Flight Deck Perspectives on Performance-Based Navigation (PBN) Departure Procedures

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14. ABSTRACT
This project examines flight deck human factors considerations for Performance Based Navigation (PBN) departure procedures (DPs), focusing on issues relevant to the Multiple Airport Route Separation (MARS) concept. MARS will expand the use of PBN routes in the terminal area to improve the flow of traffic in busy areas with multiple airports. We collected data from three sources to address research gaps identified from an earlier literature review. We learned about current issues with DPs from interviews with technical pilots and an analysis of 20 records curated from the Aviation Safety Reporting System (ASRS) database. We gathered data about factors that contribute to flightpath deviations on DPs from the ASRS records and from discussions with nine line pilots. We also gathered data on assessment of traffic threat by showing the line pilots simulated traffic overlaid on static navigation display images. Results indicate that there are many explanations for why pilots might deviate from a planned PBN departure route, some intentional and some unintentional. Our limited data on traffic-threat assessment indicate that there are conditions under which pilots may seek more information, or even prepare to take an action to avoid traffic by modifying their flightpath if traffic is in an unexpectedly close relative position.

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Instrument Flight Procedures; IFP; Multiple Airport Route Separation; MARS; TCAS; pilot deviations, ASRS

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APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

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Abbreviations

Acronym	Definition
ABQ	Albuquerque International Sunport Airport, New Mexico
AC	Advisory Circular
ACN	Accession number
ADS-B	Automatic Dependent Surveillance - Broadcast
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATL	Hartfield-Jackson Atlanta International Airport, Georgia
CAST	Commercial Aviation Safety Team
CA	Captain
CFR	Code of Federal Regulations
CLE	Cleveland-Hopkins International Airport, Ohio
CLT	Charlotte/Douglas International Airport, North Carolina
CRM	Crew Resource Management
DCA	Ronald Reagan Washington National Airport, Washington, District of Columbia
DFW	Dallas-Fort Worth International Airport, Texas
DME	Distance Measuring Equipment
DP	Departure procedure
EFB	Electronic Flight Bag
EoR	Established on RNP
FAA	Federal Aviation Administration
FMS	Flight Management System
FO	First Officer
FPM	Flightpath Management
GA	General Aviation
GPS	Global Positioning System
HDG	Heading mode
IFP	Instrument Flight Procedure
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JFK	John F. Kennedy International Airport, New York
LGA	LaGuardia Airport, New York
KTS	Knots
LAS	Harry Reid International Airport, Nevada
LAX	Los Angeles International Airport, California
MARS	Multiple Airport Route Separation

Acronym	Definition
MIA	Miami International Airport, Florida
MVA	Minimum vectoring altitude
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
ND	Navigation display
NM	Nautical Mile
ODP	Obstacle Departure Procedure
PBN	Performance Based Navigation
PDC	Pre-departure clearance
PF	Pilot Flying
PM	Pilot monitoring
RA	Resolution Advisory
RNAV	Area Navigation
RNP	Required Navigation Performance
RWY	Runway
SE	Safety enhancement
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
TRACON	Terminal Radar Approach Control
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VNAV	Vertical Navigation
VNY	Van Nuys Airport, California

Preface

This document was prepared for the FAA Human Factors Division (ANG-C1), the Aviation Safety (AVS) organization, and the Flight Technologies and Procedures Division (Flight Operations Group, AFS-410 Section B). The FAA's Technology Development and Prototyping Division (ANG-C5) and the Training and Simulation Branch (AFS-280) are stakeholders for the research described in this document.

This project is titled "Flight Deck Impacts of NextGen Operations Enabled by Performance Based Navigation (PBN) Terminal Instrument Flight Procedures." It was funded with Fiscal Year 2021 and 2022 Research, Engineering, and Development funds. This project was conducted under Interagency Agreements FG09C122, FG09C223, and FG09C323.

We thank the FAA program manager, Victor Quach, PhD (ANG-C1) and the technical sponsors, Kathy Abbott, PhD (AVS) and Jeffrey Kerr (AFS-410) for their assistance and feedback. Thank you also to project stakeholders Vartan Tenkerian (ANG-C5), Theodore Goodlin (ANG-C5 contract support), Joshua Jackson (AFS-280), and Lori Tomasson (AFS-280). Thank you to Eddie Austrian and Kevin Siragusa (ANG-C1 contract support) for their project support. We also thank Cody Nichols of the FAA's Flight Research & Analysis Branch (AFS-430) for his ongoing collaboration and input. Thank you to the MITRE Corporation for their assistance in analyzing departure procedure characteristics. Finally, thank you to Volpe team members Michael Zuschlag, PhD, for leading part of the literature review, and Patrick Elwood, for helping to develop the scenario images for the line pilot discussions.

Executive Summary

The Federal Aviation Administration (FAA) is studying a proposed Air Traffic Control (ATC) concept called Multiple Airport Route Separation (MARS). This concept will expand the use of Performance Based Navigation (PBN) in the terminal area to improve the flow of traffic in busy areas with multiple airports. Because MARS is primarily intended as an ATC operation, prior research focuses on the ATC perspective (e.g., Nichols et al., 2024) 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 (Chandra & Sparko, 2022); this study considers departures procedures (DPs). Highlights from the study will be published in Sparko and Chandra (in press).

We gathered data to address four research gaps identified from an earlier literature review. We sought to (a) update our knowledge of current operational issues with area navigation (RNAV) departures, (b) learn what factors contribute to pilot flightpath deviations on departures, (c) gather more pilot input on potential flightcrew issues related to MARS, and (d) gather flightcrew perceptions of other air traffic (e.g., whether it might be perceived as a threat) during a MARS operation. We addressed these research gaps with three data sources: interviews with technical pilots, a review of records from the public Aviation Safety Reporting System (ASRS) database, and discussions with nine line pilots.

We learned that DPs have more vertical flightpath constraints now than they did in 2015. Vertical constraints can be challenging for pilots. Another, still present, challenge is that ATC route amendments to departure clearances create pilot workload and introduce risks of errors because the pilots must reprogram and re-verify the route. As a result, pilots need a better understanding of aircraft automated systems to manage the aircraft's vertical flightpath without precipitating unexpected system behaviors.

We assessed flightpath deviations during departures with two sources of qualitative data, ASRS records and input from nine line pilots. Both data sources elucidated similar issues. Intentional deviations tend to be made in response to a small set of external events such as weather, traffic, and/or equipment malfunctions. Unintentional deviations, on the other hand, were often unexpected and could arise from a variety of circumstances. We highlight task management and ATC clearance amendments as two of the triggers that can lead to unintentional flightpath deviations.

We used a novel method to understand pilot assessment of traffic threat. We showed pilots static navigation display images with traffic overlays to assess how they might perceive traffic in a MARS operation. The images simulated the departure route of participant's aircraft as it flew an RNAV standard instrument departure (SID) with traffic nearby. Using some unusual but realistic climb gradients for the two aircraft, we constructed one scenario where traffic appeared in a location where six of the nine pilots were concerned enough to consider planning to take action (e.g., turning early). Such a scenario would be uncommon in normal operations, but it could cause some unwanted pilot behaviors. The method we used, while informative, has much room for improvement. Further research with a more diverse set of pilots, for example, could improve our understanding of how pilots might handle MARS scenarios involving PBN DPs. We conclude the paper with a general discussion, including some insights for MARS flight operations.

1. 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 (FAA, 2016). This study considered a proposed air traffic operational concept called Multiple Airport Route Separation (MARS). MARS will use PBN IFPs to improve the flow of traffic in busy areas with multiple airports. It may be applied to aircraft flying all types of IFPs in the terminal area, including approaches, arrivals, and departures. MARS may utilize existing IFPs or it may require the development of new IFPs.

As the use of PBN expands, research is needed to understand its evolving impacts on flight deck tasks. Previous research by the Volpe Center focused on flight deck human factors issues associated with PBN arrival and approach IFPs. This project examines issues associated with PBN departure procedures (DPs), with a focus on issues of relevance to MARS. Our goal is to provide research data and analyses to inform FAA personnel who update regulatory and guidance material related to PBN operations such as MARS. The study also complements previous research on MARS, which focused on the air traffic control (ATC) perspective (e.g., Nichols et al., 2024).

Figure 1 illustrates how MARS might work with two diagrams. The left side of Figure 1 shows a current conflict between two instrument landing system (ILS) approach procedures at different airports in the New York airspace. One approach procedure is for LaGuardia Airport (LGA) and the other is for John F. Kennedy International Airport (JFK); the two airports are separated by just 9 Nautical Miles (NM). Air Traffic operations can only allow one approach or the other to be flown at a time; operations at one of the airports take priority.

The right side of Figure 1 shows how MARS would resolve the conflicting approach paths between JFK and LGA. Here, approaches to both airports are deconflicted and can be flown simultaneously and independently (i.e., without coordinating the timing and position of the aircraft on each approach). In the deconflicted MARS application, a new RNAV path to the ILS approach path has been created for JFK. The new approach path has a segment that is parallel to the LGA approach. The lateral separation between the two aircraft could be less than the standard separation during that segment of the approach paths (i.e., it may be less than the 3 NM normally used for radar separation while the aircraft are on the parallel segments). MARS could be applied as long as the aircraft are "established on" the assigned IFPs.[1]

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 an aircraft deviates from its cleared route (FAA, 2020). Controllers will only be in communication with the aircraft going to/from the airport they are controlling, but they may see the traffic for nearby airports on their displays, so they would be aware of the traffic's intended route.

[1] The Pilot-Controller Glossary defines "established" as "to be stable or fixed at an altitude or on a course, route, route segment, heading, instrument approach or departure procedure, etc." (FAA, 2024a, p. E-2). The MARS program has yet to define "established on" for MARS operations.

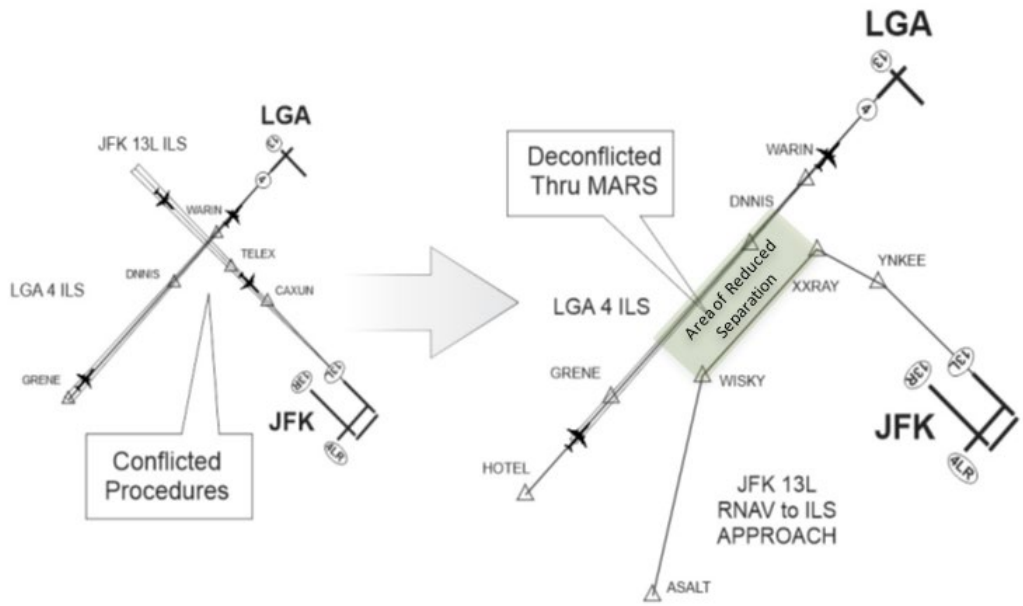

Figure 1. Example notional MARS application. (Adapted from FAA, 2020.)

It is important for both aircraft involved in a MARS operation to stay on their assigned flightpaths, vertically and laterally, to assure that they are safely separated. However, previous research has identified operational and human factors that can impact the flightcrew's ability to stay on an IFP (Chandra & Markunas, 2017; Chandra et al., 2020). 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.

The increased use of PBN IFPs is another key component of MARS[2] because PBN allows aircraft to fly more precise and predictable routes. PBN IFPs specify the lateral accuracy required to fly the IFP. PBN IFPs are flown with area navigation (RNAV) or required navigation performance (RNP). RNAV allows aircraft to fly any lateral flightpath that is defined by ground- or satellite-based navigation aids. RNP is RNAV with onboard equipment that monitors aircraft performance and provides alerts to the flightcrew if the aircraft is not meeting performance criteria. Existing PBN DPs rely on the use of RNAV. This project was primarily focused on RNAV standard instrument departures (SIDs).[3]

[2] Note that MARS requires the Global Positioning System (GPS), so it can only utilize a subset of available PBN IFPs. MARS may also use conventional IFPs, such as ILS approaches.

[3] There are two main types of instrument DPs: SIDs and obstacle departure procedures (ODPs). ODPs are not of interest to this study because they do not require an ATC clearance. There are multiple types of SIDs, including PBN SIDs (which use RNAV and/or RNP segments), conventional SIDs (which use ground-based navigation aids), vector SIDs, and Open SIDs (which have both vector and RNAV segments). For this report, we use the term "departure procedure" (DP) to refer to departure routes in general.

2. Project Overview

We conducted this work in two phases, with each phase lasting approximately one year. First, we identified research gaps based on the literature and developed a research plan to address these gaps. Section 2.1 summarizes the literature review and research gaps identified in our first research phase. The output of this first phase was a research plan, which is summarized in Section 2.2. We executed the research plan in the second phase of research. This report is the output for the research that was executed under the research plan. Highlights from the study will be published in Sparko and Chandra (in press).

2.1 Literature Review and Research Gaps

The literature review focused on flight deck perspectives related to four overlapping types of PBN IFP operations. Figure 2 depicts the operation types and how they overlap. The size of the circles represents the relative scale of each operation in the National Airspace System (NAS). The most widespread operation is the use of RNAV DPs. The next is reduced-separation operations involving PBN IFPs; this includes operations involving all types of PBN IFPs (DPs, arrivals, approaches, and missed approaches). MARS operations are a subset of reduced-separation operations involving PBN IFPs. MARS DPs are a small portion of operations where RNAV DPs, reduced-separation operations, and MARS overlap.

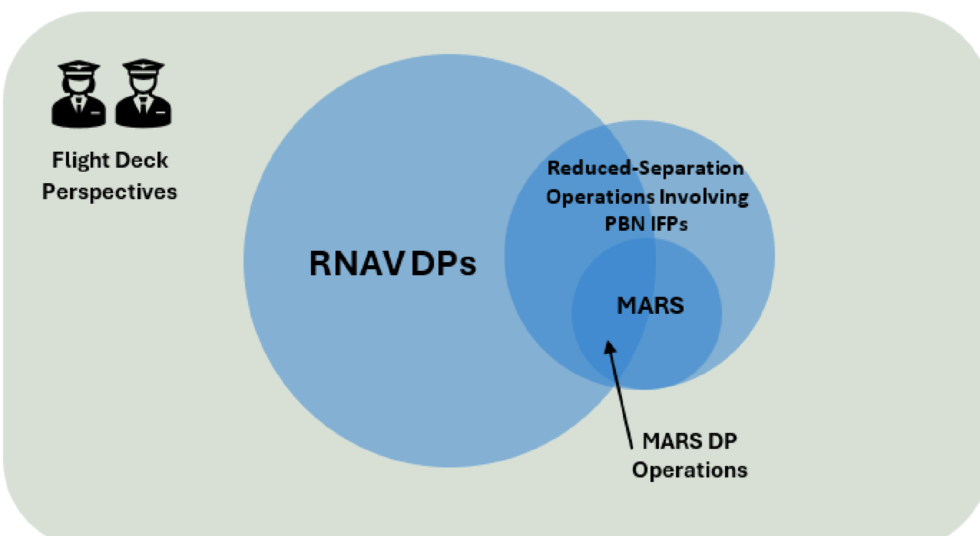

Figure 2. Blend of PBN IFP operation types covered in literature review.

2.1.1 Literature Review Highlights

This section presents an overview of research on the types of IFPs of interest to this project. The findings from the literature review informed the research gaps. Section 2.1.1.1 presents prior research on RNAV DPs and Section 2.1.1.2 discusses reduced-separation concepts involving PBN IFPs.

2.1.1.1 ***Research on RNAV DPs***

Individual DPs have been studied from a variety of perspectives. Some evaluations are done by subject-matter-experts from FAA and industry for individual IFPs. There have also been operational implementation studies by analysis and action teams (e.g., FAA, 2006). Results of these studies may produce changes to the IFP design, or other industry recommendations. For example, the Commercial Aviation Safety Team (CAST) recommended three safety enhancements (SEs) related to DPs (SE212, SE213, and SE214), which are available online.[4] However, the expert reviews and specific analyses that support committee work are generally not published in the open literature.

In the open literature, research studies have examined RNAV arrivals, departures, and even approaches. Different types of IFPs are typically covered in the same study, but this review focuses on departure procedures only. Some studies break down their findings by the type of IFPs (e.g., Smith, 2008; Butchibabu et al., 2010; Chandra et al., 2012; Chandra & Markunas, 2017; Chandra, 2019), but others do not (e.g., Berry, Sawyer, & Austrian, 2012; Berry & Sawyer, 2013; Kasim, 2017).

Butchibabu et al. found substantive differences between arrivals and departures in terms of operational errors. Specifically, Butchibabu et al. (2010) found that lateral flightpath deviations were the most common operational issue for RNAV SIDs in reports submitted to the National Aeronautics and Space Administration (NASA)'s Aviation Safety Reporting System (ASRS) between 2004 and 2009. They also found that vertical deviations were the most common issue on arrivals, which tend to have more vertical constraints (Chandra et al., 2012). Because of these different error patterns between arrivals and departures, it is not possible to clearly interpret results pertaining to DPs when a study does not analyze DPs separately.

Chandra and Markunas (2017) conducted pilot interviews for a broad study about challenges with PBN IFPs. One of their key findings was that operational complexity, which arises from daily variations, is a normal part of flying any IFP, including DPs. ATC route amendments are one source of operational complexity; they are daily variations that can create work for pilots (Chandra & Markunas, 2017; Chandra et al., 2020). Pilots must review, program, and verify each amendment in the flight management system (FMS). In particular, every constraint on an IFP requires verification, so IFPs with more constraints require more verification steps.

Chandra et al. (2012) was an objective analysis of IFP complexity that examined the number and types of altitude constraints on RNAV IFPs. They found that arrivals had more vertical constraints than DPs; this may be related to the finding that vertical deviations were more common on arrivals (Butchibabu et al., 2010). One proposal to help pilots with understanding and verifying the constraints was to depict the vertical flightpath in more detail on aeronautical charts, which pilots use when they are validating the FMS entries. Unfortunately, Chandra (2019) found that alternative depictions of the vertical flightpath would be difficult to construct and may not be as useful in real flight operations as hoped.

[4] See SE212: Area Navigation (RNAV) – Equipment and Procedures to Improve Route Entry for RNAV Departures | SKYbrary Aviation Safety, SE213: Area Navigation (RNAV) – Safe Operating and Design Practices for STARs and RNAV Departures | SKYbrary Aviation Safety, and SE214: Area Navigation (RNAV) – Procedures and Standards to Improve Path Compliance for STARs and RNAV Departures | SKYbrary Aviation Safety.

Chandra and Markunas (2017) is not the only study to discuss FMS programming issues. Smith (2008) and CAST SE212 refer to the same issue. Smith (2008) presented results of a simulation study involving both controllers and pilots, focusing on results from the flight deck perspective. Three qualified airline pilots who participated in the study as the pilot monitoring (PM) flew departures in a medium fidelity flight simulator. The participants were presented with two types of departure route amendments, either a change to the programmed transition for a SID, or a complete change of SID. Pilot workload, task completion time, and errors were recorded. The amendments were presented in two formats, voice-issued or text-issued. Although workload was generally acceptable, the task completion time (1 to 2 minutes) was far longer than the time it would have taken to merely enter the keystrokes into the FMS as modeled (under 15 seconds). Errors (slips, lapses, and mistakes) were also observed with programming the FMS, even in the text-issued-amendment scenarios.

2.1.1.2 *Research on Reduced-Separation Operational Concepts*

The literature on reduced-separation ATC operations included primarily FAA studies on proposed or existing concepts. Established on RNP (EoR) is an existing initiative based on PBN that allows reduced separation between pairs of aircraft on approach to parallel runways at a single airport, as long as one of those aircraft is established on an authorized RNAV (RNP) approach. MARS generalizes the EoR concept from one to multiple airports and from approach procedures to different types of terminal IFPs (e.g., DPs, approaches, and missed approaches).

EoR research studies identified potential flightcrew issues that have been found to be associated with PBN IFPs in general (see Chandra & Sparko, 2022, for a detailed review). Consistent with the RNAV DP literature, these issues included ATC issuing unpublished restrictions and the flightcrew loading the wrong route in the FMS (Thomas et al., 2018; Walls et al., 2017b). EoR operations may briefly put two aircraft in a head-to-head configuration under reduced separation. Studies found that this configuration could lead the flight deck's Traffic Alert and Collision Avoidance System (TCAS) to issue a resolution advisory (RA) commanding a vertical maneuver to avoid traffic (Walls et al., 2016; Walls et al., 2017a). It is standard operating procedure for flightcrews to follow the RA, which would take them off the IFP. The EoR initiative mitigated this specific configuration issue through IFP design, but MARS applications will have a greater variety of possible IFP configurations that need to be studied.

We also reviewed several FAA studies on existing and proposed PBN-based separation strategies for DPs. The strategies included those that would allow aircraft on simultaneous independent parallel DPs to reduce their divergence angle after takeoff (Essington, 2018; Flight Research and Analysis Group, 2019; Mayer et al., 2010; Mayer et al., 2011; Mayer et al., 2013; McCartor & Ramirez, 2011; Nichols and Ramirez, 2018) or delay their divergence point (Mayer, 2018; Flight Research and Analysis Group, 2019). These studies focused on efficiency benefits and ATC perspectives.

2.1.2 Research Gaps

This section presents the research gaps that we identified from the literature review discussed above.

Gap 1. *Recent data on flightcrew issues associated with RNAV DPs have not been systematically gathered and analyzed.* Most of the literature we found that specifically addressed flightcrew issues associated with RNAV DPs was published before 2018. The issues may have changed as the use of PBN evolved and expanded (e.g., to more PBN IFPs, more complicated IFP designs, and more operational concepts).

Gap 2. *Additional research is needed to determine what factors contribute to flightpath deviations on DPs.* With MARS concepts, it will be important for pilots to stay on the flightpath when they are in reduced separation. A deviation from the planned flightpath could violate the criteria for MPS and require ATC to revert to radar separation, thus suspending MARS operations for the aircraft that deviated.

Gap 3. *Existing research on RNAV DP concepts does not focus on potential flightcrew issues related to MARS.* The studies we reviewed did not focus on flight deck perspectives. Moreover, existing reduced-separation operations involve IFPs at a single airport. Most of these operations involve aircraft going in the same direction. MARS concepts might present new flightcrew issues because of the higher levels of traffic density in busy airspace with multiple nearby airports. MARS will also have more possible IFP configurations, including, eventually, opposite-direction pairings.

Gap 4. *Data are needed to understand flightcrew perceptions of traffic during MARS operations and potential behaviors that might result*. When MARS operations are in progress, pilots may see traffic from nearby airports flying in unexpected locations and closer to their own aircraft than they would normally expect. Moreover, there may be more aircraft and more variation in traffic routes as departing aircraft get further from the airport. If pilots perceive the traffic as a threat, they might consider deviating from their IFP, which would disrupt MARS operations.

2.2 Research Plan

We devised three data-collection tasks to address the research gaps described in Section 2.1.2. The first task was to hold discussions with four technical pilots about current operational issues. The second task was to identify and analyze 20 records submitted to NASA's ASRS public database to gather examples and study potential causes of flightpath deviations. The third task was to hold discussions with nine line pilots to understand their perceptions of traffic on MARS departure scenarios and what factors might lead to deviations on departures. Figure 3 maps each source of data to the four research gaps.

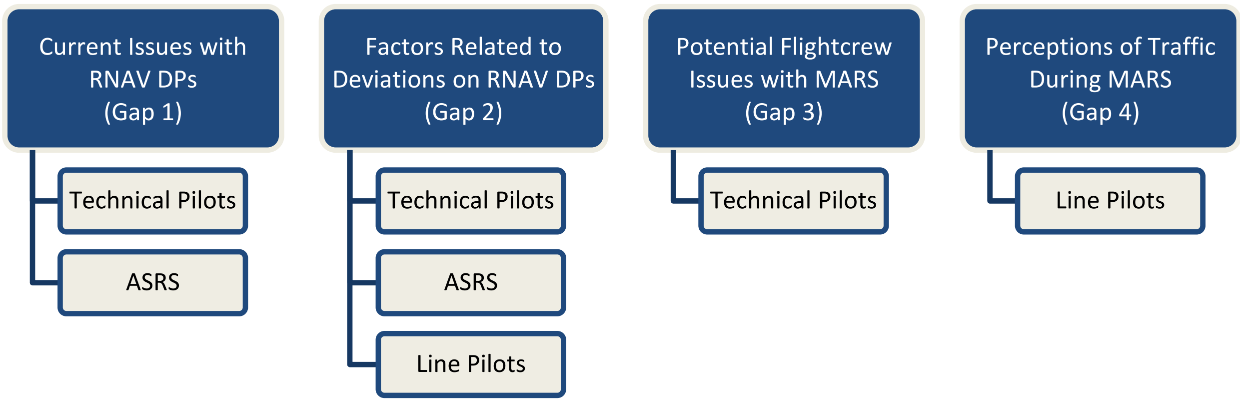

Figure 3. Mapping of data sources to research gaps.

Technical pilots are specially designated pilots who have knowledge of safety data and issues across an airline's operations. The discussions with technical pilots helped us gather their perspectives on current operational issues with RNAV SIDs (Gap 1), factors associated with flightpath deviations on RNAV SIDs (Gap 2), and potential flightcrew issues with MARS (Gap 3). We talked to the technical pilots before conducting the ASRS analysis and line pilot discussions. The discussions did not fully address the research gaps because we did not *systematically* gather data on flightcrew issues with DPs, but they provided clues to the types of issues to look for in the ASRS analysis and line pilot discussions.

We conducted the ASRS analysis to systematically gather data on current flightcrew issues with RNAV SIDs (Gap 1) and factors that contribute to flightpath deviations on RNAV SIDs (Gap 2). We analyzed records submitted between January 2019 and January 2024 that described scenarios involving flightpath deviations or other undesirable outcomes (e.g., increased pilot workload) that occurred on an RNAV SID. We selected records with scenarios that could have occurred under MARS operations or that MARS operations might need to be able to handle.

The line pilot discussions gathered flightcrew perspectives on factors related to flightpath deviations on DPs in general (Gap 2) and perceptions of traffic during MARS operations (Gap 4). We conducted the discussions in two parts. First, we asked pilots to assess the threat posed by a traffic aircraft in two notional departure applications proposed for MARS. The scenarios depicted a flight deck navigation display (ND) with the planned DP route and a traffic symbol overlay. Second, we asked pilots to describe scenarios where they would have to deviate from a planned departure route. We asked them to think of an RNAV DP if possible but did not limit the discussion to RNAV DPs.

Sections 3, 4, and 5 discuss the detailed methods and findings for each task, respectively. Section 6 provides a general discussion. Section 7 provides a summary.

3. Discussions with Technical Pilots

Our first data about flight operations on DPs came from interviews with four technical pilots, each of whom was employed and specially designated by a different domestic airline. Technical pilots participate in internal and external conversations regarding flight-safety data and practices. They are qualified to fly routine operations. Their duties also include understanding safety data and working with government and industry experts to help develop solutions to safety issues that an airline might be seeing in their flight operations. They have extensive knowledge of flight operations, flight deck systems, pilot training, and related subjects that can affect pilot actions in specific situations.

The main goals for the discussions with technical pilots were to (a) gather more information about issues that airline pilots are currently experiencing with DPs and (b) learn how flying DPs has changed over the past 5 to 10 years. In addition, the meetings were an opportunity to collect input on potential issues for MARS when it is applied to DPs,[5] and to get advice for the two other data-collection tasks in this study, which were not fully defined at the time of the interviews.

3.1 Method

The FAA connected us with volunteer technical pilots from four Title 14 Code of Federal Regulations (CFR) Part 121 operators. We set up individual 1-hour virtual meetings with each technical pilot. The pilots had experience with a variety of aircraft types, including aircraft made by Airbus, Boeing, and other aircraft manufacturers. All meetings were conducted with the same briefing slides to ensure consistency and completeness of the interview. Each researcher took notes during the meeting. The meetings were not recorded.

The first part of the presentation explained the study's background, purpose, plan for the interview, and plans for additional data collection for the study. After this introduction, we requested verbal informed consent. We assured participants of their anonymity and of the promised confidentiality of their data. They could also withdraw from the interview at any time without penalty.

The main interview was divided into four sections. The first covered current departure issues and their changes over time. This was the longest segment. The other sections covered anticipated issues for MARS departure operations, suggestions for the ASRS record search (e.g., terms, or locations), and suggestions for the line pilot interviews (e.g., types of pilots to recruit, or traffic scenarios of interest).

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[5] Similar input, on MARS operations in general (not only for DPs), was gathered from 31 line pilots experienced in New York flight operations in an earlier study. Those findings are presented in Chandra and Sparko (2022).

The first slide gave instructions for the feedback on current departure issues as follows:

> *Please tell us about any recent flightcrew issues that you are aware of related to PBN departures or instrument departure procedures in general.*
>
> *We may also ask you about previously identified departure issues to find out whether those issues have been resolved.*

A second slide on the same topic presented more detailed questions about changes over time:

- *How have DP designs changed over the past 5-10 years?*
- *How have aircraft systems for flying DPs evolved?*
- *Updates on operational difficulties flying DPs?*
- *Updates on pilot technique when flying DPs?*

The questions were open-ended; they did not limit the types of issues that the pilot could mention. The researchers asked follow-up questions as time permitted.

For the feedback on MARS departure operations, we presented the following instructions with a short description of MARS[6]:

> *Please tell us whether you anticipate any flightcrew issues with departure procedures used for Multiple Airport Route Separation (MARS) operations.*
>
> *MARS: This concept would allow aircraft flying along specially designed pairs of PBN instrument flight procedures (arrivals, departures, and approaches) to safely fly in areas of reduced separation, which could be less than 3 NM. The FAA is considering whether and how the concept could be developed for high-density airspaces such as New York and Southern California to improve traffic flows and reduce conflicts between close-by airports.*

3.2 Analysis

The notes from each interview session were organized into sections on different topics. The first section gathered general comments and notes, such as the flight experience of the technical pilot and characteristics of their airline flight operations. The next section summarized the current DP issues that were mentioned. The third section covered changes that have happened in the past 5 to 10 years. These changes included four subcategories: (a) changes to DP designs, (b) evolution of aircraft systems over time, (c) updates on operational difficulties flying DPs, and (d) updates on pilot techniques when flying DPs. The next section recorded any anticipated issues for MARs. The last section recorded the technical pilots' suggestions for our planned ASRS analysis and line-pilot discussions.

After summarizing all the interviews, we aggregated feedback across the technical pilots for current DP issues and changes over time related to operational difficulties and pilot techniques. We also aggregated their input on MARS. We incorporated suggestions for this study as appropriate. The evolution of

[6] The description of MARS in this study was similar in content and length to the one given to line pilots who participated in an earlier study (Chandra & Sparko, 2022).

aircraft systems over time was more specific to each operator and not easily comparable across companies.

3.3 Findings

Only de-identified and aggregated feedback is presented. Some issues were mentioned by more than one pilot, others by only one. Due to the time constraints for the interview, some of the feedback may have been unclear and our notes may not have captured all the nuances of the feedback. If an example was particularly complex and time consuming, we may have cut it off to get through the rest of the interview. Also, since the questions were open ended, some responses were outside the scope of the study. For example, some participants brought up problems with conventional DPs, not just with RNAV DPs; we discarded these examples, although they were also interesting. We also discarded examples that were highly specific to a location or IFP because they may be difficult to generalize, or because they are difficult to explain with sufficient accuracy and detail.

The findings are presented by topic in each of the next four sections, beginning with comments about changes to IFP designs (Section 3.3.1), then covering current operational issues (Section 3.3.2), and finally, changes to pilot knowledge and techniques for departure operations (Section 3.3.3). Feedback on MARs is provided in Section 3.3.4.

3.3.1 IFP Design Changes

The technical pilots provided overall insights into how DPs have changed over the past 5-10 years. We were able to confirm the gist of these insights using the data provided to us by MITRE on RNAV SIDs from 2015 to 2023.

For example, two technical pilots mentioned that there are more altitude restrictions on DPs today. One of these pilots said that there are more "at or above" restrictions at locations with terrain or multiple airports. The MITRE data were not specific to locations with terrain or multiple airports, but they do show that, for RNAV SIDs with altitude constraints, the percent of waypoints with altitude constraints has increased over time (from about 17% of the total number of waypoints to over 22%). The MITRE data also show that the number of "at or above" restrictions increased for departures (from approximately 12% of the total number of waypoints to almost 17% between 2015 and 2023).[7] The other technical pilot mentioned that with increasing use of RNAV, there are also "tighter" constraints, but the data cannot confirm how tight the altitude constraints are.

Another technical pilot said that there are more RNAV departures than before. Data from the FAA's IFP Inventory confirm this; the total number of published RNAV SIDs increased from 438 in April 2014 to 1401 in July 2024 (FAA, 2024b; FAA, 2014, as found in Internet Archive, n.d.).[8] The same technical pilot mentioned that (similar to 10 years ago) Standard Terminal Arrival Routes (STARs) have more altitude

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[7] This number remained steady for RNAV STARs at about 14% of the total number of waypoints.

[8] The number of RNAV STARs also increased during this period, from 251 STARs to almost 1098 (FAA, 2024b; FAA, 2014, as found in Internet Archive, n.d.).

constraints than SIDs. The MITRE data confirm this. RNAV STARs do have more altitude constraints than RNAV SIDs. In 2023, RNAV STARs with altitude constraints had an altitude constraint on 44% of the total number of waypoints, while RNAV SIDs with altitude constraints had an altitude constraint on only 22% of the waypoints. In 2015, 38% of the RNAV STAR waypoints had an altitude constraint, while just under 17% of waypoints on RNAV SIDs had an altitude constraint. Although STARs still have relatively more altitude constraints, the number of constraints has increased for both RNAV STARs and RNAV SIDs over time.

3.3.2 Current Operational Issues with DPs

The operational issue mentioned most often by technical pilots was that changes to the DP clearance on the ground are a problem (especially if there are multiple changes prior to takeoff). There are many potential negative consequences in these situations. Lateral deviations are associated with changes to the departure route on the ground that are not properly loaded or verified in the FMS. However, high workload is a more common scenario.

Amending a DP can create high workload for pilots because they must reprogram and re-verify the route. High workload can impact task management and prioritization in turn. The late change may be poorly timed relative to other high priority tasks involved in preparing for takeoff. Pilots may need to wait for updated performance data before they can accept the revised clearance. Even if new takeoff data are not necessary, pilots can become busy and distracted during route verification.

In some cases, pilots receive the revised clearance in text form via a pre-departure clearance (PDC). These clearances are usually accurate, but still need to be verified; pilots may become complacent in the route verification because the PDC routes are usually correct.

The full route must be verified, including confirming the name of the new DP, plus any change to the transition, and confirming whether the new clearance is for an RNAV DP or for a conventional DP, which requires a different automation setup. Pilots may forget to disengage RNAV if there is a change to "fly runway heading," for example.

As mentioned previously (Section 3.3.1), vertical constraints are now more common on RNAV DPs. As a result, it appears that vertical deviations may be becoming more common; this indicates a potential change from the findings of Butchibabu et al. (2010). In particular, "at or above" constraints are more common. These altitude constraints can be an issue for aircraft that are flying fully loaded and heavier. Crews may have to inform ATC that the aircraft is too heavy to meet these altitude constraints, and they may not know whether the aircraft can meet the constraint unless appropriate parameters are entered in pre-flight performance calculations. Another hotspot mentioned by one technical pilot is "at or below" constraints that are placed near 10,000 ft altitude; this is the altitude at which the FMS typically wants to accelerate the aircraft, and the aircraft can exceed the required altitude in this situation.

One other current operational issue mentioned has to do with how ATC tries to help pilots verify their route prior to takeoff. At some airports, ATC will call out the first waypoint on the departure at the time of the takeoff clearance. This works well for ATC, but the timing is off for pilots, because at that point, if there is an error it is a bad time to try to reprogram the FMS. An earlier callout of the first departure waypoint would be more useful to pilots, but this is not a practice that ATC can easily incorporate. Another problem with this callout is its inconsistency. Some facilities give it while others do not. If the pilot is expecting an ATC callout, they may forget to check the first waypoint without the ATC callout; they may not be in the habit of checking on their own.

3.3.3 Changes to Pilot Knowledge and Techniques for Departure Operations

Nowadays, airline pilots use the FMS by default to fly RNAV DPs. The FMS lateral navigation mode is a necessity. Airbus aircraft today routinely activate the lateral navigation automatically immediately after takeoff (at 49 ft altitude). One technical pilot for an airline with Boeing aircraft said that they had recently updated their operating procedures so that the pilot activates the lateral navigation at 400 ft, which is a lower altitude than previously; lateral navigation used to be activated when flaps were retracted. By activating lateral navigation at lower altitudes, pilot workload of flying the RNAV DP can be reduced.

Another change from the past is that pilots now routinely use vertical navigation (called VNAV on Boeing aircraft and Managed Climb on Airbus aircraft) for the initial climb. These systems can manage altitude constraints for the pilot, thereby reducing pilot workload when there are other challenges (e.g., turbulence or poor weather). [9] Although there is no mandate whether to hand-fly or not, the flight director is used when hand-flying.

As mentioned in the section on IFP design changes (Section 3.3.1), today's RNAV DPs have more precise vertical profiles. With more constraints, the workload of monitoring and meeting constraints has increased for pilots. Late detection of a constraint that will not be met can become a problem for ATC. It is also difficult for pilots to monitor and understand how to modify the route in the FMS if the pilot attempts to preemptively manage a constraint that might be missed.

This points to another current issue with departure operations: pilots need a deeper understanding of the flightpath management automated systems to be able to fly today's RNAV DPs. When there are changes to the DP, pilots must understand these changes fully. They need to understand the VNAV/Managed Climb system in detail to be able to recognize, trap, and resolve potential flightpath errors. One technical pilot mentioned that it takes recurrent training (beyond initial training) for pilots to grow their knowledge about the VNAV/Managed Climb logic to the point where they can do "reasonableness" checks as mentioned in the FAA Advisory Circular (AC) 120-123 on flightpath management (FAA, 2022).

There are many potential pitfalls for a pilot using VNAV/Managed Climb for departures. For example, one technical pilot said that good pilots recognize that VNAV lags and that they can fly the vertical path more tightly than the vertical navigation system. While the automated system might prioritize meeting the speed first, then the altitude, a good pilot can manage both at the same time. Similarly, if the aircraft is going to miss an altitude constraint, the pilot might try to slow the aircraft down to meet the

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[9] One carrier in our sample also provides pilots with a separate software tool to manage climb rates more precisely than the FMS.

constraint. However, doing so could cause compression, which is a different problem for ATC (where a faster aircraft closes in on a slower aircraft longitudinally).

It is also important for pilots to know when various actions might cause the automated system to delete altitude constraints unexpectedly. For example, when flying an "open SID"[10] the pilot could inadvertently delete the altitude restrictions by selecting the Vertical Speed mode. Managing a climb through turbulence also requires more detailed knowledge of the FMS logic and careful setup. If the pilot tries to climb quicker through turbulence by disabling VNAV and going into flight-level change mode or speed mode, those will delete the altitude constraints. Alternatively, the pilot could fly at slower airspeed, but then he/she might pick the speed-intervention mode, which changes the vertical navigation schedule as well.

Pilots' understanding of "climb via" clearances is another remaining challenge. Although pilots now understand "climb via" better than they used to in terms of altitudes, some may not be clear about speed restrictions, which always apply. Also, one technical pilot mentioned that pilots might default to assuming that altitude restrictions *always* apply, so that they can "stay out of trouble." However, ATC assumes that pilots will not try to meet the original altitude constraints when they lift altitude restrictions (e.g., by using the phrase "climb and maintain").

3.3.4 Feedback on MARS

Feedback from the technical pilots was similar to what we learned from an earlier study (Chandra & Sparko, 2022). This is reasonable, given that we provided the same short paragraph describing MARS to both groups of pilots. The technical pilots brought up the issues TCAS traffic advisories (TAs) or RAs, and the prevalence of vertical constraints on DPs. They also mentioned that weather and late changes to the DP are currently a risk, implying they would also be a risk for MARS. Another comment was that ATC phraseology to confirm the SID is not standardized.

4. Analysis of ASRS Records

We analyzed public ASRS records to understand operational issues that flightcrews have encountered while flying RNAV DPs. More specifically, we selectively pulled out records with challenges that might occur during a MARS application involving departure routes. This analysis addressed two research gaps identified for this project. First, we gathered and analyzed current flightcrew issues associated with PBN DPs. Second, we used these records to identify factors that contribute to flightpath deviations on DPs.

We focused on ASRS records that documented problems with adhering to RNAV DP flightpaths because MARS operations will be suspended if the aircraft deviates from its assigned IFP. In these records, pilots either (a) deviated from the flightpath that ATC expected, or (b) had difficulty maintaining the desired flightpath while flying a departure route below 18,000 ft altitude. The situations described in these

[10] An open SID is composed of a mix of vector and RNAV segments. For further information, see an FAA Flight Standards memorandum from September 2, 2015.

records could have happened during a MARS scenario or are ones that MARS operations should be prepared to handle.

The limitations of ASRS records are well known. The events are self-reported, subjective, and written from memory and the narratives can be incomplete and difficult to interpret. They can also be biased because of difficulty in observing one's own behavior. They are not a random sample of events so the frequency of events in the dataset may not represent the frequency of occurrence in actual operations. The records may reference IFPs that are no longer in use, and for which charts are no longer available. In addition, de-identified ASRS records may have fields and other text deleted (e.g., location or IFP name); this can impact results of searches based on those fields or text. There is also a delay in entering data due to processing time, typically a few months, so ASRS records may not be an early indicator of issues.

In Section 4.1, below, we describe how ASRS records were identified and selected for this study. The selection process was iterative and based on several different searches with different criteria; this is a different method than we used for our previous analyses of ASRS records (Chandra et al., 2020; Chandra & Sparko, 2022; Chandra et al., 2021). Section 4.2 describes our process for analyzing the records in the dataset. Section 4.3 describes how we grouped the records and presents examples. Section 4.4 presents takeaways from the ASRS analysis, highlighting key insights. Appendix A provides summaries of each record in the final analysis.

4.1 Data Collection

We identified ASRS records for the analysis by iterating on search terms and results. The dataset was constructed from records obtained from several different searches. Well over 100 records were screened and analyzed to some extent. The final set was curated to illustrate the breadth of situations we found in the larger set. They include, for example, flightpath confusion, wake encounters, traffic conflicts, and aircraft system malfunctions.

We first screened records based on their synopsis field. If a record was selected for further analysis based on its synopsis, we evaluated the narrative in detail, then coded it using a rubric that captured basic facts as well as our interpretation of threats and outcomes. If the coding process revealed that the situation was not as relevant to MARS as we initially anticipated, the record was discarded.

After several records were fully coded, we examined the set to decide whether each one should be included or excluded from the curated set. All three reviewers met to decide whether to keep or discard each analyzed record. More than a dozen records were fully analyzed before they were discarded for a variety of reasons.

Once the records in the dataset were finalized, their data were entered into a summary spreadsheet to generate a consolidated view. In the final data-processing step, we generated the summaries in Appendix A by reviewing the coding rubrics, spreadsheet, and full record together.

Details about each of the steps used to identify and select the records are provided below. In Section 4.1.1, we describe the different searches. Section 4.1.2 describes the screening and selection process.

4.1.1 Search Criteria

One criterion for our search was that all the records were from within the past five years (i.e., occurred between January 2019 and January 2024). Another criterion was that the report had to describe a situation involving a Title 14 CFR Part 121 or Part 135 operator.

We did not use the typical research strategy of constructing a search query and then analyzing the records that were returned. Instead, we tried many different search queries, with different terms for the text narratives and synopses (e.g., RNAV, RNAV SID, RNAV departure, deviation, traffic, conflict, parallel). We also applied varying filters for fields in the records (e.g., "Flight Phase", "Event Type"). Some of the searches focused on specific locations, particularly Hartfield-Jackson Atlanta International Airport, Georgia (ATL), Dallas-Fort Worth International Airport, Texas (DFW), and Los Angeles International Airport, California (LAX), which all have parallel runways and busy airspace. One of the searches identified reports from government reporters (i.e., air traffic controllers), who may have a broader perspective of traffic conflicts. We also tried some of the terms suggested by the technical pilots, such as the names of specific airports. This approach, using multiple searches, was helpful for ensuring that all the reports were relevant to MARS.

We ran our searches between September 2023 to January 2024.[11] We did not check whether some reports were found across different searches, so it was not possible to track how many unique records were returned and checked for this study.

4.1.2 Screening and Selection

We first screened records based on their synopsis field only (which was one or two sentences long), looking for cases that were relevant to MARS. We grouped the records based on their similarity, using only the synopsis text. Then, we discarded groups of records that were outside the scope of this study, such as those involving conflicts with aircraft flying under visual flight rules (VFR), bird strikes, events on the airport surface, or failures of the Global Positioning System (GPS). Finally, we picked out reports from each of the remaining groups to construct a small sample that was representative of the larger set for further evaluation.

After screening the records based on the synopsis, we examined the full record, including the detailed narratives, and again checked for relevance to MARS. If the situation was not as pertinent to MARS as we anticipated, the record was discarded at this point.

Sometimes the record's relevance to MARS was ambiguous. For example, we checked whether flightcrew narratives referred to a deviation while flying an RNAV DP, but the route in use was not always specified. We sometimes had to make inferences about whether the aircraft was flying a conventional or PBN DP. We discarded the record with accession (ACN) number 2001268, for example, because we determined the aircraft was probably on a conventional DP rather than an RNAV DP. In some records, the aircraft was on takeoff or at a low altitude off the ground, so the type of IFP was not

[11] Because records are continuously added to the ASRS public database, even from past years, these same search queries may yield more reports now than when they were originally run.

evident. While we preferred reports where it was clear an RNAV DP was involved, we did not explicitly exclude reports where the IFP could not be determined.

We also attempted to ensure that the situations occurred in the terminal area (i.e., inside of 30 miles from an airport and at an altitude below 18,000 ft). For example, in ACN 1792383, there was severe turbulence while flying an RNAV DP, but the aircraft was at Flight Level 370 and more than 30 miles from the airport, which is outside the terminal area. These parameters were unavailable in some records, and we did not explicitly exclude a report if the location and altitude were not in the record.

Similarly, we wanted to examine data from “busy airports with high traffic densities” but we were not able to select reports based on this criterion because the location was de-identified for many of the records found from our searches.

After several reports were fully coded, having passed the multiple rounds of screening, the team discussed whether to keep or discard each report. At this point, more subtle distinctions were made. For example, if the scenario involved parallel runway departures, both aircraft should be IFR and on an IFP. We discarded ACN 1900060 because one of the aircraft was not on an IFP. We also discarded records that were redundant with other records in the final set (e.g., ACN 1894025).

4.2 Data Processing

We first coded the records using a rubric that captured basic facts as well as our interpretation of threats and outcomes. Use of the rubric ensured that each record was analyzed thoroughly and consistently. At least two reviewers examined the record in detail to enter and confirm rubric entries. The rubric design was based on earlier versions we used to examine operational complexity (Chandra et al., 2020) and airspace complexity (Chandra et al., 2021; Chandra & Sparko, 2022).

The rubric had fields for identifying data (e.g., the ACN, location, date, altitude, type of flight operation). The event outcome(s) were also captured (e.g., TCAS TA or RA, loss of separation, lateral/vertical deviation, ATC vectors required, terrain alert, wake turbulence, or other). Threats in the record were also interpreted and listed.

We previously described airspace complexity for pilots as being composed of four types of threats that are external to the pilot: environment, airspace, ATC interaction, flight deck equipment (Chandra et al., 2021; Chandra & Sparko, 2022). Airspace complexity excludes factors that are crew-specific (e.g., lack of knowledge, crew-resource management). Crew-related factors were still captured in the rubric for this study, just separately, as “pilot factors.”

We generated summaries of each ASRS record from the rubrics. Each summary has the fields shown in Table 1. The summaries for all of the 20 records are in Appendix A. To create these summaries, we tightened the format and consolidated threats captured in the rubrics. Each summary is approximately one-half page long. Consolidating the threats was useful for revealing broader patterns. For example, whereas the rubric captured distractions and interruptions, the summaries identified broader task management issues.

Table 1. Contents of the summaries of each ASRS record.

Field	Explanation
Where (When)	The location and altitude fields from the ASRS record are noted, plus the DP that the flight was on, and the month and year the events occurred.
Reporter(s)	This field notes the type of flight operation (e.g., Title 14 CFR Part 121), the number of report narratives, and the reporters' roles.
What	This is a short paragraph, prepared by Volpe researchers, that describes the key events. This paragraph is more detailed than the synopsis within the ASRS record.
Trigger(s)	Triggers are a highlighted subset of the threats. They are the threats that initiated the situation.
External threats	External threats are external to the pilot. This list includes both triggers and other types of threats that were present.
Pilot factors	Pilot factors are threats associated with pilot behavior during the situation.
Outcome(s)	These are the deviations or other undesired outcomes that occurred.

4.3 Results

Descriptive statistics for the dataset are provided in Section 4.3.1. In Section 4.3.2, we describe how the reports were categorized.

4.3.1 Descriptive Statistics

Table 2 lists the ACN for each of the reports in our dataset as a function of the location of the report. The seven records with an ACN starting with 16 were from 2019; the other reports were from January 2021 through May 2023. As identified in Table 2, two of the records were submitted by air traffic controllers and had no pilot narratives. The location of the event was not identified in eight records, although one of these was likely at Ronald Reagan Washington National Airport, Washington, District of Columbia (DC) based on the narrative text.[12] Two of the records were on unknown DPs. In 1921245, the pilot expected and flew the RNAV DP but ATC expected the flight to be on a conventional DP. In 1935343, the record does not specify the IFP, but it implies an RNAV DP.

[12] The ATC facility field for ACN 1665677 is de-identified, but the restricted area P-56, near the White House in Washington, DC, is mentioned in the narrative.

Table 2. ASRS records in the dataset and their locations.

Location	Record(s)
Albuquerque International Sunport Airport, New Mexico (ABQ)	1654249
Hartfield-Jackson Atlanta International Airport, Georgia (ATL)	1921245
Charlotte/Douglas International Airport, North Carolina (CLT)	1619807
Cleveland-Hopkins International Airport, Ohio (CLE)	1619842 (ATC narrative only)
Dallas-Fort Worth International Airport, Texas (DFW)	1935343; 1852539
Harry Reid International Airport, Nevada (LAS)	2001258
Miami International airport, Florida (MIA)	1915613 (ATC narrative only); 1877481
Southern California Region	1617336 (Van Nuys Airport, California, VNY)
Washington, DC Region	1612427; 1887363; 1665677
Unknown	1914982; 1967367; 1940527; 1826339; 1783812; 1781176; 1681024

Table 3 lists the most common outcomes in the dataset records.[13] We cannot use these data to estimate the frequencies of various issues in the broader population, however, due to the limitations of the public ASRS dataset. Although there were four reports where hand-flying became necessary, there were also five records where hand-flying was in progress before the triggering event.[14] There were also several outcomes that we saw only once in our dataset. For example, there was one instance each of a TCAS TA, TCAS RA, and loss of separation. The full list of outcomes is provided in Appendix A.

Table 3. Most common outcomes in the selected ASRS records.

Outcome	Number of Records
Lateral Deviation	11
Vertical Deviation	4
Hand-flying Required	4
ATC Vectors Required	4

[13] A single record may have more than one outcome, so the sum of outcomes exceeds the number of records in the dataset.

[14] Hand-flying was a precursor to the main issue in the following records: 1619807, 1681024, 1781176, 1826339, and 1887363.

4.3.2 Categorization of Records

The records in our dataset were sorted into four groups. The first group has three records where the deviations were intentional (see Table 4). The second group contains 12 records with unintentional deviations (see Table 5). The third group has two records with a combination of intentional and unintentional deviations (see Table 6). The final group has three records where there was no actual deviation, but other undesirable outcomes resulted (see Table 7).

Table 4. ASRS records with intentional deviations.

Record	Volpe Summary	Trigger(s)
1935343	Wake turbulence resulted in pilot decision to deviate laterally	Intentional pilot response to external threat (wake turbulence) + Intentional pilot action related to flightpath management (FPM) (decision making)
1914982	Engine failure required deviation from DP	Intentional pilot response to external threat (aircraft system malfunction)
1826339	Flightcrew received and followed two TCAS RAs against the same small aircraft	Intentional pilot response to external threat (traffic)

Table 5. ASRS records with unintentional deviations.

Record	Volpe Summary	Trigger(s)
1887363	Flightcrew received an ATC amendment for a complex IFP while in flight; the crew unintentionally responded incorrectly while managing multiple tasks, resulting in a lateral deviation	Complex IFP Design + Unintentional pilot response to external threat (ATC amendment) + Unintentional pilot action related to FPM (task management)
1654249	Pilot mistakenly entered incorrect top altitude, resulting in failure to comply with a "climb via" clearance and a vertical deviation	Unintentional pilot action related to FPM (entered incorrect top altitude)
1781176	Crew was task-saturated while hand-flying a lightly loaded aircraft with the flight director; a vertical deviation resulted	Unintentional pilot action related to FPM (task management)
1877481	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.	Unintentional pilot action related to FPM (failure to verify route on ground)
1921245	Captain expected to fly an RNAV DP, but the clearance was to fly runway heading. The aircraft made a turn to follow the programmed in DP, resulting in a lateral deviation.	Unintentional pilot action related to FPM (expectation bias)
1665677	Received a change to the SID at pushback. Crew unintentionally did not verify the programmed route due to numerous tasks and rushed preparation, resulting in a lateral deviation.	Unintentional pilot response to an external threat (ATC amendment) + Unintentional pilot action related to FPM (time pressured task management)
1783812	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.	Unintentional pilot response to external threat (ATC amendment) + Unintentional pilot action related to FPM (task management)
1940527	For unknown reasons, the FMS dropped a waypoint from the planned route, resulting in a lateral deviation and terrain alert to ATC.	Unexpected behavior of automated system (FMS dropped a waypoint)
1852539	Crew attempted to avoid wake turbulence and inadvertently deviated laterally from planned route. A loss of separation also occurred.	Unintentional pilot response to external threat (traffic) + Unintentional pilot action related to FPM (task management)
1967367	The aircraft experienced severe turbulence at 7000 ft altitude resulting in a vertical deviation.	Unintentional pilot response to external threat (severe turbulence)
1612427	For unknown reasons, the aircraft dropped out of the lateral navigation mode and was in heading (HDG) mode instead, with a strong crosswind. This resulted in a request for ATC vectors and a lateral deviation.	Complex IFP design + Unintentional aircraft problem (navigation mode change)
2001258	Crew were informed of a possible vertical deviation; they were unaware and tried to understand what happened.	Unintentional pilot action related to FPM (task management) + Unintentional pilot response to external threat (ATC amendment)

Table 6. ASRS records with both intentional and unintentional deviations.

Record	Volpe Summary	Trigger(s)
1619807	In response to a perceived TCAS TA, the crew proactively reduced climb speed, but before they could reduce power, the aircraft speed exceeded 250 knots (KTS) below 10,000 ft altitude.	Intentional pilot response to external threat (traffic) + Unintentional Pilot action related to FPM (speed management)
1681024	Malfunction of the FMS caused crew to request ATC vectors. While hand-flying, the crew turned too far, resulting in a lateral deviation.	Intentional pilot response to external threat (aircraft system malfunction) + Unintentional pilot action (lateral deviation while hand-flying)

Table 7. ASRS records with other undesired outcomes.

Record	Volpe Summary	Trigger(s)
1617336	The pilot was surprised to notice an altitude constraint soon after takeoff that was based on distance measuring equipment (DME), which was not in the FMS. This resulted in high workload and unexpected hand-flying.	Complex IFP design + Unintentional pilot action related to FPM (failure to catch during route verification)
1619842	ATC amended the lateral route of a SID in flight, then expected the pilot to meet the vertical constraint along the original lateral path. Pilot disagreed and extra radio communications resulted.	ATC amendment
1915613	Controller report of a crew that did not appear to understand clearance phraseology change from "climb via" to "climb and maintain." This caused extra radio communications to avoid a traffic conflict because the aircraft did not climb when the controller expected it to.	ATC amendment ("climb via" clearance phraseology)

4.4 Takeaways from ASRS Analysis

As mentioned earlier, we cannot use ASRS records to estimate the frequencies of various issues. However, we noticed that several of the unintentional deviations were related to *task management* and to *ATC amendments*.

In general, pilot actions during departures are highly sensitive to the timing of distractions and interruptions. Pilots can quickly become saturated with tasks. During a short period of time, they select and configure their automated systems, manage their flightpath while changing the aircraft configuration (setting flaps, retracting landing gear, etc.), and completing checklists. They also need to be aware of traffic, which is most dense in the vicinity of the airport. Pilots must complete these tasks in exactly the right sequence and at exactly the right time.

Crews prepare for departure as well as they can before takeoff, but sometimes, problems are discovered at just the wrong time. On the ground, pilots must program and verify the DP, the departure runway, and the departure transition, but a short taxi route can cause the flightcrew to rush setting up the SID in the FMS, increasing the risk of a programming error. Any problems in the timing or setup of automation modes (e.g., engagement of lateral navigation or autopilot) that are missed by the crew may only be recognized during takeoff, adding workload at a high workload time.

In flight, an ill-timed TCAS TA (announced by a distinctive yellow traffic symbol and an aural alert) can capture limited attention resources at an inopportune moment causing pilots to consider maneuvering, even though TCAS is not issuing a more urgent RA. Unexpected wake turbulence can also be a jarring interruption that suddenly captures the pilots' attention. In-flight route amendments can also increase the risk of route deviations due to reprogramming errors or timing delays. Even crossing 10,000 ft altitude is an important transition, where interruptions may be especially distracting; the flightcrew is completing the checklist as the aircraft starts to accelerate.

Sometimes the consequences are high workload and extra radio communications, instead of route deviations, but these are still undesired outcomes from the perspective of MARS. Because of the high level of workload on departure, crews may not have time to inform ATC of the problem before deviating from the planned flightpath.

5. Discussions with Line Pilots

We talked to nine line pilots to understand pilot perceptions of traffic on MARS departure scenarios and what factors might lead to deviations on departures. The line-pilot participants were volunteers from four major airlines (Title 14 CFR Part 121 operators). They were not compensated for their participation. We found the volunteers through our technical pilot contacts. We sent the technical pilots a description of the study with our contact information and asked them to share it with a few line pilots with RNAV DP experience. Interested pilots contacted us directly to schedule a time to meet.

Two researchers conducted one-hour virtual meetings with each participant. The meeting protocol is depicted in Figure 4.

We started each meeting by reviewing the purpose and plan for the study. During the introduction we also explained that participants' data would be kept anonymous and confidential, and that they could withdraw participation at any time. At this point, participants gave their verbal informed consent to take part in the study. All of the participants agreed to have the rest of the meeting recorded to generate a transcript. The transcript was de-identified immediately after the meeting.

The rest of the meeting was divided into four parts. First, we reviewed the participant's flight experience. Second, we asked participants to assess traffic in two hypothetical departure scenarios depicted on static images of a Boeing 737 ND. The scenarios were based on notional MARS departure applications in the New York area. The order of the scenarios was reversed between participants. Third, we asked participants to describe scenarios in which they might have to deviate from a planned departure route, either intentionally or unintentionally. Finally, we wrapped up the session with a short debriefing and discussion.

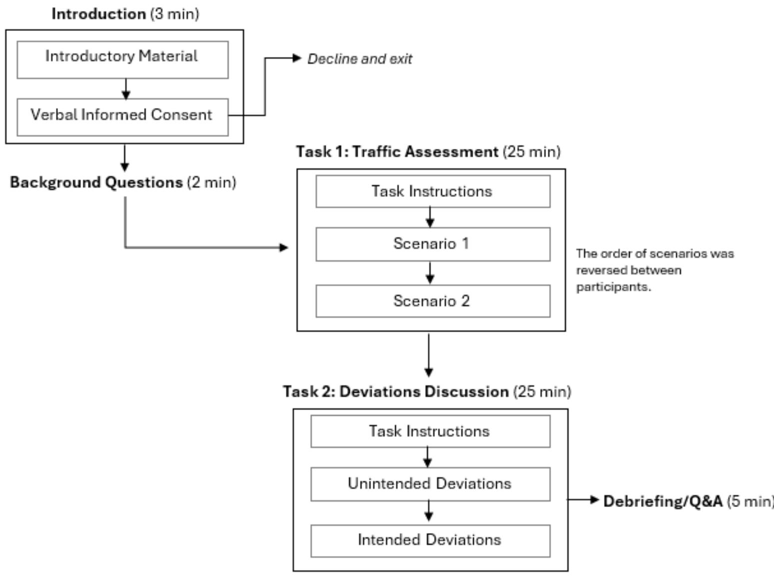

Figure 4. Protocol for discussions with line pilots.

Sections 5.1 describes the study participants. Section 5.2 explains the traffic-assessment task method and findings. Section 5.3 presents the method and findings related to pilot deviations. Section 5.4 summarizes the takeaways from the line pilot discussions.

5.1 Participants

We collected pilot demographic information via an online questionnaire. Table 8 lists the questions and response fields in the questionnaire. We emailed participants a link to the questionnaire prior to their scheduled session. The email provided each participant with a unique identification number (to keep their responses anonymous) and asked them to enter number in the "Participant Number" field of the questionnaire.

The nine participants included two first officers (FOs), four captains (CAs), and three check airmen from four major airlines. We originally wanted to limit participants to CAs and FOs, who could speak directly to their experience flying on a regular basis. We expanded our criteria to check airmen after having difficulty finding enough pilots to participate within our short data collection timeframe.

Participants' 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 participants currently flew Airbus aircraft and one flew Boeing aircraft. Eight participants had some familiarity with Boeing NDs, but only half of the participants considered their familiarity to be "high" (i.e., above 5 on a 10-point rating scale). All of the participants were used to seeing traffic on their NDs.

Table 8. Pilot questionnaire.

Question	Response Field
Participant number	Text
Total flight hours (approximate)	Text
How many years have you flown for your current company?	Text
What model/type of aircraft do you fly currently?	Text
What is your current role (e.g., Captain, First Officer, Check Airman) on this aircraft and how long have you been in that role?	Text
On a scale of 1-10, rate your comfort with RNAV SIDs (1=Not Comfortable, 10=Very Comfortable).	Text
On a scale of 1-10, rate your general familiarity with Boeing navigation displays (1=No Familiarity, 10=High Familiarity).	Text
Are you used to seeing traffic on the navigation display?	Yes or No
On a scale of 1-10, rate how often you fly in regions with a lot of air traffic and multiple close by airports (e.g., New York, Southern California, etc.) (1=Never, 10=Always).	Text
On a scale of 1-10, rate your familiarity with the New York airspace (1=No Familiarity, 10=High Familiarity).	Text

5.2 Traffic Assessment

This section describes the traffic scenario stimuli and findings. Section 5.2.1 describes the content of each image in general. Section 5.2.2 describes how the scenarios were constructed. Section 5.2.3 explains the protocol that we used for the line pilot discussions. The limitations of our methodology are presented in Section 5.2.4. Our analysis method and findings are presented in Section 5.2.5. In Section 5.2.6, we assess the traffic-assessment task overall.

5.2.1 Traffic Scenario Images

We showed participants two hypothetical traffic scenarios based on notional MARS DP applications. The scenarios were depicted on static images of a simulated Boeing 737 ND; an example image is shown in Figure 5. There were four images for each scenario. Each image depicted the ownship aircraft (participant's aircraft) as it flew an RNAV SID. Each image showed ownship (represented by the white triangle at the bottom of the image) at a different position along the route. The ND had a TCAS traffic overlay, using standard TCAS symbols (FAA, 2011; FAA, 2017). A traffic aircraft was visible in seven of the eight images. The example image (Figure 5) shows traffic, represented by the unfilled cyan diamond in the lower left corner of the ND. The "+09" means that the traffic is 900 feet above ownship and the downward arrow (↓) indicates that traffic is descending at a rate greater than 500 feet per min.[15]

[15] TCAS defines proximate targets as non-threat traffic within 6 NM and ±1200 ft altitude. They are displayed as cyan or white filled diamonds. Non-proximate targets are displayed as unfilled cyan or white diamonds. An up or down arrow indicates a climb or descent greater than 500 feet per minute.

We generated the scenario images in Volpe's Boeing 737-800 Next Generation flight simulator. A Volpe Center research pilot hand-flew the ownship DP in the simulator and recorded a video of the ND. We created static images from the video and digitally added the TCAS symbol onto the images. The next section discusses how we developed the scenarios and determined where to place the ownship and traffic aircraft in the images.

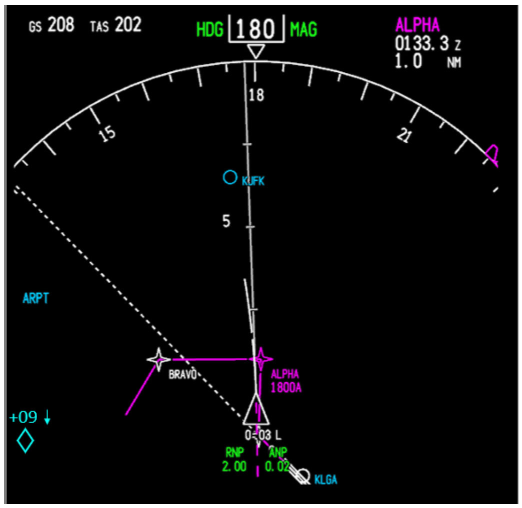

Figure 5. Example traffic scenario image on simulated navigation display.

5.2.2 Scenario Development

The scenarios were based on notional MARS departure operations. We selected the scenarios based on input from a representative from the FAA MARS Program. Both scenarios were in the New York airspace. Figure 6 and Figure 7 shows the overhead view of Scenario 1 and Scenario 2, respectively, created with Google Earth (n.d.). We used the overhead view to plot and measure the distance between the ownship and traffic aircraft at different positions along their routes. We did not show these overhead views to participants in the study.

Scenario 1 involved two existing RNAV DPs; the ownship aircraft departed from JFK 31L on the SKORR 3 RNAV SID and the traffic aircraft departed LGA 13 on the GLMDN 8 RNAV SID. In Scenario 2, the ownship aircraft departed LGA 13 on a hypothetical RNAV SID (i.e., one proposed for the MARS concept) and the traffic aircraft was on the ILS approach to JFK 22R. A MARS Program representative provided waypoint positions (latitude and longitude) and altitude constraints for us to plot the hypothetical SID route. We obtained waypoint positions for the existing IFPs from the FAA's Location Identifiers Search Tool[16] and altitude constraints from the FAA published aeronautical charts for the existing SIDs.

[16] https://www.faa.gov/air_traffic/flight_info/aeronav/aero_data/Loc_ID_Search/Fixes_Waypoints/

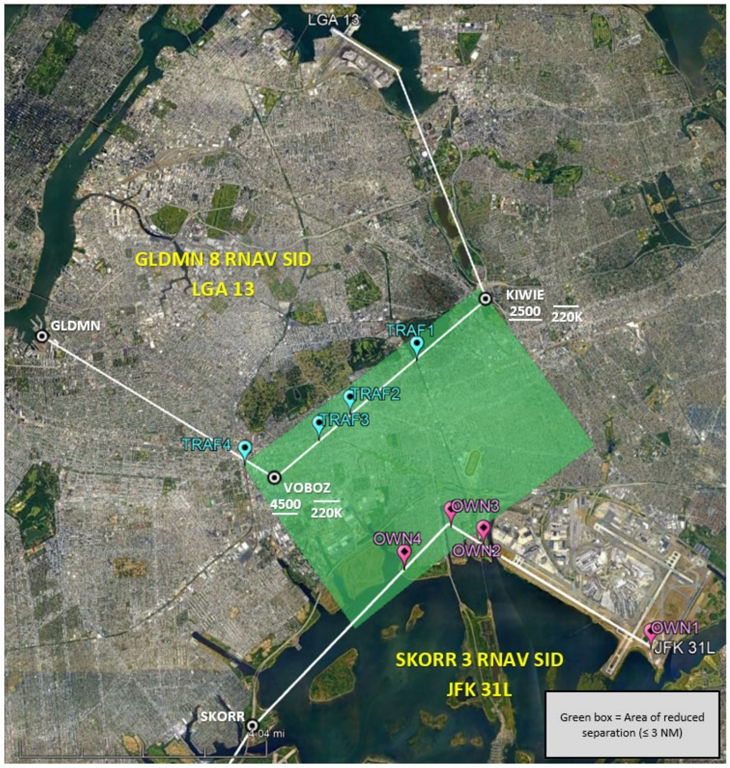

Figure 6. Overhead view of Scenario 1.

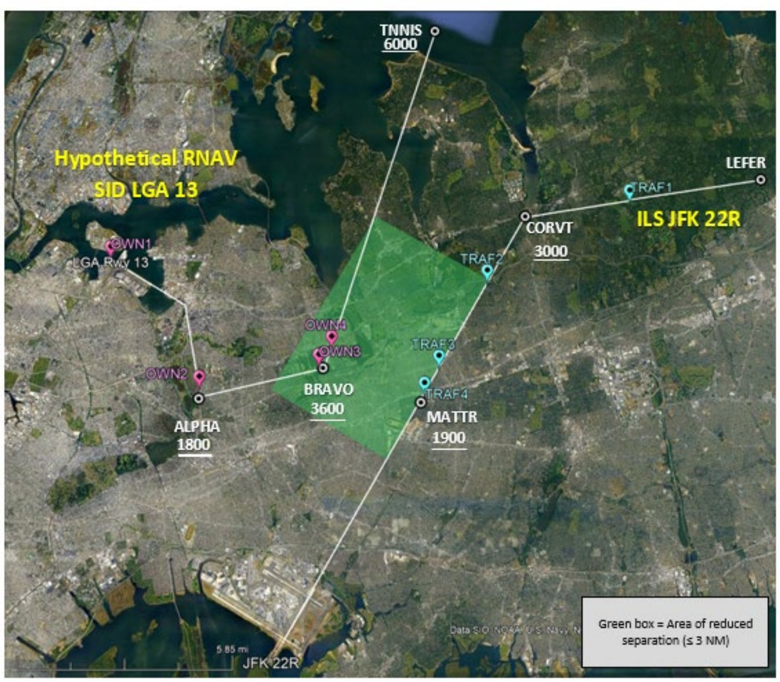

Figure 7. Overhead view of Scenario 2.

The overhead views in Figure 6 and Figure 7 show the positions of the ownship aircraft ("OWN") and traffic ("TRAF") aircraft on each of the four ND images that we showed to pilots (e.g., OWN1 is the ownship position on ND image 1). We determined where to place the aircraft in each ND image in two steps. First, we watched live data from Automatic-Dependent Surveillance – Broadcast (ADS-B)[17] to determine approximately how long it would take an average aircraft to fly each IFP under normal conditions. Then we experimented with climb rates and climb gradients to see whether it was possible for the ownship aircraft and the traffic aircraft to come within both 3 NM and 1000 feet of each other at a given time (i.e., reduced lateral and vertical separation). We based the climb rates and gradients on operational data from the two existing DPs and verified that they were realistic with FAA subject-matter experts.[18] We found that we could put the Scenario 1 aircraft within 3 NM and 1000 ft of each other by making the ownship aircraft climb quickly and the traffic aircraft climb slowly. We could not do the same with the Scenario 2 aircraft; even with extreme climb rates and gradients, the aircraft were always separated by at least 1000 ft because of the altitude constraints on each IFP as shown in Figure 7.

We tested the traffic assessment protocol on three technical pilots before we met with the line-pilot participants. We also reviewed it with the FAA MARS Program representative.

5.2.3 Protocol

We started the task by telling participants what they could expect to see. We told them that they would see two DP scenarios depicted on a Boeing-737 ND and that each scenario had four static images. Each image depicted ownship at a different position along the departure route. We also told them that the ND had a TCAS traffic overlay and that they would see traffic in some of the images. Then we showed participants an example display and reviewed the symbology and settings we used (e.g., range, data shown). This was an opportunity for participants who did not fly Boeing aircraft to familiarize themselves with the ND.

Next, we gave instructions for the task. Participants were told that both scenarios were in the New York area, and that we would tell them which DP they were flying and show them a diagram of the local Class B airspace before each scenario. We did not tell them that the scenarios were based on MARS applications. We did not explain MARS to participants at all.

We showed each scenario image one at a time. We asked participants to examine each image to understand the situation. When they were ready, we asked them to talk through the scenario and describe how they interpreted the situation. Specifically, we asked them to describe the following:

- How they would assess the threat posed by the traffic aircraft
- What actions they might take if they were flying the DP in actual operations
- What other flight deck tasks they might be doing during that part of the DP

We told participants to ignore the lateral accuracy of the ownship aircraft on the DP. Because the

[17] https://globe.adsbexchange.com/

[18] The FAA's Flight Research & Analysis Branch (AFS-430) provided us with summary statistics for operational climb rate and climb gradient data on the two existing DPs.

scenarios were hand-flown in the simulator by a member of the research team, the lateral-path accuracy was lower than professional pilots would expect. This was not important to the study; we were only interested in their perceptions of the traffic.

The participants told us when they were ready for each image. Participants could ask us to return to previous images if they had additional comments. The conversation was open-ended. We occasionally asked follow-up questions. Both researchers took notes and the meeting transcript supplemented these notes.

5.2.4 Limitations

This task had several limitations that should be stated before presenting results. A major limitation was that we had only small number of participants, too few to statistically represent the population of pilots who might encounter MARS operations. For example, the participants were only from major airlines; regional airlines and Title 14 CFR Part 135 operators, who might have different equipment or possibly less overall flight experience, were not in our sample. Most of the participants flew Airbus aircraft, so they were not as familiar with the Boeing ND we used in the scenarios. In addition, almost all the participants were highly familiar with the New York airspace where the scenarios took place. Pilots who are unfamiliar with the New York airspace or high-traffic airspaces in general might perceive traffic differently. The participants were highly experienced volunteers who were highly motivated to participate in the study, which may also affect how well they represent the full population.

We also had some methodological limitations. We asked participants to assess the traffic, so they expected to see it in the images. We do not know whether they would have noticed the traffic otherwise. We used static images for the scenarios. A dynamic view, such as a video or live simulation, might produce different results because the participants would have more information about the movement of the traffic aircraft. We also did not tell participants anything about MARS. With a larger sample of pilots, we could have informed half of the participants about MARS and assessed the effect of that information on participants' perceptions of the traffic. The data were also qualitative, not quantitative.

The scenario images were limited in terms of the type of display and accuracy. We did not match the type of traffic display with the one that the participant was used to. We used standard TCAS symbology, which is familiar to all pilots, but some pilots might be used to using other types of traffic displays (e.g., ADS-B In). More informative flight deck traffic displays (based on ADS-B data) might be more common when MARS is eventually implemented. Although the lateral-path accuracy of the ownship aircraft was lower than our participants would have preferred, this did not appear to affect participants' traffic perceptions.

5.2.5 Analysis and Findings

We used the researchers' notes as the primary data source and referred to the meeting transcripts as needed for more information. We categorized the level of perceived traffic threat based on what participants 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 TA)
4. Planning for action (e.g., preparing for a TCAS TA or RA, considering asking ATC for an early turn)

Together, two researchers reviewed the notes from each participant and agreed on the level of perceived threat for each image. We also summarized other topics that participants mentioned during the discussions that may or may not have been related to traffic threat assessment. The following sections review the perceived traffic threat findings and the other topics, respectively.

5.2.5.1 *Perceived Traffic Threat*

The images and results for each scenario image are presented in the figures below. The captions indicate how many participants were at each threat level.

Figure 8, Figure 9, Figure 10, and Figure 11 show the Scenario 1 images. In this scenario, the ownship aircraft departs from the JFK 31L runway on the SKORR 3 RNAV SID and the traffic aircraft departs from LGA 13 runway on the GLMDN 8 RNAV SID. Scenario 1 was the more "threatening" scenario, where the ownship and traffic aircraft came within 3 NM and 1000 ft of each other in three of the four images. As expected, the perceived level of threat increased as the traffic got closer to ownship and was the highest when the traffic was in the 12 o'clock position. When traffic was in the 12 o'clock position (Figure 10), six of the nine participants were planning to take action.

Figure 12, Figure 13, Figure 14, and Figure 15 show the Scenario 2 images. The ownship aircraft departs LGA 13 runway on a hypothetical RNAV SID (developed for the MARS concept) and the traffic aircraft is on the ILS approach to the JFK 22R runway. Scenario 2 was the simpler (less threatening) scenario. Most participants were unconcerned or just paying attention to the traffic throughout the scenario. More participants were paying attention to the traffic when it was closer to ownship and near the 12 o'clock position (Figure 14).

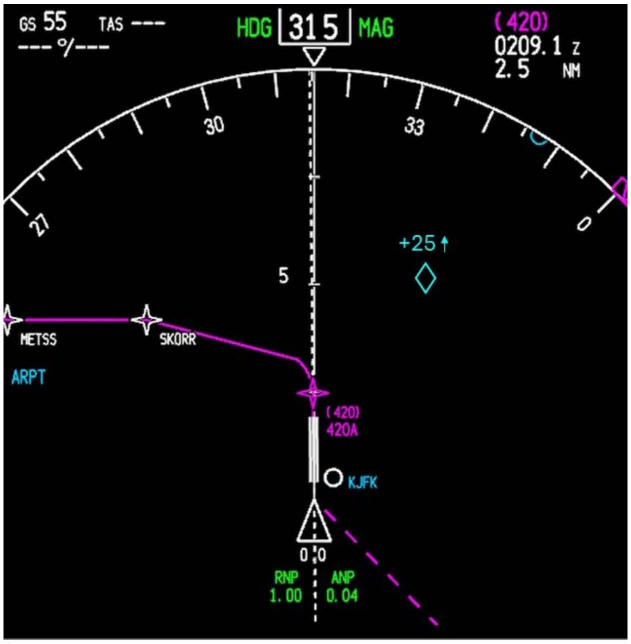

Figure 8. Scenario 1, image 1. Five participants perceived no traffic threat, four were aware of and paying attention to traffic.

Figure 9. Scenario 1, image 2. Four participants were aware of and paying attention to traffic, five were seeking information.

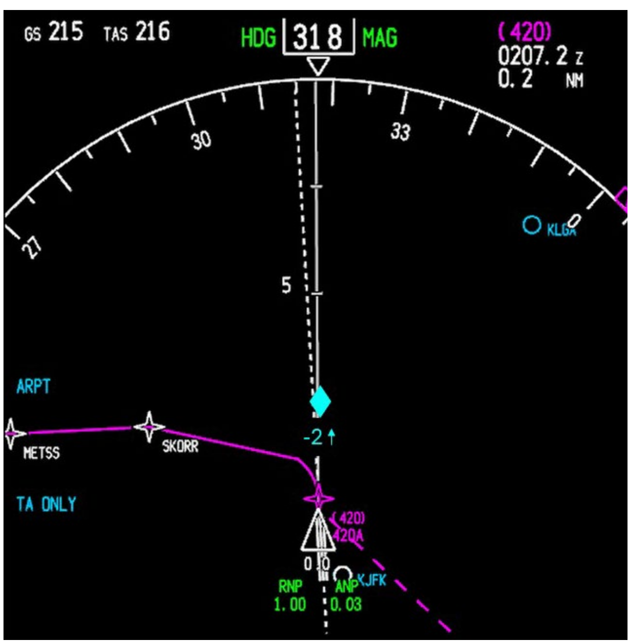

Figure 10. Scenario 1, image 3. One participant was aware of and paying attention to traffic, two were seeking information, six were planning for action.

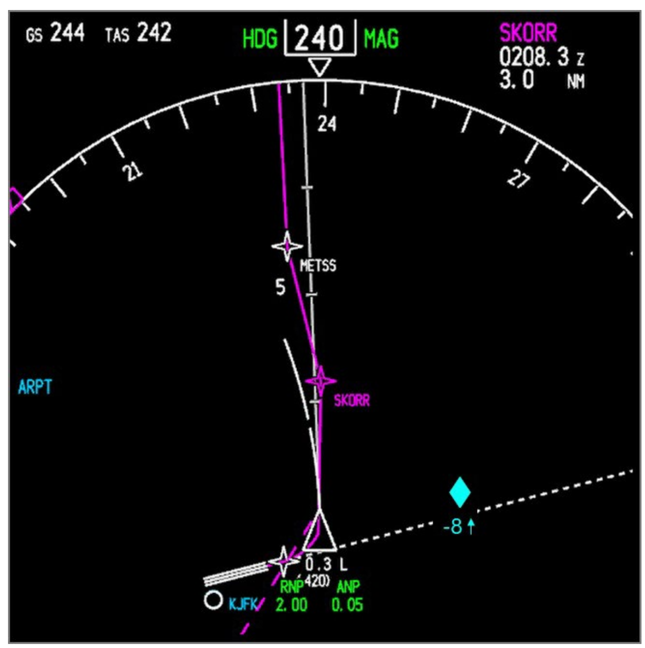

Figure 11. Scenario 1, image 4. Two participants perceived no threat, five were aware of and paying attention to traffic, two were seeking information about traffic.

Figure 12. Scenario 2, image 1. No traffic displayed.

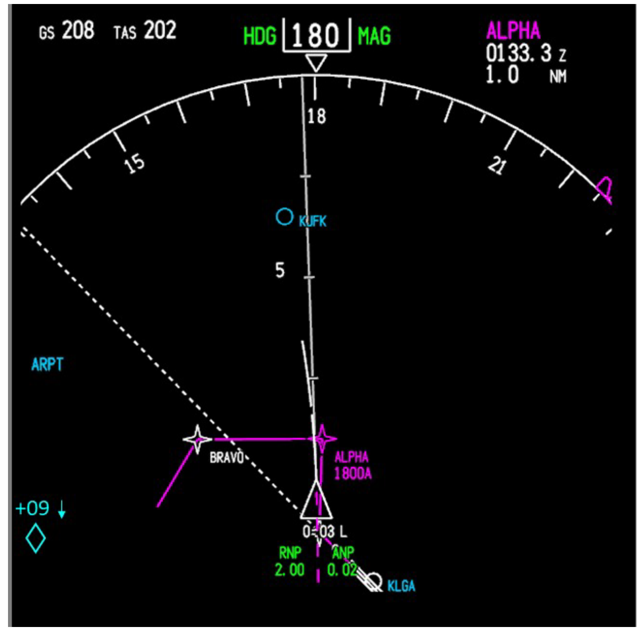

Figure 13. Scenario 2, image 2. Five participants perceived no threat, three were aware of and paying attention to traffic, one was seeking information about traffic.

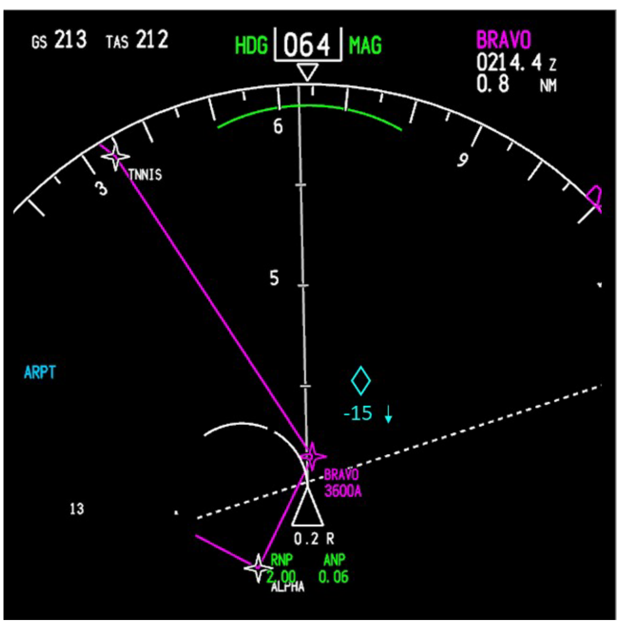

Figure 14. Scenario 2, image 3. Four participants perceived no threat, four were aware of and paying attention to traffic, one was seeking information about traffic.

Figure 15. Scenario 2, image 4. All participants perceived no threat.

5.2.5.2 *Other Participant Feedback*

Participants talked about other factors that would help them to assess the traffic in the real world. For example, 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., radio frequency, out-the-window view). Participants 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. Pilots would also use information about their own aircraft, such as their altitude and climb performance, to determine the level of threat. Other environmental factors, such as wind and whether they were flying in instrument meteorological conditions (IMC) or visual meteorological conditions (VMC) would also affect their threat assessment.

In addition to assessing the traffic threat, we used this task as a way of walking through pilot tasks and strategies for DPs. These sidebar questions helped us to understand what else a pilot would be doing other than searching for traffic. We learned how the participants would configure their TCAS traffic display, whether they had any experience with TAs and/or RAs, and whether they would hand-fly or use the autopilot during departures.

In terms of configuring the traffic display parameters, several participants mentioned that they would set it to show traffic in the "above" mode (see FAA, 2017). In this mode, the display shows targets whose altitude is up to 9900 ft above ownship and 2700 ft below. This mode gives them better awareness of traffic that they may be heading towards as they climb. The "normal" mode shows traffic within ±2700 ft of ownship.

We also learned that it is standard operating procedure to set the TCAS to provide both TAs and RAs during departures. Participants said that they have seen TAs during departures, usually due to abrupt level-offs. RAs, while infrequent, do occur occasionally. Several participants wondered if the traffic aircraft in Scenario 1 (the more "threatening" scenario) might lead to a TCAS TA.[19] Participants said they might consider taking an action (e.g., taking a slight early turn) in response to a TA if they could not get in touch with ATC. This scenario may be more common in regions with dense traffic and congested frequencies, where MARS is most likely to be implemented, even though increased use of PBN IFPs is expected to reduce radio communications.

Participants said that they prefer to hand-fly DPs initially but would engage the autopilot early if there was a need to reduce workload. Workload might be higher if they were unfamiliar with the DP, in solid IMC, or in busy airspace with lots of traffic. They are required to turn the autopilot off if they get a TCAS RA. With MARS, pilots will be required to use the flight director when hand-flying.

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[19] This hypothesis could be tested in a TCAS simulation, but in our estimation, the climb rate of ownship was far greater than that of the traffic aircraft, so a TA was unlikely to be generated.

5.2.6 Review of Traffic Assessment Task

The traffic assessment task was a simple way to get basic data on pilot perceptions of traffic during MARS DP scenarios. Participants performed the task successfully and the data answered our research question. However, there are many ways to improve the traffic assessment task to address its limitations (see Section 5.2.4) and answer additional questions. We would certainly recommend conducting this study with more pilots and pilots with more diverse experience. In particular, we would include pilots with less experience in the airspace where the scenarios were based. With more pilots, we could also analyze the effect of providing information about MARS on their perceptions of the traffic (by providing half of the pilots with a briefing on MARS to familiarize them with the concept). Another improvement would be to provide pilots with more information about the traffic and/or the environment, either on the traffic display (e.g., with ADS-B data) or via the additional cues from a human-in-the-loop simulation (e.g., ATC communications, out-the-window view). Pilots offered many examples of additional data or other factors that would affect their assessment of the traffic threat. With a higher-fidelity simulation, we might also get more detail on the other tasks that pilots might be doing while flying the DP scenarios.

The process of designing the traffic scenarios was particularly informative. MARS operations are conducted simultaneously and independently, so even though the routes are defined by the assigned IFP, we could vary the relative positions of ownship and the traffic by manipulating their positions at the start of the scenario. We could also manipulate the climb performance of each aircraft within reasonable limits. Our intention was to create a "worst-case" scenario because the possibility of the aircraft being within the area of reduced separation motivated our examination of how flightcrews might act in such situations. This worst-case scenario would be where the two aircraft traffic were within 3 NM and 1000 ft of each other[20] and the traffic appears in front of the participant's aircraft at its closest point (so if ownship continued straight, the traffic would be more of a threat).

We discovered, through some trial and error, that even with extreme climb rates and gradients, it was difficult to place both aircraft within 3 NM and 1000 ft of each other at any point in the second scenario. In other words, MARS applications may be unlikely to result in both reduced lateral and vertical separation except in unique cases.[21] We also determined that, for some MARS scenarios, the traffic conflict appears for only a short time (seconds, not minutes), and it may not even be noticed. The proposed MARS designs already minimize the time in the area of reduced separation by design. We also learned that some MARs scenarios are *usually* vertically separated by altitude constraints on the IFPs,

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[20] We used the 3 NM and 1000 ft boundaries to denote the area of reduced separation. We believe that 1000 ft vertical separation is normally required for pairs of aircraft going to different airports in the terminal area but were not able to find specific guidance on this point in the ATC handbook (FAA Order JO 7110.65) (FAA, 2023a), the Aeronautical Information Manual (FAA, 2023b), or the MARS ConOps v2.0 (FAA, 2020). Instead, we asked three subject-matter experts, who all agreed that the 1000 ft vertical separation limit applied. This guidance may need to be clarified.

[21] We expect MARS would most often produce non-proximate targets on the TCAS display (i.e., targets that are outside of ±1200 ft vertical separation but within 6 NM).

especially if one of the IFPs is an instrument approach which has recommended altitudes to meet the required descent path (as was the case in our second scenario for the line pilots).

5.3 Deviations from DPs

For this task, we asked participants to describe scenarios in which they might deviate from the planned departure route. We asked them to describe two types of scenarios, one where the deviation was intentional and one where the deviation was unintentional. The scenarios could be real or hypothetical. We asked them to think of a specific DP if possible, preferably and RNAV DP, but most of the responses were general.

All of the participants provided several examples of each deviation type. We summarize the examples in the following sections.

5.3.1 Intentional Deviations

Participants provided a few similar examples of intentional deviations. These were commonly associated with an outside disturbance, such as weather, traffic, or equipment problems.[22] Pilots may deviate to avoid severe weather like 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, flightcrews must fly their company's engine-out procedure, which typically requires them to fly straight on runway heading initially. Other, less common, issues like a bird or wildlife strike that affect aircraft controllability could also lead to the decision to deviate.

5.3.2 Unintentional Deviations

In contrast to describing a few examples of intentional deviations, participants offered multiple different situations that could produce unintentional deviations. Participants described both general and specific (e.g., to a particular airport) examples of unintentional deviations. The general examples were 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 changes the clearance (an issue that was also mentioned in Smith, 2008). Changes on the ground can be particularly challenging due to time pressure. Sometimes pilots receive multiple changes at once (e.g., to the runway, SID, and/or transition), and pilots might unintentionally re-program only some of the changes into the FMS.

Participants also described how changes in the air can lead to FMS programming errors. For example,

[22] This feedback matches the types of intentional deviations we found in ASRS records (Table 5, Section 4.3.2).

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.[23] 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/Managed Climb.

More specific examples of unintentional deviations involved local issues, such as compass anomalies on some departures from specific runways out of LGA or winds in the New York area. The FMS can take time to gather real-time wind data and it may not be accurate immediately after takeoff, leading to poor turn anticipation. Other examples were related to specific IFP designs. One participant mentioned a sweeping turn on a SID out of San Diego International Airport, where pilots learning to hand-fly a new aircraft might take the turn wide. Another example was from Detroit Metro Wayne County Airport, where some DPs have speed restrictions of 230 KTS. Depending on the type and weight of the aircraft, its minimum speed in a clean configuration may be higher than 230 KTS. So, to meet the speed restriction, the pilot must delay cleaning up the aircraft configuration. If the pilot cleans up the configuration at the usual time, the aircraft may unintentionally exceed the speed restriction.

5.4 Takeaways from Discussions with Line Pilots

The results of the traffic assessment task indicated that participants could become somewhat concerned about traffic during MARS operations depending on the traffic’s relative position and trajectory. In some situations, participants wanted additional information about the traffic, which could add to their workload and/or distract them from other tasks. Several participants said they would ask ATC about the traffic, which would add workload for both the flightcrew and ATC. Increasing radio communications about traffic would be the opposite of the intended effect of introducing more PBN IFPs, which usually reduce the need for radio communications.

In some cases, the traffic was concerning enough that participants said they would prepare for a potential TCAS TA or RA, especially if they could not reach ATC to ask about the traffic. The preparation itself is an additional task that pilots must manage during an already high-workload situation. If pilots decided to execute their plans by deviating from the DP, it would suspend MARS operations for that aircraft and require ATC to revert to providing radar separation. The intentional deviation in this example would at least take pilots away from traffic, but that may not always be the case. The worst-case scenario is that they deviate toward another aircraft.

Participants provided a few common factors that can lead to intentional deviations, including weather and aircraft system malfunctions. These factors may not provide the flexibility to move away from traffic. One example is for engine-out procedures, which usually require aircraft to go straight at first.

[23] A similar situation was observed in ASRS ACN 1612427 (Table 5, Section 4.3.2).

Intentional deviations are usually triggered by factors that are outside the pilots' control.

Unintentional deviations were usually due to pilot error with the automated systems, but they were often precipitated by ATC amendments (an external factor). Participants described various ways that an unintentional deviation could happen, compared to the relatively few triggers for the intentional deviations. These types of issues may be harder to predict and catch. ATC will be less likely to receive advanced warning of an unintentional deviation.

6. General Discussion

This discussion is divided into three sections. Section 6.1 compares the three data sources we used for this study. Section 6.2 has an assessment of progress towards addressing each of the four research gaps. Section 6.3 summarizes insights for MARS flight operations.

6.1 Data Sources

In this study, we gathered data from three sources: technical pilot discussions, an analysis of records from the NASA ASRS database, and line pilot discussions. Each source of data contributed in different ways to our understanding of issues related to flying DPs.

Technical pilots have a view of DP issues that considers factors specific to that airline (e.g., based on their aircraft equipment characteristics, their routes of flight and areas of operation, and their training practices). The input was detailed, but hard to generalize as a result. However, technical pilots may be more aware of emerging and receding issues. Because of their processing delay, ASRS records may not be an early indicator of issues.

ASRS narratives are less specific than the examples given by technical pilots. Therefore, it was hard to correlate ASRS records with the examples that the technical pilots gave, although there was some general overlap. For example, technical pilots mentioned, and ASRS records illustrated, problems when there is time pressure on the ground and the departure clearance is changed, which creates a risk that the DP will be flown incorrectly (ACN 1665677 and ACN 1877481 are examples in Section 4.3.2). We also saw one example of a flightcrew that forgot to activate lateral navigation when there was a change to a SID (see ACN 1921245). However, the technical pilots also mentioned issues that we did not find in ASRS records, such as multiple changes to a departure clearance on the ground.

The line pilot discussions had two components, a traffic assessment task and input about flightpath deviations. There were many limitations of the traffic assessment task (see Section 5.2.4). Even so, the data we gathered was informative. Line pilot input on flightpath deviations was general, but it was consistent with findings from the ASRS records. The ASRS records gave us more specific examples of scenarios with flightpath deviations, but the line pilot input gave us more insight into their decision-making. In other words, the two sources of data were complementary.

6.2 Progress on Research Gaps

We identified four research gaps to address in this study (Section 2.1.2). Each gap is repeated below, and then each one is addressed individually.

> Gap 1. *Recent data on flightcrew issues associated with RNAV DPs have not been systematically gathered and analyzed.*
>
> Gap 2. *Additional research is needed to determine what factors contribute to flightpath deviations on DPs.*
>
> Gap 3. *Existing research on RNAV DP concepts does not focus on potential flightcrew issues related to MARS.*
>
> Gap 4. *Data are needed to understand flightcrew perceptions of traffic during MARS operations and potential behaviors that might result*.

Gap 1. We used two data sources (technical pilots and ASRS records) to address this research gap.

The technical pilots contributed to our understanding of recent flightcrew issues associated with PBN DPs. However, the technical pilot input was from a sample of just four individuals, and it was not in a form that we could systematically analyze independently.

The technical pilot input was the main source for data on how DPs and related flight operations changed in the past 5-10 years, findings that were related to Gap 1. A MITRE data analysis also documented the change to DP altitude constraints over time.

The curated ASRS records provide a broad look at current issues with DPs. Some of these were also identified by technical pilots, but there were several issues that did not overlap across the two sources of data, as described above (Section 6.1).

Gap 2. We used all three data sources (technical pilots, ASRS records, and line pilots) to address this gap. Of these sources, the technical pilot data was the most generic; the ASRS records and line pilot discussions addressed this gap more directly than the technical pilot interviews. We learned that there are many causes of unintentional deviations, and relatively few causes for intentional deviations.

Gap 3. This gap was only discussed with technical pilots, and it was a small part of that conversation. Their responses were general, mentioning weather impacts, and changes to DPs. The traffic-assessment component of potential MARS impacts was separated into its own category (Gap 4).

Gap 4. This gap was addressed directly by the line pilot discussions in this study, and in particular, by the traffic-assessment task. We learned that there are MARS scenarios that could be perceived as threatening enough for pilots to seek more information about traffic and to prepare to take action to avoid that traffic.

6.3 Insights for MARS Flight Operations

This study provides a variety of insights for MARS operations. From the technical pilots, we corroborated data from Chandra and Sparko (2022), where pilots mentioned that MARS will need a way to be turned on and off quickly. This may be important, for example, when there is significant weather that impacts multiple aircraft. Another example that would require a quick response from ATC is when 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 path for a single-engine situation).

From the line-pilot traffic-assessment task, we learned that there were situations where pilots might seek more information about the traffic and might even prepare to take action. Some of the information that pilots wanted about the traffic, such as its type and trajectory, could be provided in the future by ADS-B In traffic displays. These displays could influence how pilots perceive the threat posed by an aircraft in a MARS operation. Interestingly, the participants in our study were highly experienced with flight operations at airports with high traffic densities; they were actually relatively comfortable with traffic in close proximity. Pilots with less experience in high-traffic areas may react differently and pilots with less flight experience overall may also have a different reaction.

This study also garnered insights about flightpath deviations, from both the ASRS analysis and line-pilot input. Some of these insights are not new. We once again found that ATC amendments could trigger unintended deviations. For departures, specifically, task management is also a key issue; departure tasks are highly time sensitive. From a MARS perspective, designers should be aware that if ATC amends a MARS IFP, as with any other route amendment, the risk of a deviation may increase. The lowest risk option is to ensure that the route is specified early so that the pilot can enter it and verify without time pressure. MARS designers should also be aware that IFP designs that are difficult to fly in operations could have an increased risk of deviations. This is, again, not a new observation. However, given the potential impact of a flightpath deviation at exactly the wrong time (i.e., while the aircraft is within the area of reduced separation), it is important to emphasize that the IFP should be flown reliably and accurately, without a need for significant pilot intervention. Finally, regarding deviations, this study found that there were many possible reasons for an unintended deviation. MARS should have procedures in place for handling deviations such as these.

The final operational insight for MARS gained from this study pertains to hand-flying, which was brought up in both the ASRS records and the line-pilot discussions. Pilots hand-fly departures regularly and MARS allows this, as long as they use the flight director. However, MARS designers should be aware that, operationally, flying with the flight director may not produce the exact same flightpath as an autopilot would produce. For example, a check airman who participated in the line pilot discussions mentioned that when learning to fly a new aircraft type, pilots may make wider turns than an autopilot would. (As another example, if necessary, a pilot could choose to hand-fly with a bank angle that is steeper than the limitations placed on an autopilot.) Also, if pilots become busy or distracted, they may miss a flightpath constraint, as seen in ACN 1781176. In rare cases, such as a TCAS RA, hand-flying is a requirement.

7. Summary

The research described in this report addresses four research gaps related to the flight deck perspective on flying PBN DPs as part of a proposed ATC operational concept called MARS, which aims to deconflict traffic in busy areas with multiple airports. We first updated our knowledge of operational issues with DPs through discussions with technical pilots who study safety issues for their airlines. These pilots made us aware of recent trends, such as the increase in vertical flightpath constraints on DPs. There are also continued challenges with time pressure and handling multiple time-sensitive tasks, including handling ATC revisions to departure clearances.

We next analyzed a curated sample of ASRS records related to RNAV DPs. These records provide us with an overview of challenges that pilots may face during departure, many of which may cause a deviation from the cleared flightpath. Some of these deviations are intentional, but more seem to be unintentional. Input from line pilots on the subject of flightpath deviations confirmed what we learned from the ASRS records. The ASRS records also showed that sometimes there are undesired outcomes even when a deviation does not happen, such as extra radio communications or high pilot workload.

We used a novel method to understand how pilots might assess the threat of traffic that is part of a MARS operation, flying on a paired IFP with ownship. We constructed two scenarios, one with more threatening traffic than the other. By showing line pilots just a few snapshots in time, we observed how their perception of the threat posed by the traffic changed. In the most threatening snapshot, with traffic at 12 o'clock, less than 3 NM away, just below ownship and climbing, most participants wanted at least more information about the target (e.g., its aircraft type and, by inference, its climb performance), and some participants were preparing to take action to avoid a conflict. This particular scenario was not a likely one because it relied upon some unusual climb gradients for the two aircraft, but it could cause some unwanted pilot actions. The method we used, while informative, was a proof-of-concept only, with much room for improvement. Additional data from a more diverse set of pilots, for example, could improve our understanding of how pilots in general might handle MARS scenarios involving DPs.

Results of this study illustrate how pilot tasks during departures are similar to, but also different from, pilot tasks during arrivals and approaches, which were studied previously (Chandra & Sparko, 2022). Departures are time-sensitive and dynamic, requiring pilots to manage changing tasks and priorities effectively. Once takeoff is initiated, multiple tasks must be done in the correct sequence at the correct time; small errors can propagate quickly, especially where there are many aircraft nearby. MARS, and any related contingency procedures, should fit neatly into the pilot's workflow.

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Appendix A: ASRS Record Summaries

Intentional Deviations

ACN 1935343

Where (When): DFW Airport on unknown DP (likely RNAV) at unknown altitude (September 2022)

Reporter(s): Title 14 CFR Part 121 pilots, both crewmembers

What: Encountered wake twice in sequence from the Airbus they were following on the SID out of DFW, at 1000 ft and 2000 ft altitude. There were light winds, keeping the wake in their path. Crew compensated by flying upwind side of SID. Unknown DP, but probably RNAV because the reporting aircraft seems to be directly following a preceding aircraft.

Busy airspace (tight spacing between departures) and interesting crew strategy (intentional lateral deviation from SID).

Trigger(s): Intentional pilot response to external threat (wake turbulence) + Intentional pilot action related to FPM (decision making)

External (Non-pilot) Threats

- Traffic – wake turbulence from preceding aircraft
- Light winds – kept the wake turbulence in the flightpath longer
- ATC Time pressure – minimal spacing between departing aircraft
- Nighttime

Pilot Factors

- Decision making – pilot decided to fly to the side of the SID

Outcome(s)

- Lateral deviation – Flew upwind side of SID

ACN 1914982

Where (When): Unknown Tower on unknown route at unknown altitude (July 2022)

Reporter(s): ATC

What: Engine failure causes Title 14 CFR Part 121 aircraft to go straight after departing a parallel runway instead of turning away. Eventually returned to departure airport, but pilots were busy and not communicating with ATC for a while, which backed up aircraft taxing out for departure until they sorted out the landing runway. Separately, there was a fire on the Right runway, which caused that one to be unavailable. Aircraft had to switch to land on Center runway.

Trigger(s): Intentional pilot response to external threat (aircraft system malfunction)

External (Non-pilot) Threats

- Aircraft problem – engine malfunction on takeoff
- Time pressure – ATC had to move other traffic around the disabled aircraft and unavailable runway

Outcome(s)

- Lateral deviation – Flight returned to departure airport
- ATC moved multiple aircraft around on the ground and in the air

ACN 1826339

Where (When): Unknown Terminal Radar Approach Control (TRACON) on RNAV DP at 10000 ft (July 2021)

Reporter(s): Title 14 CFR Part 121 pilots, both the CA acting as pilot flying (PF) and the FO acting as PM

What: Crew received two TCAS RAs against the same small aircraft, first one while approaching 10,000 ft to "maintain vertical speed" and then later "Descend, Descend Now". A small twin-engine aircraft was the conflicting traffic. ATC gave changing instructions to the small aircraft.

Trigger(s): Intentional pilot response to external threat (traffic)

External (Non-pilot) Threats

- Traffic
- ATC – time pressured communication, radio congestion
- ATC gave changing instructions to the small (non-reporting) aircraft

Pilot Factors

- Task management – leveling at 10,000 ft

Outcome(s)

- TCAS RA
- Near-mid-air Collision

Unintentional Deviations

ACN 1887363

Where (When): Potomac TRACON on RNAV DP at 10000 ft (March 2022)

Reporter(s): Title 14 CFR Part 121 pilots, both crewmembers

What: CA was hand-flying the JCOBY4 RNAV DP out of IAD (departed RWY 30, vectors to join RNAV portion of the DP). At 10000 ft, tried to change the FMS waypoint (because of an ATC reroute) as turbulence hits, lost the programmed route. FO incorrectly entered the full DP (according to CA). CA had to switch back to HDG mode to reconnect the flightpath. Synopsis says track deviation but unclear how much of a deviation. FO's narrative also mentions other tasks he/she was doing.

Trigger(s): Complex IFP Design + Unintentional pilot response to external threat (ATC amendment) + Unintentional pilot action related to FPM (task management)

External (Non-pilot) Threats

- Complex IFP design – ATC vectors to the first RNAV waypoint
- ATC route amendment
- ATC Communications – time sensitive
- TCAS Traffic Advisory
- Wake from unknown aircraft

Pilot Factors

- Task management – crossing 10000 ft, handling wake
- Hand-flying
- Time-pressure related to FPM – setting up FMS
- Lack of knowledge of aircraft autoflight systems (FO)

Outcome(s)

- Lateral deviation

ACN 1654249

Where (When): Albuquerque (ABQ) Airport on RNAV DP at 10000 ft (June 2019)

Reporter(s): Title 14 CFR Part 121 Pilot (PF) and TRACON Controller

What: Pilot failed to comply with Climb Via, missed the altitude restriction at MNZNO (at or above 11,500 ft) and flew below minimum vectoring altitude (MVA) for about 4 miles. Pilot had set 10,000 ft in altitude select window instead of the top altitude of 20,000 ft.

Trigger(s): Unintentional pilot action related to FPM (entered incorrect top altitude)

External (Non-pilot) Threats

- Terrain/MVA
- Recent changes to SID

Pilot Factors

- FMS programming issue – entered incorrect top altitude

Outcome(s)

- Vertical deviation – missed altitude constraint
- Flew below MVA

ACN 1781176

Where (When): Unknown TRACON at 10000 ft (January 2021)

Reporter(s): Title 14 CFR Part 121 Pilot (PF/FO)

What: PF was hand-flying with a flight director but did not follow the guidance. PM was task saturated as they crossed 10000 ft altitude (accelerating and completing a checklist) with a lightly loaded aircraft. Missed the hold-down symbol on the multi-function display. Deviation was 400 ft. The aircraft was light, possibly due to light passenger levels in January 2021.

Trigger(s): Unintentional pilot action related to FPM (task management)

External (Non-pilot) Threats

- Environment – Low-level wind shear at takeoff; night-time
- Aircraft performance – light aircraft

Pilot Factors

- Task management – climb checklist; starting to accelerate after 10000 ft; frequency change; missed the hold-down symbol on the multi-function display

Outcome(s)

- Vertical deviation

ACN 1877481

Where (When): Miami (MIA) TRACON on RNAV DP at 4500 ft (February 2022)

Reporter(s): Title 14 CFR Part 121 pilots, both crewmembers

What: Crew failed to verify the route after the auto-upload and did not notice a problem until in the air. Many factors mentioned as possibilities (e.g., fatigue, nighttime, complacency). At first, they deviated intentionally due to wake, but then realized their route was not in the FMS. The wake was not the reason for the failure, it was a distraction. The failure happened on the ground, when the autoload PDC deleted the SID.

Trigger(s): Unintentional pilot action related to FPM (failure to verify route on ground)

External (Non-pilot) Threats

- Wake turbulence from preceding departure
- Nighttime

Pilot Factors

- FMS programming issue – autoload of the PDC unexpectedly deleted the planed SID
- Confusion unrelated to FPM – did not understand how the autoload function on the FMS worked
- Generic crew error – accidentally executed the autoload then failure to verify route

Outcome(s)

- Lateral deviation

ACN 1921245

Where (When): ATL TRACON, unknown altitude, unknown RNAV DP (July 2022)

Reporter(s): Title 14 CFR Part 121 pilot (CA/PF)

What: CA (PF) cleared for takeoff to fly runway heading (26L), but his actions indicate that he expected to be given an RNAV DP, and he began to fly that instead. After takeoff, aircraft encountered wake from preceding A321 with 25° roll to the right. CA was focused on returning aircraft to level attitude (hand-flying) and began to erroneously navigate to first fix on RNAV SID (JACCC2-MPASS) instead of staying on runway heading. Post wake encounter, CA called for the rest of the takeoff profile until ATC advised that they were not given an RNAV clearance.

Trigger(s): Unintentional pilot action related to FPM (expectation bias)

External (Non-pilot) Threats

- Traffic – wake turbulence from preceding aircraft

Pilot Factors

- Generic error – CA expectation bias
- Lack of familiarity with local operations – RNAV clearances given later in the day
- Lack of knowledge/training – FO did not realize that clearance for runway heading was different from clearance to fly the SID
- Crew resource management (CRM) – FO should have questioned the CA's expectation
- Task management – after avoiding wake turbulence, began to navigate to the wrong point

Outcome(s)

- Lateral deviation
- ATC vectors required

ACN 1665677

Where (When): Record field says Unknown TRACON (implied at Potomac TRACON) on RNAV DP at 4000 ft (July 2019)

Reporter(s): Title 14 CFR Part 121 Pilots (both CA and FO)

What: Ground ATC changed SID at pushback due to changed flow. CA updated FMS but did not ask FO to confirm entries during rushed preparation. Numerous distractions and hurry-ups cited. CA/PF visually and manually flew upriver to avoid P-56 while sorting out FMS route. New (45 hour) FO did not speak up about needing time to review the plan.

Trigger(s): Unintentional pilot response to an external threat (ATC amendment) + Unintentional pilot action related to FPM (time pressured task management)

External (Non-pilot) Threats

- ATC amendment – received new SID at pushback, on ground
- Time pressure – short taxi time and time-sensitive route amendment to both runway and SID
- FMS programming issue – time pressured setup
- Complex IFP design – prohibited areas nearby
- Traffic – traffic on final

Pilot Factors

- Lack of familiarity with local operations (FO, not CA)
- CRM
- Decision making
- Distraction
- Crew physical condition – fatigue/poor sleep

Outcome(s)

- Lateral deviation
- Hand-flying necessary (over river to avoid P-56)

ACN 1783812

Where (When): Unknown TRACON on RNAV DP at 10000 ft (January 2021)

Reporter(s): Title 14 CFR Part 121 Pilot (CA/PM)

What: On an RNAV SID, ATC told pilot to climb to 10000 ft (changing the unidentified SID) and cleared direct to a later waypoint (shortcut). The pilot had trouble completing all the necessary tasks (including handling an ECAM message) in time. Result was a lateral deviation because the aircraft turned a few seconds too late.

Trigger(s): Unintentional pilot response to external threat (ATC amendment) + Unintentional pilot action related to FPM (task management)

External (Non-pilot) Threats

- ATC amendment to lateral and vertical path
- Time pressure – Time sensitive route change, setting up FMS, and other tasks to complete
- Complex IFP – short distance to initial waypoint
- Aircraft malfunction – ECAM alert for pressure regulator fault

Pilot Factors

- Task management – handling after takeoff checklist, ECAM alert, and ATC amendment
- Generic – lack of recent flight experience due to one-month COVID leave

Outcome(s)

- Lateral deviation – aircraft continued along preset route to second waypoint before route change was executed

ACN 1940527

Where (When): Unknown TRACON on RNAV DP at 8500 ft (October 2022)

Reporter(s): Title 14 CFR Part 121 pilots, both crewmembers

What: Crew got an updated departure clearance via data link. They used the autoload function and verified the route thoroughly. Still, they are not sure how, one waypoint was dropped and they cut the corner on the route. The lateral deviation resulted in a low-altitude (terrain) warning from ATC. Neither crew member could explain how it was missed.

Trigger(s): Unexpected behavior of automated system (FMS dropped a waypoint)

External (Non-pilot) Threats

- Aircraft problem (unexpected behavior) – FMS dropped a waypoint
- Terrain

Pilot Factors

- Generic error – did not catch the problem during briefing or route verification

Outcome(s)

- Lateral deviation
- ATC received terrain alert (no terrain alert on the flight deck)

ACN 1852539

Where (When): DFW Airport on RNAV DP at unknown altitude (November 2021)

Reporter(s): Title 14 CFR Part 121 Pilot

What: Lateral deviation after handling interruptions from wake turbulence and cleaning up aircraft configuration on initial climb. They mention they should have let ATC know. Reporter states there may have been another path to avoid wake that might have worked better.

Trigger(s): Unintentional pilot response to external threat (traffic) + Unintentional pilot action related to FPM (task management)

External (Non-pilot) Threats

- Traffic
- Wake – from previous departure

Pilot Factors

- Hand-flying
- Task management –cleaning up aircraft configuration; did not tell ATC they were handling wake turbulence
- Lack of flightpath awareness – unaware of lateral deviation at first

Outcome(s)

- Lateral deviation
- Loss of separation
- ATC vectors required

ACN 1967367

Where (When): Unknown TRACON on RNAV DP at 7000 ft (January 2023)

Reporter(s): Title 14 CFR Part 121 pilots, both crewmembers

What: This flight experienced severe turbulence near 7000 ft that caused it to climb 1700 ft, resulting in a 700 ft overshoot relative to the next crossing restriction (8000 ft or below) on an RNAV SID. Previous flight had reported moderate to severe turbulence between 3000 and 9000 ft.

Trigger(s): Unintentional pilot response to external threat (severe turbulence)

External (Non-pilot) Threats

- Severe turbulence

Pilot Factors

- n/a

Outcome(s)

- Vertical deviation
- Hand-flying required
- Checklist (QRH) for off-schedule descent required

ACN 1612427

Where (When): DCA Airport on an RNAV DP (January 2019)

Reporter(s): Title 14 CFR Part 121 Pilot (CA/PM)

What: CA was the PM, but PF was less experienced with the PBN DP at DCA. CA does not know how it happened but somehow they dropped out of lateral navigation mode and were in HDG mode with a strong crosswind pushing towards the restricted areas. Told ATC, who gave vectors in response.

Trigger(s): Complex IFP design + Unintentional aircraft problem (navigation mode change)

External (Non-pilot) Threat(s)

- Complex IFP design – prohibited areas
- Task management – checklist and frequency change
- Time pressure – short taxi and IFP close to prohibited areas
- Aircraft problem (unexpected behavior) – switched out of lateral navigation mode for unknown reason
- Crosswind

Pilot Factors

- Time-pressure related to FPM
- CRM

Outcome(s)

- Hand-flying required
- Lateral deviation
- ATC vectors required

ACN 2001258

Where (When): Las Vegas TRACON on RNAV DP at 11,700 ft (May 2023)

Reporter(s): Title 14 CFR Part 121 Pilot (FO)

What: Departed RWY 26R at LAS on the JOHKR RNAV DP. ATC informed pilot of a possible vertical deviation at KRUGR. ATC lowered the top altitude close to the constraint. Unclear whether the ATC amendment was related to the vertical deviation at KRUGR or just coincidental. Crew not aware of deviation until mentioned by ATC. They provide a theory as to how it happened, related to distractions from the checklist (engine setting) and possible wake turbulence.

Trigger(s): Unintentional pilot action related to FPM (task management) + Unintentional pilot response to external threat (ATC amendment)

External (Non-pilot) Threats

- ATC amendment – lowered the top altitude close to the constraint that was missed, but unclear if this was related to the deviation

Pilot Factors

- Task management – wake from preceding aircraft and aircraft checklist item related to engine setting
- CRM – crew coordination related to engine power setting

Outcome(s)

- Vertical deviation – missed altitude constraint

Records with both Intentional and Unintentional Deviations

ACN 1619807

Where (When): CLT Airport on an RNAV DP at 7000 ft (February 2019)

Reporter(s): Title 14 CFR Part 121 Pilot (CA/FM)

What: The crew noticed a TA while on the RNAV SID. They proactively reduced climb speed, but before they could reduce power, they exceeded 250 KTS (at 7000 ft). They report that the separation between an unspecified STAR and the BOBZY 4 RNAV SID (a current IFP) is too tight. Some of the details are unclear about the traffic aircraft.

Trigger(s): Intentional pilot response to external threat (traffic) + Unintentional Pilot action related to FPM (speed management)

External (Non-pilot) Threat(s)

- Traffic
- High-density terminal airspace design – STAR/SID crossover

Pilot Factors

- Hand-flying – led to speed deviation

Outcome(s)

- TCAS TA - possibly
- Airspeed exceedance – Exceeded 250 KTS below 10,000 ft

ACN 1681024

Where (When): Unknown Airport on RNAV DP at unknown altitude (September 2019)

Reporter(s): Title 14 CFR Part 135 Pilot

What: Seconds after departure, FMS Number 1 lost position. Advised ATC, requested vectors. FMS Number 2 was out of operation (but okay to fly based on the “minimum equipment list”) . Updated position for FMS #1 using a nearby VOR as a reference. Completed trip using FMS 1 with VOR backup. Received ATC vectors until FMS position was sorted out.

Trigger(s): Intentional pilot response to external threat (aircraft system malfunction) + Unintentional pilot action (lateral deviation while hand-flying)

External (Non-pilot) Threat

- Aircraft system malfunction – FMS 1 lost position reference with FMS 2 out of operation

Pilot Factors

- Hand-flying – turned too far

Outcome(s)

- ATC vectors required
- Lateral deviation

Records without Pilot Deviations

ACN 1617336

Where (When): Van Nuys (VNY) Apt (SoCal) on an RNAV DP at 1000 ft (February 2019)

Reporter(s): Title 14 CFR Part 135 Pilot (CA)

What: The pilot was surprised during the departure to suddenly notice that an altitude constraint based on DME was not programmed in the Garmin box. The pilots missed this during their dual route verification. Workload increased, but there was no official deviation. ATC was unhelpful.

Trigger(s): Complex IFP design + Unintentional pilot action related to FPM (failure to catch during route verification)

External (Non-pilot) Threat(s)

- Complex IFP design – prohibited areas
- Time pressure (shortened runway for takeoff)
- Aircraft problem (unexpected behavior) – unknown (constraint not in database)
- Weather (Instrument Meteorological Conditions,)
- Busy airport operations
- Closed runways/airport construction

Pilot Factors

- Time-pressure related to FPM

Outcome(s)

- Hand-flying required
- High workload

ACN 1619842

Where (When): CLE Airport on RNAV DP at 9000 ft (February 2019)

Reporter(s): Title 14 CFR Part 121 Pilot (CA/PF)

What: Departure controller modified the RNAV SID by clearing fight direct to a later waypoint. The controller then expected the flight to meet an altitude constraint at a waypoint earlier on the SID, which the aircraft had already passed. Controller and pilot disagreed on whether the altitude constraint was in effect.

Triggers(s): ATC amendment

External (Non-pilot) Threats

- ATC Amendment – originally a climb via, modified to direct to later waypoint

Pilot Factors

- CRM – FO was a bit behind; he/she confirmed they were cleared to climb via, and the CA quickly corrected to say that they were cleared direct

Outcome(s)

- Disagreement with controller and extra radio communications

ACN 1915613

Where (When): MIA TRACON on RNAV DP at 5000 ft (July 2022)

Reporter(s): ATC

What: Confusion related to climb via clearance for FOLLZ2 RNAV DP. There is a mandatory 5000 ft altitude constraint at MARCK, more than 30 miles out. Departure controller gave aircraft 'climb and maintain 16000', which deletes altitude restriction, but aircraft was still flying to meet the constraint. ATC held down the flight at 5000 ft for crossing traffic then recleared to 16000 ft. Crew asked whether to climb now or after MARCK; confusion between climb and maintain vs. climb via phraseology. Reporter says pilots always ask.

Trigger(s): ATC amendment (climb via clearance phraseology)

External (Non-pilot) Threats

- ATC amendment – Departure controller changed 'climb via' clearance given by clearance delivery on the ground to 'climb and maintain'

Pilot Factors

- No pilot report, however, it appears that pilots did not understand the revised clearance language.

Outcome(s)

- Extra communication to avoid a traffic conflict

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