse experience, providing more dynamic traffic information and high-fidelity simulations, and examining whether training pilots about MARS affects their perceptions of traffic.

The full study is documented in [6]. Our methodology and findings will be of use to MARS researchers and PBN IFP designers. MARS is being studied and implemented in phases. The FAA is currently working to understand MARS operations involving arrivals and approaches from the ATC perspective. Our study may help to inform how MARS might incorporate departure operations.

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The views expressed herein are those of the authors and do not necessarily reflect the views of the Volpe National Transportation Systems Center, the FAA, or the United States Department of Transportation.

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