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Pairwise Trajectory Management (PTM) Concept Description and Documentation

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Abstract

Pairwise Trajectory Management (PTM) is an Interval Management (IM) concept that utilizes airborne and ground-based capabilities to enable the implementation of airborne pairwise spacing capabilities in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage an “at or greater than” inter-aircraft spacing. Due to the accuracy of Automatic Dependent Surveillance-Broadcast (ADS-B) information and the use of airborne spacing guidance, the minimum PTM spacing distance will be less than distances a controller can support with current automation systems that support oceanic operations. Ground tools assist the controller in evaluating the traffic picture and determining appropriate PTM clearances to be issued. Avionics systems provide guidance information that allows the flight crew to conform to the PTM clearance issued by the controller. The combination of a reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace. This document provides an overview of the proposed application, a description of several key scenarios, a high level discussion of expected air and ground equipment and procedure changes, a description of a NASA human-machine interface (HMI) prototype for the flight crew that would support PTM operations, and initial benefits analysis results. Additionally, included as appendices, are the following documents: the PTM Operational Services and Environment Definition (OSED) document and a companion “Future Considerations for the Pairwise Trajectory Management (PTM) Concept: Potential Future Updates for the PTM OSED” paper, a detailed description of the PTM algorithm and PTM Limit Mach rules, initial PTM safety requirements and safety assessment documents, a detailed description of the design, development, and initial evaluations of the proposed flight crew HMI, an overview of the methodology and results of PTM pilot training requirements focus group and human-in-the-loop testing activities, and the PTM Pilot Guide.

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Symbols & Abbreviations

AC: Aircraft

ADS-B: Automatic Dependent Surveillance-Broadcast

ADS-C: Automatic Dependent Surveillance-Contract

ANSP: Air Navigation Service Provider

ASA: Aircraft Surveillance Applications

ASSAP: Airborne Surveillance and Separation Assurance Processing

ATC: Air Traffic Control

ATOP: Advanced Technology and Oceanic Procedures

ATS: Air Traffic Services

CDTI: Cockpit Display of Traffic Information

CEP: Central East Pacific

CPDLC: Controller-Pilot Data Link Communications

CGD: Configurable Graphics Display

DO: RTCA numbering convention

FAA: Federal Aviation Administration

FIM: Flight Deck Interval Management

FL: Flight Level

FMC: Flight Management Computer

FOV: Field-of-View

HF: High Frequency radio

HITL: Human-in-the-Loop

HMI: Human-Machine Interface

IM: Interval Managment

kts: knots

M: Mach

MAX: Maximum

MCP: Mode Control Panel

MFD: Multi-Function Display

MIN: Minimum

N: Number of observations

NASA: National Aeronautics and Space Administration

NM: Nautical Miles

OSED: Operational Services and Environment Description

PCD: Projected Closest Distance

PTM: Pairwise Trajectory Management

RNP: Required Navigation Performance

RTCA: formerly Radio Technical Commission for Aeronautics

SD: Standard Deviation

SLOP: Strategic Lateral Offset Procedure

Definitions

Add PTM Mach: Clearance from air traffic control (ATC) to increase the number of designated aircraft included in an ongoing Pairwise Trajectory Management (PTM) operation.

Automatic Dependent Surveillance – Broadcast (ADS-B): A means by which aircraft, aerodrome vehicles, and other objects can automatically transmit and/or receive data such as identification, position, and additional data, as appropriate, in a broadcast mode via a data link.

Automatic Dependent Surveillance – Contract (ADS-C): A means by which the terms of an ADS-C agreement will be exchanged between the ground system and the aircraft, via a data link, specifying under what conditions ADS-C reports would be initiated and what data would be contained in the reports.

Background aircraft: Any ADS-B Out aircraft, within ADS-B signal range, not serving as a pending or designated aircraft in an ownship aircraft's PTM operation.

Cancelled PTM: A mode within the airborne Flight Deck Interval Management (FIM) equipment that occurs when a Cancel PTM clearance is received.

Cleared PTM Mach: Clearance from ATC to initiate a PTM operation.

Cockpit Display of Traffic Information (CDTI): A pilot interface that includes, at a minimum, a graphical plan-view (top down) traffic display. The CDTI receives position information for traffic and ownship aircraft from an airborne surveillance and separation assurance processing (ASSAP) function, which receives such information from surveillance sensors and ownship aircraft position sensors.

Configurable Graphics Display (CGD): A flight deck display located in the primary field-of-view that can be used by multiple applications to convey information necessary for performing the current operation. During PTM operations, the CGD will be used to display PTM Guidance, notifications, and alerts.

Continue PTM: Clearance from ATC requiring the PTM equipped aircraft to maintain a PTM operation with a specific designated aircraft.

Controller-Pilot Data Link Communication: A means of communication between controller and pilot, using data link for ATC communications.

Designated aircraft: An aircraft with which the PTM equipped aircraft must get no closer than a set distance during a PTM operation. (Note: In earlier PTM research efforts and documentation, designated aircraft were referred to as engaged aircraft.)

Engaged PTM: A mode within the airborne FIM equipment that occurs when a PTM clearance has been accepted by the flight crew and PTM is being actively performed with one or more designated aircraft.

FIM equipment: The avionics on board the PTM equipped aircraft that supports FIM applications. This includes the hardware, software, and displays necessary to perform PTM operations. The term "FIM equipment" does not imply any specific avionics architecture.

Ground automation system: Computer automation that assists the controller by providing a means for communication, separation, and decision support.

Limit Mach: The limit Mach is calculated for each PTM operation and is sent to each PTM aircraft that enters a specific PTM operation. This is a Mach number that the PTM aircraft may be required to fly at some point during the PTM operation.

No PTM: A mode within the airborne FIM equipment that occurs when there are no active or pending PTM operations.

Non-PTM aircraft: An aircraft that has not been cleared to conduct a PTM operation. A non-PTM aircraft may serve as a designated aircraft.

Non-PTM separation: Separation applied by ATC for a given airspace and aircraft equipage level. For example, 50 NM longitudinal and lateral separations can be applied with ADS-C reporting in intervals of 27 minutes and Required Navigation Performance 10 (RNP10) aircraft. Non-PTM separation specifically refers to a separation standard that is not associated with PTM separation.

Pending aircraft: An aircraft that has been included in a PTM clearance being reviewed by the flight crew. If the clearance is accepted, this aircraft will become a designated aircraft. If the clearance is rejected, this aircraft will become a background aircraft.

Pending PTM: A mode within the airborne FIM equipment that occurs when a PTM clearance has been received, but the flight crew has not yet engaged the FIM equipment and begun conducting the PTM operation with the aircraft included in the clearance.

Pending PTM guidance: During a Pending PTM mode, this guidance information provides the flight crew with a preview of what the PTM Guidance will be if the PTM clearance is accepted.

Procedural control: Term used to indicate that information derived from an air traffic services surveillance system is not required for the provision of air traffic control service.

Procedural separation: The separation used when providing procedural control.

PTM Chain: A sequence of aircraft following the rules stated in the PTM Chain rules (see Appendix A).

PTM equipped aircraft: An aircraft that has FIM equipment installed on-board.

PTM geometry types:

Ahead of: PTM clearance geometry in which the PTM equipped aircraft is physically located in front (ahead) of a designated aircraft.

Behind: PTM clearance geometry in which the PTM equipped aircraft is physically located behind a designated aircraft.

Crossing: PTM clearance geometry in which the PTM equipped aircraft and designated aircraft are not located in-trail of each other and their routes will intersect.

Merge ahead of: PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located in front (ahead) of the designated aircraft once both aircraft are on the same track.

Merge behind: PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located behind the designated aircraft once both aircraft are on the same track.

PTM Pair: A pair of aircraft where one aircraft is a designated non-PTM aircraft and one aircraft is a PTM aircraft with a clearance to get no closer than a set distance from the designated aircraft.

PTM Mach guidance: A series of Mach commands and restrictions provided by the FIM equipment to ensure that PTM operations are maintained.

PTM separation standard: A procedure that, when applied, allows for PTM operations to be conducted while ensuring the required PTM separation standard distance.

PTM separation standard distance: A horizontal distance (currently proposed to be 5 NM) that aircraft get no closer than during a PTM operation. The horizontal distance between a PTM equipped aircraft and a designated aircraft shall never be less than the PTM separation standard distance while a PTM operation is in effect.

PTM spacing distance: A distance comprising the PTM separation standard distance plus a distance buffer. The FIM equipment provides Mach guidance to the flight crew to ensure the PTM spacing distance is maintained.

PTM String: A sequence of aircraft following the rules stated in the PTM String rules (see Appendix A).

Remove PTM: Clearance from ATC to stop performing PTM on a specific designated aircraft.

Separation standard: A procedure that ATC applies to aircraft traffic to ensure required separation between aircraft. When ATC is applying a separation standard, the distance between aircraft shall never be less than the separation standard distance.

Separation standard distance: A minimum distance that shall never be infringed upon during aircraft operations.

Sequence: An ordered series of aircraft operating on a common track.

Side mounted display: A flight deck display that can be located outside of the flight crew's forward field-of-view and is used for information that is not required to operate the aircraft. A CDTI can be hosted on a side mounted display. During PTM operations, this equipment will be used for situation awareness and to review, engage, and acknowledge cancelation of all PTM operations.

Introduction

Interval Management (IM) is a set of capabilities designed to support a range of IM operations and concepts whose goal is precise inter-aircraft spacing. IM is defined as the overall system, including both ground and airborne domains that enables improved management of traffic flows, aircraft spacing, and separation assurance. This includes both the use of ground and airborne tools, where ground tools assist the controller in evaluating the traffic picture and determining appropriate clearances to space aircraft efficiently and safely, and airborne tools that allow the flight crew to conform to the clearance.

Pairwise Trajectory Management (PTM) is an IM concept that utilizes airborne and ground-based tools to enable airborne inter-aircraft spacing in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage “at or greater than” inter-aircraft spacing. Due to the Automatic Dependent Surveillance-Broadcast (ADS-B) information and the use of airborne spacing guidance, the minimum PTM spacing distance will be less than distances a controller can support with current communication and automation systems that support oceanic operations. Ground tools assist the controller in evaluating the traffic picture and determining appropriate PTM clearances to be issued. Avionics systems provide guidance information that allows the flight crew to conform to the PTM clearance issued by the controller. The combination of a reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace.

PTM was designed to improve operations that can occur in a variety of oceanic environments and situations. These oceanic regions are characterized by reduced surveillance and limited communication capabilities. In such airspace, air traffic is managed procedurally with reliance on specified navigation performance, periodic position reports to the ground, and separation standards that are larger than commonly applied in domestic airspace. These airspace regions also involve a variety of route structures including fixed routes, organized track system routes, and user preferred routes. This document describes a number of generic PTM operations and scenarios. These scenarios were used to explore the operational requirements needed to support PTM operations.

NASA has been developing the PTM concept for a number of years (ref. 1). This paper provides an updated overview of the proposed application, a description of key scenarios, a high-level discussion of expected air and ground equipment and procedure changes, a description of a NASA human-machine interface (HMI) prototype for the flight crew that would support PTM operations, and initial benefits analysis results. A detailed description of the PTM concept is provided in the form of an Operational Services and Environment Definition (OSED) document in Appendix A, and a companion “Future Considerations for the Pairwise Trajectory Management (PTM) Concept: Potential Future Updates for the PTM OSED” paper is provided in Appendix B. Furthermore, a detailed description of the PTM algorithm and related PTM Limit Mach rules, initial PTM safety requirements and safety assessment documents, a detailed description of the design, development, and initial evaluations of the proposed flight crew HMI, an overview of the methodology and results of PTM pilot training requirements focus group and human-in-the-loop (HITL) testing activities, and the PTM Pilot Guide are included in Appendices C through L.

Application Description

It is anticipated that there will be continued growth in oceanic air traffic. Even with recent improvements to oceanic surveillance and communications systems, required separation standards in oceanic airspace are still large enough to cause aircraft operational inefficiencies. These inefficiencies include operating at other than their desired altitude, routes, and speeds for extended periods of time, flights being unable to operate on their desired routes, and flights required to change altitudes for crossing traffic. These system inefficiencies increase flight time and fuel burn.

PTM is designed to enable operations that are not possible with current non-PTM separation standards. These operations will be enabled by more efficient spacing assignments issued by controllers and managed by aircraft. The controller, using ground-based decision support automation, issues a pair-specific PTM clearance to a PTM-equipped aircraft. When accepted, this clearance will allow the PTM aircraft to operate on the same flight level (FL) and track of the designated aircraft (the paired aircraft), or to cross the track of the designated aircraft with reduced spacing as compared to current non-PTM separation standard minimums. The PTM clearance requires the flight crew of the PTM aircraft to use their ADS-B-enabled on-board Flight Deck Interval Management (FIM) equipment to manage their spacing relative to the designated aircraft.[1] The FIM equipment will provide Mach guidance to ensure that the inter-aircraft spacing is no closer than the PTM spacing distance during the PTM operation. When the controller assesses (with ground automation system support) that a non-PTM separation standard has been achieved and the PTM operation is no longer required, the controller may terminate the PTM operation. The controller is not required to terminate the PTM operation as soon as non-PTM separation standards are available and may allow the PTM operation to continue for operational reasons.

PTM will support same track operations (typically found in oceanic organized track systems) and intersecting track operations (typically found with oceanic user preferred routes). Due to the reduced PTM spacing distance minimum, the PTM aircraft may not be required to modify its current speed in many intersecting track situations. PTM should save fuel and reduce delays by improving operations that increase time on an aircraft's optimal trajectory (track, speed and altitude). The airborne managed distance can allow for higher throughput and generally more efficient aircraft operations.

PTM may be employed, depending on local constraints and traffic characteristics, to support several different types of operations. For example, a PTM clearance could be used to resolve a short-term conflict (e.g., one aircraft climbing through the altitude of another) or could be used for an extended period of time (same track, same altitude).

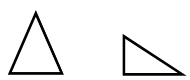
The availability of a PTM resolution to a conflict does not necessarily make it the preferred option for the controller. PTM is not intended to take away the controller's discretion in managing the traffic in their sector. PTM is simply an additional tool for the controller to use as needed or desired.

There are also times when PTM is not an available option for the controller. One example of this is when the two aircraft are out of ADS-B range from each other (since the PTM aircraft must be receiving the ADS-B signal of the designated aircraft to accept

[1] The term "FIM equipment" in this document is used to refer to any avionics on board the PTM aircraft that supports the PTM application.

the clearance and manage spacing). Additionally, other operational conditions may cause the flight crew to refuse the PTM clearance. This could include situations when PTM operations would require the flight crew to fly a speed that is faster or slower than the aircraft can maintain. In addition, certain traffic encounter geometries may prevent the availability of PTM to be used by either the controller or the flight crew (e.g., head on traffic encounter geometries).

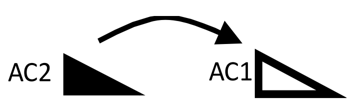
The following sections include descriptions of two typical PTM scenarios that illustrate details of the PTM concept. For all graphic depictions in this document, the following applies for planform and profile views of aircraft:


These symbols are directional, and the color indicates background aircraft.


These symbols are directional, and the bold border indicates designated aircraft.


These symbols are directional, and the color indicates PTM aircraft.


These symbols are directional, and the color indicates the aircraft are PTM aircraft as well as serving as a designated aircraft for another PTM aircraft.



These symbols indicate aircraft 2 (AC2) is a PTM aircraft and aircraft 1 (AC1) is the designated aircraft for the PTM operation that AC2 is conducting.

Same-Track, Altitude Change Scenario

Figure 1 is a profile view representation of two aircraft (AC1 and AC2) operating at different altitudes on an identical track with a distance between them of 9 nautical miles (NM). In this scenario, the flight crew of AC2 has requested, for operational reasons, an altitude change from FL330 to FL340. Using non-PTM separation standard distances, the requested climb would be denied due to traffic (i.e., AC1) at FL340. However, because AC2 has indicated in its flight plan that it is PTM equipped, the ground automation system would indicate the possibility of issuing a PTM clearance to AC2, which if accepted, would allow the controller to subsequently issue a climb clearance.

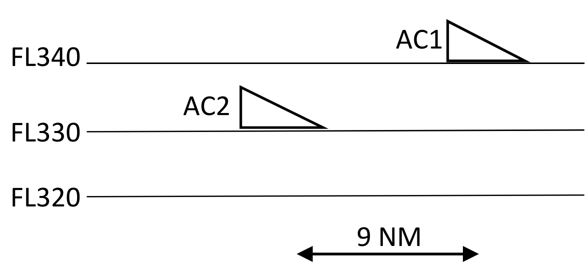


Figure 1. Same-track, altitude change scenario, time 1.

If PTM is acceptable from a controller's perspective, the controller would issue a PTM clearance to AC2 instructing it to conduct PTM on AC1. Once the clearance is received by AC2 (the PTM aircraft), the PTM clearance information would be loaded into the FIM equipment. The FIM equipment would check the acceptability of the PTM clearance and display PTM Mach guidance the flight crew would be expected to follow should they accept the clearance. The flight crew would review the pending PTM Mach guidance (presented on the flight crew's HMI as "Pending PTM Guidance" in the form of either a single Mach value or a range of Mach values, as described in subsequent sections of this document) to determine if the pending Mach guidance would be operationally acceptable. The flight crew would also review other information that could influence their decision to accept or reject the PTM clearance. This would include assessing potential future speed restrictions based on the current speeds of the designated aircraft (e.g., the eventual speed the PTM aircraft may be required to fly due to the speed of the designated aircraft). Other information that could influence the flight crew's decision would include aircraft performance, weather conditions, available ride information, and general traffic situation awareness.

If the proposed Mach guidance (referred to as "Pending PTM Guidance") and clearance are acceptable, the flight crew would engage the FIM equipment and accept the clearance. With the PTM operation engaged, a single Mach value or a range of Mach values is continuously displayed by the FIM equipment to the flight crew. If, instead, the pending Mach guidance or situation is unacceptable, the flight crew clears the pending PTM guidance in the FIM equipment, rejects the clearance with air traffic control (ATC), and continues normal operations.

Once the controller has received confirmation that the PTM clearance has been accepted, the controller would then clear AC2 to climb to and maintain FL340. The PTM aircraft would then start a normal climb to FL340. The flight crew would follow the Mach guidance provided by the FIM equipment until the PTM operation is terminated by the controller. Figure 2 below is an illustration of the situation once the climb to FL340 has been completed.

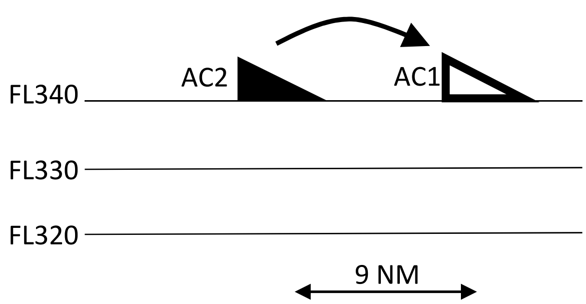


Figure 2. Same-track, altitude change scenario, time 2.

Messages have been developed for PTM and are included in recently published versions of RTCA documents DO-350, DO-351 and DO-352 (refs. 2, 3, and 4). These documents contain the standards that have been adopted for Baseline 2 Air Traffic Services (ATS) Data Communications.

The combination of messages used to support PTM operations is called a message queue. The message queue consists of a list of Controller-Pilot Data Link Communications (CPDLC) messages showing the destination, the sender, and the message. The CPDLC application allows addressed communications (i.e., only the intended aircraft receives the message) between the ground controller and the flight crew, to provide air traffic services.

Due to the complexity and importance of the structure of these messages, it is anticipated that the logic for generating these message queues would be built into ground automation systems used to support PTM operations.

A sample of communications for this scenario is listed below. The format of these messages includes the recipient of the message (the destination) and who is sending the message (sender).

> Message Queue [Destination, Sender]
> [ATC, AC2] REQUEST CLIMB TO FL340
> [AC1, ATC] MAINTAIN MACH 0.83
> [ATC, AC1] WILCO
> [AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.83
> [ATC, AC2] WILCO
> [AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
> [ATC, AC2] WILCO
> [ATC, AC2] LEVEL FL340

Intersecting Track Scenario

There will be cases where PTM will be used to support intersecting track situations. For the intersecting track situation shown in Figure 3, AC2 and AC1 are moving towards a loss of separation situation in an oceanic environment with a 30 NM minimum separation distance. The aircraft are both at FL310 and Mach 0.80. Without PTM, the controller would need to instruct one of the two aircraft to change its altitude or speed. However, because AC2 has indicated that it is PTM equipped in its flight plan, the ground automation system would indicate the possibility of issuing a PTM clearance for the controller. The controller can use a PTM clearance to resolve the conflict. If PTM is acceptable from the controller's perspective, the controller would issue a clearance to AC2 instructing it to conduct PTM on AC1.

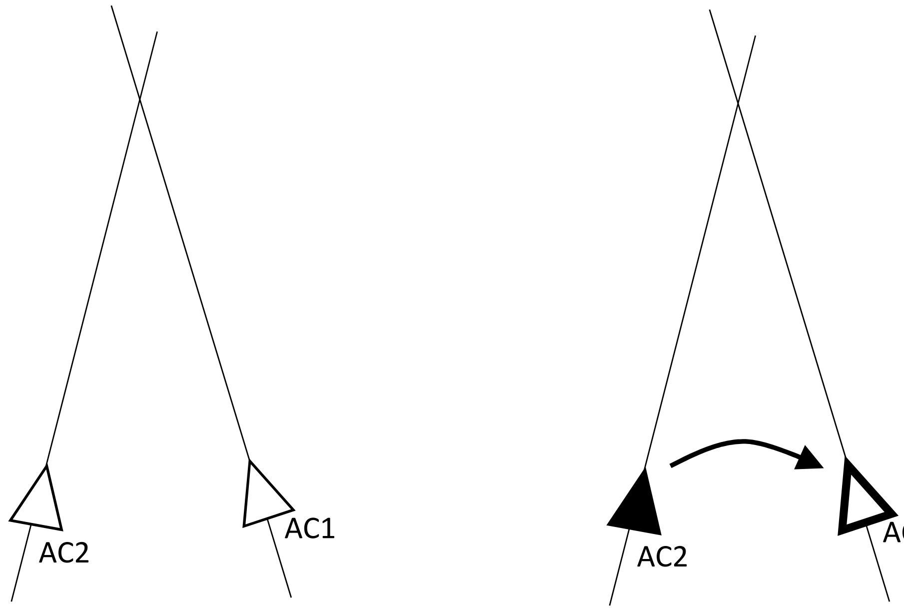


Figure 3. Intersecting tracks scenario prior to (on the left) and after (on the right) PTM is engaged.

When the PTM clearance is received by AC2, the PTM clearance information would be loaded into the FIM equipment. The acceptability of the PTM clearance would be checked against associated criteria required for PTM operations. The FIM equipment uses data received from AC1 and the ground automation system to predict the time, location, and distance at the closest point of approach. The system displays Mach guidance to the flight crew that would ensure the required spacing between the PTM aircraft and the designated aircraft is satisfied during the PTM operation.

As before, the flight crew would review the pending PTM Mach guidance (i.e., "Pending PTM Guidance" shown as either a single Mach value or a range of Mach values) to determine if the pending Mach guidance would be operationally acceptable. The flight crew would also review other information that could influence their decision to accept or reject the PTM clearance. This would include assessing potential future speed restrictions (e.g., the eventual speed the PTM aircraft may be required to fly due to the speed of the other aircraft) based on the current speed of the designated aircraft. Other information that could influence the flight crew's decision would include aircraft performance, weather conditions, available ride information, and general traffic situation awareness.

If the pending Mach guidance was acceptable, the flight crew would engage the FIM equipment and accept the clearance. It is likely that, while the aircraft will pass too close for a non-PTM separation standard, the aircraft will be significantly farther apart than required for the PTM separation standard. The flight crew follows the Mach guidance provided by the FIM equipment throughout PTM operations. Once the aircraft have passed the closest point of approach and the controller determines that a non-PTM separation standard has been achieved (e.g., 30 NM), the controller may terminate the PTM procedure.

A sample of the messages used for this scenario is listed below.

Message Queue [Destination, Sender]
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH CROSSING AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC2, ATC] CANCEL PTM, RESUME NORMAL MACH
[ATC, AC2] WILCO

Assumptions and Constraints

There are several key assumptions and constraints associated with PTM operations. These are outlined below.

PTM Separation Standard and PTM Spacing Distance

A key component of PTM is a reduced minimum distance, referred to as the PTM separation standard distance, enabled by active ADS-B In monitoring and real-time, closed-loop interval management control. The PTM separation standard distance is a horizontal distance between aircraft that the PTM aircraft must not get closer than during PTM operations. PTM aircraft can be at distances that are greater than this PTM spacing distance, but the horizontal distance between a PTM aircraft and all designated aircraft must never be less than the PTM separation standard distance while a PTM operation is in effect. The PTM separation standard distance is a horizontal distance and is applicable in along-track as well as intersecting track operations. This PTM separation standard distance will be determined by safety and performance analyses. Initial analyses, documented in Appendices C through G, indicate that the PTM separation standard distance could be set at 5 NM.

The PTM spacing distance is the PTM separation standard distance plus a buffer. The size of the buffer is operation specific. The proposed buffer is 1.5 NM for along-track operations and 3.5 NM for intersecting track operations. This results in a total PTM spacing distance of 6.5 or 8.5 NM. The intent of this buffer is not to imply precise management of the PTM spacing distance or to drive the PTM aircraft to a specific spacing objective, but to ensure that the PTM separation standard distance is not violated for wide-ranging operational behaviors and situations. As with the PTM separation standard distance, the final magnitude of these values will be determined through the conduct of additional safety and performance analyses.

Along-Track PTM Spacing Distance

When aircraft are on the same track, a spacing buffer must be applied to ensure that aircraft do not get closer than the PTM separation standard distance during normal operations. One typical scenario that demonstrates the importance of this buffer is when two aircraft are on the same route and the route includes a turn at a waypoint. In situations such as these, the along-track distance will remain the same but the absolute range will be reduced below the along-track range.

This is shown in Figure 4 where the PTM separation standard distance is assumed to be 5 NM and the PTM spacing distance is 6.5 NM (i.e., a 1.5 NM buffer). Prior to the turn at the waypoint, both aircraft have an absolute range and along-track range of 6.5 NM. Once the aircraft are on opposite sides of the turn, the absolute range will be less than 6.5 NM but the along-track range will remain at 6.5 NM.

The extent of this buffer affects the acceptable geometries for feasible PTM operations, generally limiting turn angles to no greater than 45 degrees.

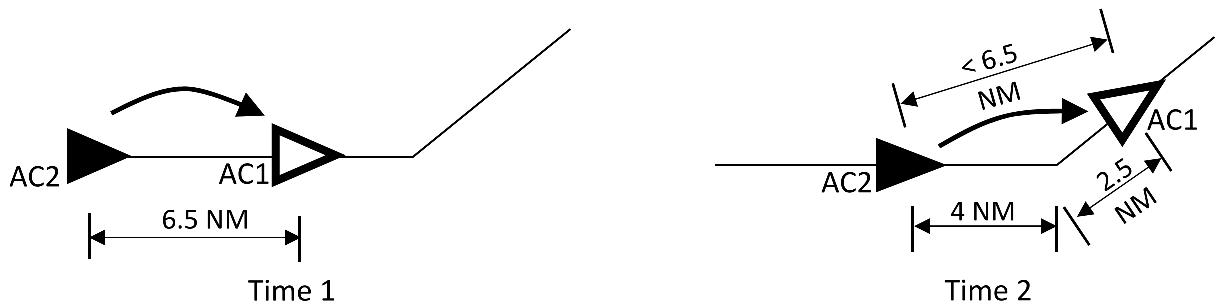


Figure 4. Along-track PTM spacing distance.

Intersecting Track PTM Spacing Distance

Similar to the along-track scenario, the specific geometry of the operation must be considered when determining the PTM spacing distance needed to ensure the 5 NM PTM separation standard distance is not violated. The same nominal buffer of 1.5 NM would apply to these geometries as well. However, the intersecting track case requires an additional buffer to account for the possibility of aircraft performing a Strategic Lateral Offset Procedure (SLOP). A lateral offset of up to 2 NM to the right can be performed by aircraft in oceanic operations, at any time, without clearance or notification to ATC. Aircraft that are performing SLOP can also return to centerline without clearance or notification. The possible SLOP combinations could lead to an error in the position of the assumed intersection point as depicted in Figure 5.

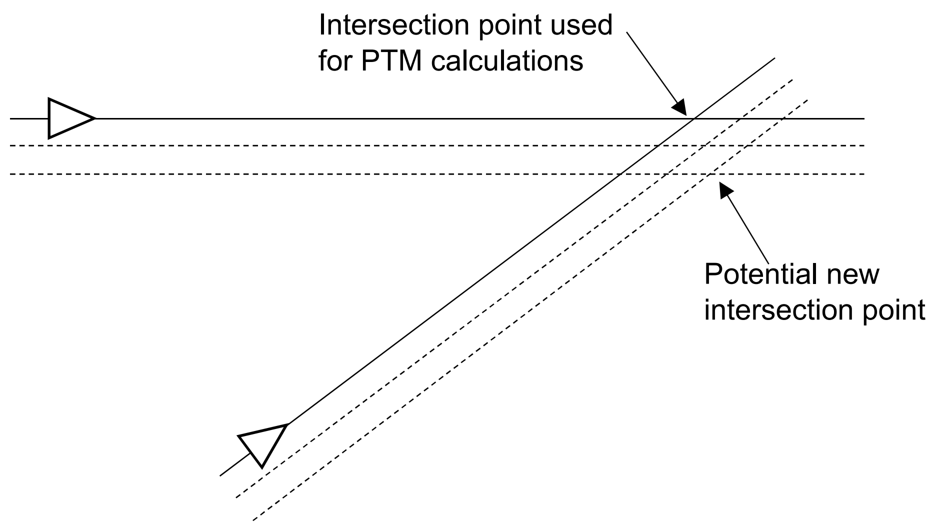


Figure 5. Intersecting track PTM spacing distance considerations.

This error is accounted for by an additional 2 NM buffer bringing the total buffer to 3.5 NM and the total PTM spacing distance to 8.5 NM. It should be noted that the effect of SLOP in same-track operations is accounted for in the original 1.5 NM buffer, but the potential difference in path length from SLOP combinations is much smaller. Similar to the along-track scenario, the acceptability of this 8.5 NM PTM spacing distance is predicated on assumed geometries, such as intersection angles of no greater than 45 degrees.

Importantly, since ensuring this PTM separation is the operational intent, the PTM spacing distance is assessed as a horizontal range between the aircraft at an estimated point of closest approach.

PTM Operations during Altitude Change Maneuvers

There are scenarios (as demonstrated in the “Same-Track, Altitude Change Scenario” section above) where PTM is used to enable altitude change maneuvers. These include situations where an aircraft desires a change to the same altitude of another aircraft or where an aircraft is flying “through” the altitude of another aircraft.

The first step in this procedure is to establish PTM operations with the designated aircraft. This is to ensure that during altitude change maneuvers, there is valid longitudinal and lateral separation between the PTM aircraft and the designated aircraft before vertical separation is lost and throughout the ensuing PTM operation. Once PTM is established, the altitude change clearance can be issued.

It is important to point out that with PTM, FIM equipment will provide PTM Mach guidance to manage spacing with designated aircraft, even if those aircraft are at different altitudes. This is because the PTM separation standard is a longitudinal and lateral separation standard and takes no “credit” for vertical separation.

In the illustration below (Figure 6), for an aircraft climbing, PTM is first established between AC2 and AC1. Once engaged, the FIM equipment will provide PTM Mach guidance that will enable AC2 to manage spacing with AC1 even while AC2 remains at the original altitude. Once the controller has received a reply from the flight crew that PTM has been established between AC2 and AC1, AC2 is cleared to climb. AC2 then climbs to the desired altitude and continues to follow the PTM Mach guidance.

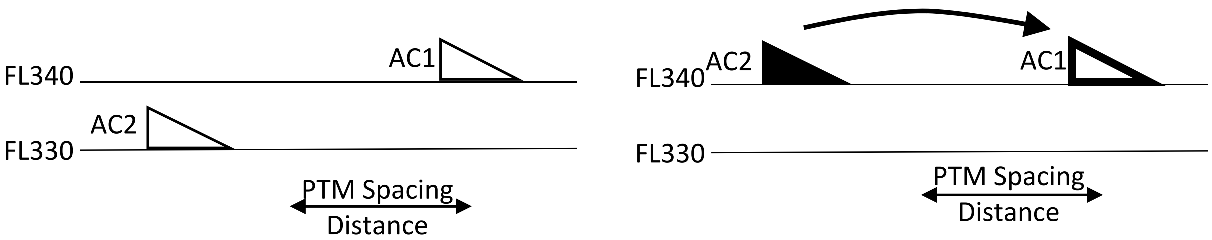


Figure 6. PTM operations during altitude change maneuvers.

Multiple PTM Operations within a non-PTM Separation Distance

When there are multiple aircraft performing PTM in a sequence within a non-PTM separation standard distance, some special rules apply. In this case, PTM must be conducted on all aircraft that are within the non-PTM separation standard distance. This ensures there is an appropriate separation standard being used between all pairs of aircraft.

In Figure 7, PTM aircraft AC2 is conducting PTM on designated aircraft AC1. PTM aircraft AC3 is conducting PTM operations on AC2 (in the direction of the designated aircraft AC1). However, because AC3 and AC1 are within the minimum non-PTM separation standard distance, AC3 must also conduct PTM on the designated aircraft AC1. Without this addition, there is no applicable separation between AC3 and AC1.

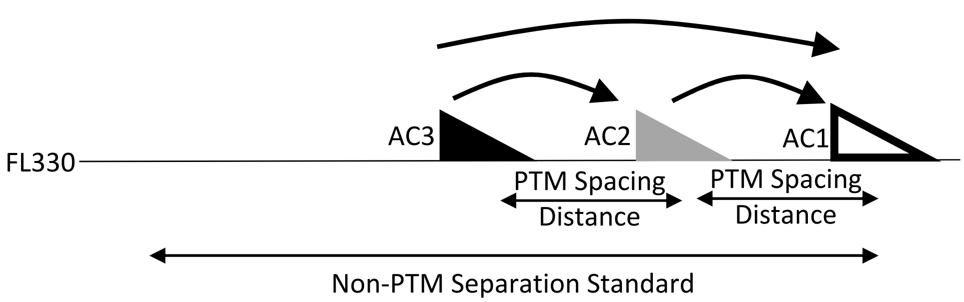


Figure 7. Multiple PTM operations within a non-PTM separation distance.

"Separation by Order"

It has been recommended that the concept for the PTM separation standard be revised to include the concept of "separation by order." Currently, the proposed PTM separation standard does not account for the fact that aircraft AC2 is between AC3 and AC1. Rather than require AC3 to conduct PTM on AC1, the revised PTM separation standard would only require AC3 to conduct PTM on AC2. AC3 would be separated from AC1 by virtue of the fact that AC2 is between the two aircraft and that AC3 would get too close to AC2 before it would get too close to AC1; essentially taking advantage of the order of the aircraft.

If this revision to the proposed PTM separation standard was adopted, PTM aircraft would only need to conduct PTM operations on aircraft that are closest to them (as depicted in Figure 8). This would simplify PTM operations, the flight crew's HMI, and the PTM message queues.

Prior to adopting this simplification, a thorough, updated safety analysis must be performed. One advantage of the current approach is that if AC2 has a problem and must suddenly exit out of the String (e.g., if AC2 has an engine failure), there is already a PTM operation in place between AC3 and AC1. With the revised concept, if AC2 leaves a String, a PTM operation would have to be initiated between AC3 and AC1. Due to the relatively small speed differences (low closure rates) between aircraft operating in oceanic airspace regions, there should be sufficient time to apply PTM to these aircraft before they get closer to each other than the minimum PTM spacing distance.

"Separation by Order" is not assumed for the purposes of this paper.

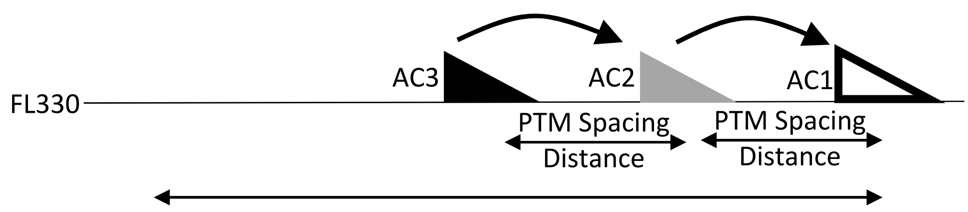


Figure 8. PTM operations including the separation by order revision to the PTM separation standard.

PTM Algorithm

A PTM algorithm, described in detail in Appendix H, has been developed to provide part of the airborne functionality needed to perform PTM operations. There is a top-level module named the executive module. The executive module receives PTM clearances from ATC and, using the PTM operations criteria and other information, advises the flight crew as to whether the PTM clearance should be accepted or rejected. If the flight crew accepts the PTM clearance, the executive module is invoked continuously to provide Mach guidance to the flight crew to ensure appropriate spacing from the designated aircraft. The executive module also receives clearances to add designated aircraft to an existing PTM operation and to terminate PTM operations with existing designated aircraft.

Other modules and functions that comprise the airborne PTM algorithm include the Along-Track module, the Intent Speed Resolution module, and the Alert function. The Along-Track Module calculates the Mach guidance using a state projection of the ownship and designated aircraft. The Intent Speed Resolution module calculates a Mach guidance using the current location, the next waypoints, the next-plus-one waypoints, and the estimated time of arrivals to the waypoints of the ownship and designated aircraft. The alert function produces predicted, imminent, and actual loss of spacing alerts. The executive module selects between the Along-Track and Intent Speed Resolution modules to produce the Mach guidance. Selection is determined by the type of clearance, geometry, waypoint locations, and other criteria.

Calculation of along-track PTM Mach guidance

The along-track algorithm generates Mach guidance that, if followed, will ensure that the inter-aircraft spacing is no closer than the PTM spacing distance during the PTM operation. The objective of the algorithm is for the PTM aircraft to manage spacing from the designated aircraft in a safe and efficient manner.

The spacing is the sum of a separation standard minimum distance and buffer distance. The algorithm provides Mach guidance to achieve the spacing. If the along-track distance is greater than the spacing, the algorithm could give Mach guidance such that the along-track distance can be reduced. When the along-track distance is at or near the spacing, the algorithm will give Mach guidance to maintain the spacing.

An overview of how this works is provided in the following example. In Figure 9, AC1 is a designated aircraft for PTM aircraft AC2. AC1 is flying at a Mach of M=0.80. AC2 is flying at M=0.75 and, for operational reasons, AC2 can fly no slower than M=0.75. AC2 is currently 25 NM away from AC1. Since AC2 is behind AC1, the along-track algorithm will calculate an upper bound of the Mach guidance that AC2 can fly.

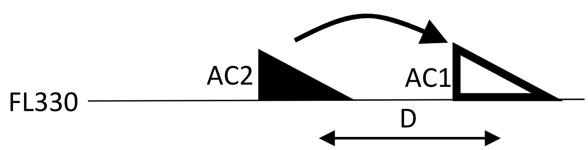


Figure 9. Closing PTM aircraft behind a designated aircraft.

For this situation, the along-track algorithm will provide an upper bound of the Mach guidance of M=0.86. At this distance, the flight crew would be provided a PTM Mach guidance range of M=0.75 (the lower bound) to M=0.86 (the current algorithm calculated upper bound). As a result, if the flight crew chose to fly at the upper bound of M=0.86, AC2 would close to a distance of 6.5 NM with AC1 in 30 minutes. However, as AC2 gets closer to AC1, the Mach guidance will change, and the upper bound of the Mach guidance will be less than M=0.86.

The Mach guidance will be updated as the operation continues. This is done in increments of M=0.01. At each update, the upper bound of the Mach guidance will ensure that it would take at least 30 minutes to close the distance to 6.5 NM. However, once the PTM Mach guidance is within M=0.01 of the designated aircraft's Mach (in this case M=0.80), the upper bound of the Mach guidance would stay M=0.01 above the designated aircraft Mach until the two aircraft are within 6.5 NM (with hysteresis effects built into the logic to minimize short-term fluctuations in the Mach guidance). Table 1 contains sample Mach guidance that could be provided to the flight crew for various distances between the two aircraft.

Table 1. Changes to Mach guidance based on distance to designated aircraft.

Distance	25 NM	7 NM	6.5 NM
Upper bound of the Mach guidance	M=0.86	M=0.81	M=0.80
Lower bound of the Mach guidance	M=0.75	M=0.75	M=0.75

Flight crew input of operating Mach number range

The default maximum and minimum possible values of Mach numbers provided to flight crews during operations would be set based on the maximum and minimum possible values the aircraft is capable of flying. During focus group sessions and preliminary HITL testing activities conducted by researchers at NASA Langley Research Center (described in Appendices I and J), flight crews expressed a desire to have a method to input the operating Mach range they are able and/or willing to fly at a given time. The PTM algorithm is designed in such a way that it would permit the flight crew to enter minimum and maximum possible values at any time during the flight. If the flight crew is currently conducting PTM operations, the current PTM Mach guidance provided by the PTM algorithm will be contained within the minimum and maximum bounds set by the flight crew.

ADS-B Signal Range Impact on PTM Operations

For oceanic operations, there are widely varying separation standards applicable for the controller to use with a specific aircraft pair. These typically vary from as small as 30 NM to as large as approximately 120 NM (based on a 15-minute separation standard) between the aircraft. It should be noted that there is other work being done to further reduce these standards, and these should be considered as they are approved (ref. 5). During normal operations, most ground automation systems report projected losses of separation (traffic conflicts) and often display which separation standards may be available to the controller to solve the traffic conflict. If the ground automation system reports that the conflict is with a PTM aircraft and a suitable designated aircraft, PTM would be one of the potential options listed as being available to the controller.

It is possible that at the time the conflict is first reported by the ground system, the onboard FIM equipment may not be receiving a signal from the designated aircraft identified due to ADS-B signal range limitations. Typically, ADS-B signals are received up to an average of 180 NM away. If the two aircraft are at a distance that is greater than a nominal ADS-B signal range at the time the PTM clearance was issued, it is likely that the flight crew would not be able to identify the designated aircraft and it would be necessary for the flight crew to refuse the clearance.

To maximize acceptance of PTM clearances, the controller should wait until the ground automation system computes that the two aircraft are close enough to each other (within an expected ADS-B range) so that there is a high probability that the FIM equipment will be able to identify the designated aircraft and enable acceptance of the PTM clearance. This expected ADS-B range could be an air navigation service provider (ANSP) facility configurable parameter that could be adjusted as experience with ADS-B signal range is obtained.

Another aspect of operations that would go into this decision-making process is the time or distance prior to a predicted loss of separation when the controller needs to issue a clearance. This is often determined either by local policy and/or controller comfort levels. For example, in most US managed oceanic airspace, controllers are notified by ground automation of a conflict two hours prior to the loss of separation and should be in the process of resolving the conflict at least 30 minutes prior to the predicted loss of separation.

As a result, the nominal ADS-B range (approximately 180 NM) and time prior to loss of separation that traffic conflicts are resolved impact the use of PTM operations. This is particularly true for intersecting track geometries.

If a controller has a conflict with two aircraft with a 30 NM separation standard, and the controller wants to issue a clearance 40 minutes prior to the predicted loss of separation in an environment with a 180 NM expected ADS-B range, the crossing angle for PTM would be limited to approximately 30 degrees. This is illustrated in the following example.

In Figure 10, the two aircraft are about 40 minutes away from a loss of separation (both flying at M=0.80). With a 30-degree crossing angle, the range of the two aircraft would be approximately 170 NM 40 minutes prior to the loss of separation.

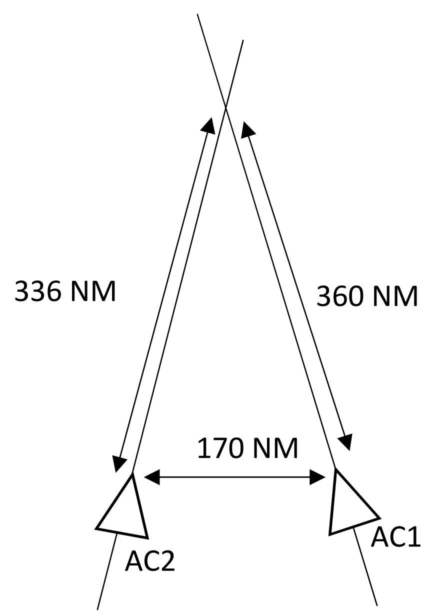


Figure 10. Impact of ADS-B range on intersection track operations.

In this example, it is assumed that the current minimum separation available with the ATC automation system is 30 NM. The ground automation will report a traffic conflict between these two aircraft. The controller will review the situation to determine the best resolution to the conflict, including whether PTM is a suitable solution. An important part of that decision will be determining when it will be possible to issue the PTM clearance. The ATC automation system will indicate whether PTM is available now or at some later time. With a 30-degree crossing geometry, the earliest time to issue a PTM clearance would be approximately 40 minutes prior to the predicted loss of separation. The controller could then issue a PTM clearance.

If the aircraft are currently further away from the predicted loss of separation (e.g., 60 minutes from the predicted loss of separation), the ground system would indicate to the controller that PTM is not available at that moment but will be available in 20 minutes. The controller would then have the freedom to either wait for 20 minutes before issuing the clearance or decide to use a different approach for resolving the traffic conflict (e.g., issue a flight level change to one of the aircraft if that was available).

Aircraft Sequence Geometries

PTM operations can involve a number of different geometric orientations. These are based on the number of PTM aircraft and designated aircraft. The most basic PTM geometry involves two aircraft, a PTM aircraft and one designated aircraft. These two aircraft together form a PTM Pair.

When there are more than two PTM aircraft in a sequence and only one designated aircraft at either end of the sequence, these aircraft form a PTM String. Finally, if there are two designated aircraft at either end of a sequence with one or more PTM aircraft between them, that situation is called a PTM Chain. A more detailed description of these geometries is contained below.

PTM Pairs – single target geometries

A PTM Pair, shown in Figure 11, is formed when:

- There are two aircraft in a sequence.
- The separation standard between the two aircraft is PTM separation.
- There is one PTM aircraft and one designated aircraft.

Figure 11. PTM Pairs – single target geometries.

PTM aircraft can be ahead of or behind a designated aircraft. Figure 11 shows an example of these different situations. It is important to point out that a designated non-PTM aircraft could be PTM equipped, but it has not been cleared and is not conducting a PTM operation.

In the diagram on the left, within Figure 11, the PTM aircraft is behind the non-PTM (designated) aircraft. In the diagram on the right, the PTM aircraft is ahead of the non-PTM (designated) aircraft. The arrow shows the “direction” of the PTM operation.

The obvious effect here is that the behavior of the Mach guidance bounds would be reversed. With the PTM aircraft behind the designated traffic, the upper bound of the Mach guidance would be based on the speed of and distance to the designated aircraft;

while if the PTM aircraft were ahead of the designated traffic, the lower bound of the Mach guidance would be based on the speed of and distance to the designated aircraft.

PTM Strings

A PTM String is formed when:

- There are more than two aircraft in a sequence.
- There is only one designated aircraft in the sequence.
- The designated aircraft is leading or trailing the sequence.

Figure 12 illustrates two types of PTM Strings. The arrows indicate the direction of the PTM operation. In the diagram on the top, within Figure 12, aircraft AC3 is the designated aircraft in the String. Aircraft AC2 is conducting PTM operations with aircraft AC3. Aircraft AC1 is conducting PTM operations on aircraft AC2. In the diagram on the bottom, aircraft AC1 is the designated aircraft in the PTM String; aircraft AC2 is conducting PTM operations with AC1; and aircraft AC3 is conducting PTM operations with AC2.

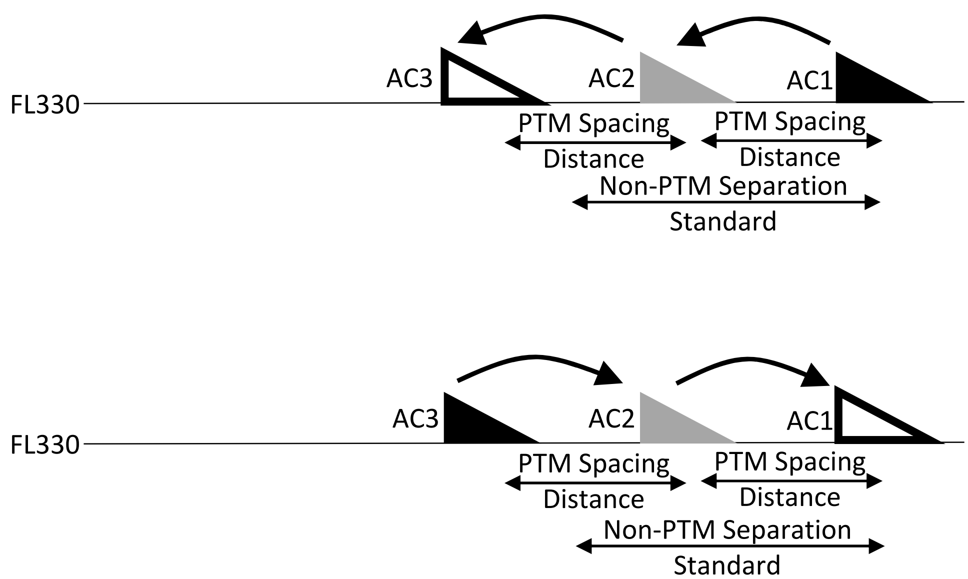


Figure 12. PTM Strings – multiple PTM aircraft, one designated aircraft.

PTM Chains

A PTM Chain, shown in Figure 13, is formed when:

- There are more than two aircraft in a sequence.
- There are two designated aircraft in the sequence, one leading and one trailing.
- The separation standard between the two designated aircraft is a non-PTM separation standard.
- All PTM aircraft in the sequence must be assigned and maintain PTM separation from all designated aircraft that are in front and all designated aircraft that are behind (within the non-PTM separation standard distance).

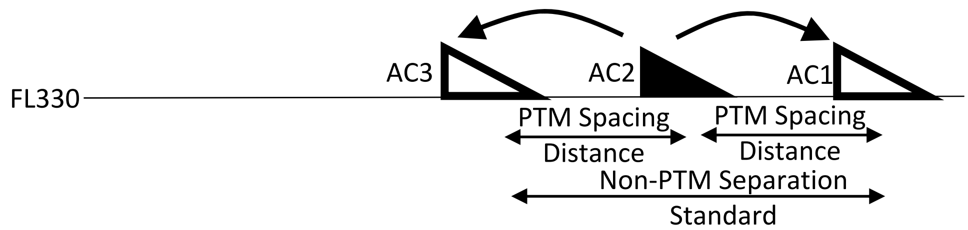


Figure 13. Example of a PTM Chain.

Due to the complexity of the rules necessary for Strings and Chains, it is anticipated that they will be included in the ground automation system, as well as in the airborne equipment (as needed).

A rule that must be enforced by the ground automation is the independence of PTM operations. That is, the PTM concept does not allow for "interacting" PTM operations. For purposes of interacting operations, a PTM operation is represented by the aircraft contained in a PTM Pair, String, or Chain. Interacting operations are defined to be when a single designated aircraft is involved in two different PTM operations. For example, an intersecting track PTM operation cannot be performed with an aircraft in a String if at least one of the aircraft would be a designated aircraft for the String and the intersecting track operation.

Limit Mach

As part of a PTM clearance, PTM aircraft are assigned a Limit Mach by ATC. The objective of this Limit Mach is to ensure PTM flight crews are not directed to fly a Mach during a PTM operation that they are unwilling or unable to fly. For trailing operations (where the PTM aircraft is behind the designated aircraft), the Limit Mach would be a minimum Mach number the aircraft could be directed to fly by the FIM equipment. For leading operations (where the designated aircraft is behind the PTM aircraft), the Limit Mach is a maximum Mach number the aircraft could be directed to fly by the FIM equipment. While the Limit Mach serves to restrict the interactions between the PTM aircraft and designated aircraft, it also serves as a limit to allow the controller to separate the PTM aircraft from other operations. Flight crews will be required to review the assigned Limit Mach and determine if it is acceptable. If the assigned Limit Mach is unacceptable, flight crews should refuse the PTM clearance.

Limit Mach is calculated by the ground automation system based on a set of rules developed for determining Limit Mach for clearances and PTM operations. The following figures help illustrate how Limit Mach is calculated and used during PTM operations (Limit Mach rules are described in further detail in Appendix K).

In Figure 14, AC1 is an ADS-B out aircraft flying at FL340 and M=0.80. AC2 is a PTM capable aircraft flying at FL330 and M=0.79. AC2 sends a request to ATC for an altitude change from FL330 to FL340. ATC's ground automation indicates this climb can be supported using PTM. If AC1 does not have a current Mach assignment, ATC sends a Mach assignment clearance to AC1 to maintain 0.80 or greater.

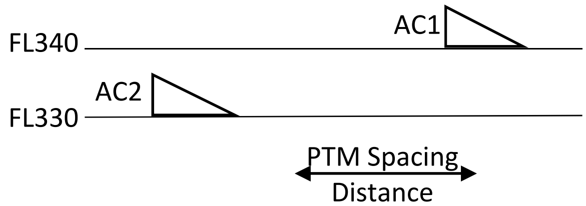


Figure 14. Example of Limit Mach assignment scenario (trailing operation) prior to PTM clearance.

The ground automation then calculates the Limit Mach that would be assigned to AC2. Since this operation is a trailing operation (the designated aircraft, AC1, is ahead of AC2), the Limit Mach is defined to be the minimum of the designated aircraft's assigned Mach or the PTM aircraft's current Mach. For this example, the Limit Mach would be the Mach of the PTM aircraft's current Mach (M=0.79). ATC sends a PTM clearance to AC2 to follow behind AC1 (while AC2 is still at FL330). The Limit Mach is sent to the aircraft as part of the clearance message.

At the time the clearance is received, the FIM equipment and flight crew evaluate the clearance to determine if the clearance can be accepted. Part of this evaluation includes an evaluation of the ability of AC2 to fly the Limit Mach of 0.79. The flight crew determines if the clearance, including the Limit Mach, is acceptable. The flight crew for AC2 engages PTM, and the slowest Mach value given by the Mach guidance will be M=0.79. The upper bound of the Mach guidance is determined by the PTM algorithm and is a function of the distance between the PTM aircraft and the current speed of the designated aircraft. The flight crew then accepts the clearance, and ATC clears AC2 to climb to FL340. Figure 15 shows the result of receiving the appropriate clearances (which includes the Limit Mach number) and then climbing to FL340.

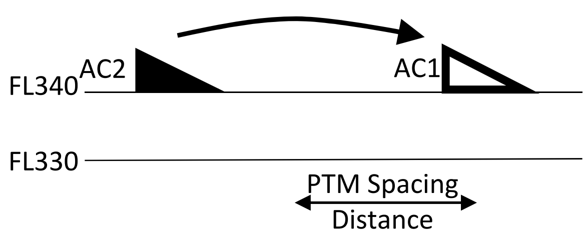


Figure 15. Example of Limit Mach assignment scenario (trailing operation) after PTM clearance acceptance and climb to new altitude.

The messages used to support the PTM climb scenario are shown below.

<u>Message Queue [Destination, Sender]</u>
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.80 OR GREATER
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.79

[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

An example of how Limit Mach is determined and used for a PTM operation in a leading operation is shown in Figure 16. AC1 is an ADS-B Out aircraft flying at FL340 and M=0.80. AC2 is a PTM capable aircraft, flying at FL330 and M=0.79. AC2 sends a request to ATC for an altitude change from FL330 to FL340. ATC's ground automation indicates this climb can be supported using PTM. If AC1 does not have a current Mach assignment, ATC sends a Mach assignment clearance to AC1 (in this case M=0.80).

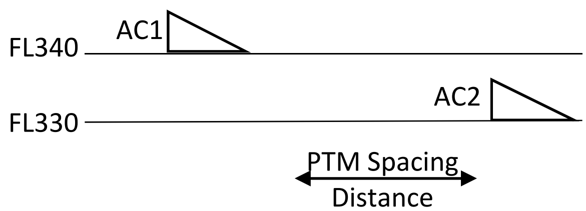


Figure 16. Example of Limit Mach assignment scenario (leading operation) prior to PTM clearance.

The ground automation then calculates the Limit Mach that would be assigned to AC2. Since this operation is a leading operation (the PTM aircraft is ahead of the designated aircraft), the Limit Mach is defined to be the maximum of the designated aircraft's assigned Mach or the PTM aircraft's current Mach. For this example, the current speed of AC2 is (0.8 or 0.79 or 0.78 or etc.) Therefore, the Limit Mach would be the maximum of 0.8 and (0.8 or 0.79 or .78 or etc.) = 0.8. ATC sends a PTM clearance to AC2 to conduct PTM ahead of AC1 (while AC2 is still at FL330). The Limit Mach is sent to the aircraft as part of the clearance message.

At the time the clearance is received, the FIM equipment and flight crew evaluate the clearance to determine if the clearance can be accepted, including the Limit Mach of 0.80. The flight crew for AC2 engages PTM, and the upper bound given by the Mach guidance is M=0.80. The lower bound of the Mach guidance is determined by the PTM algorithm and is a function of the distance between the PTM aircraft and the current speed of the designated aircraft. The flight crew then accepts the clearance, and ATC clears AC2 to climb to FL340. Figure 17 shows the result of receiving the appropriate clearances (which includes the Limit Mach number) and then climbing to FL340.

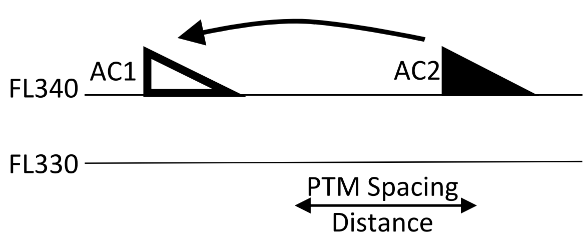


Figure 17. Example of Limit Mach assignment scenario (leading operation) after PTM clearance acceptance and climb to new altitude.

Operational Scenarios

The following scenarios are included to illustrate the concept but are not intended to represent the complete range of possible PTM geometries or supporting systems' functionalities. Each scenario description gives an overview of the operation that is being performed, and what aspects of PTM each scenario is stressing.

Same-Track, Co-Altitude Scenario

In this first scenario, shown in Figure 18, a PTM equipped aircraft (AC2), operating at FL 330, is closing on a co-altitude ADS-B Out aircraft on the same route.

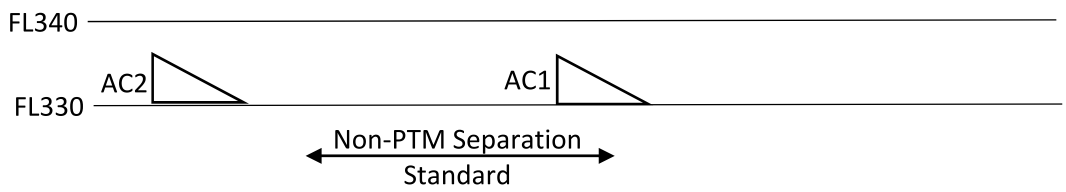


Figure 18. Same-track, co-altitude scenario, time 1.

When the controller determines that a conflict exists and intervention action is required, the controller might issue a speed restriction or altitude change to aircraft AC2 to eliminate the closure rate and ensure that AC2 gets no closer than a non-PTM separation standard distance.

However, if the ground automation indicates that a PTM clearance is available, the controller would have the option to issue a clearance to AC2 to conduct PTM on AC1 and maintain the current flight level. This clearance would allow AC2 to close to and maintain a distance greater than or equal to the PTM spacing distance with AC1, as shown in Figure 19. Since this spacing distance is significantly less than the non-PTM separation distance, AC2 will be able to operate at the desired speed for a longer period of time, increasing the aircraft's overall performance.

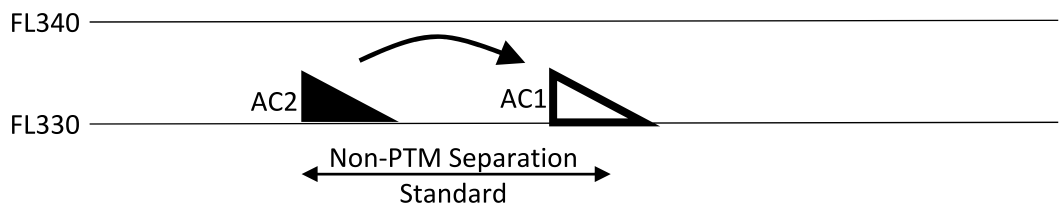


Figure 19. Same-track, co-altitude scenario, time 2.

Same-Track, Altitude Change Scenario

In this scenario, illustrated earlier in the paper, aircraft AC2 is requesting a climb that would cause a conflict with an ADS-B Out aircraft. Initially, it is possible that this will be the most common application of PTM.

General conditions:

- Aircraft are currently vertically separated.
- Aircraft are on the same route.

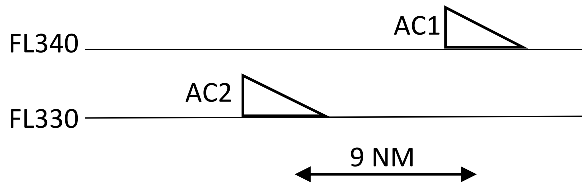


Figure 20. Same-track, altitude change scenario, time 1.

Figure 20 shows two aircraft (AC1 and AC2) operating on the same track. In this scenario, the crew of AC2 has requested, for operational reasons, an altitude change from FL330 to FL340.

The controller receiving the request would observe that the climb would result in an immediate conflict with AC1 at FL340 using non-PTM separation standard distances. However, because AC2 has indicated that it is PTM equipped (in the flight plan), the ground automation system would indicate the possibility of a PTM clearance (for the controller to issue) that would provide a separation standard that would authorize a climb. The controller would issue a clearance to AC2 instructing it to conduct PTM on AC1.

The clearance information would be loaded into the FIM equipment, and the flight crew would determine acceptability of the PTM clearance. If acceptable, the flight crew engages PTM, follows the PTM Mach guidance, and accepts the clearance with ATC. With PTM engaged, a single Mach value (or range of Mach values) will be commanded by the FIM equipment.

Once the controller has received confirmation that the PTM clearance has been accepted, the controller would then clear AC2 to climb to and maintain FL340. The PTM aircraft would then start a normal climb to FL340. The flight crew follows the Mach guidance provided by the FIM equipment throughout PTM operations, as shown in Figure 21.

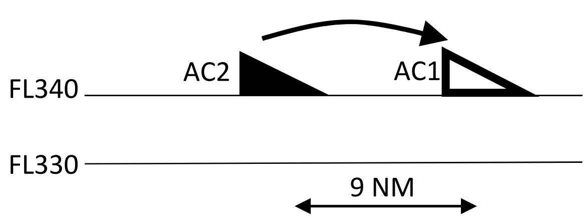


Figure 21. Same-track, altitude change scenario, time 2.

Same-Track Loading, Multiple Aircraft Interactions (Track Loading)

It is anticipated that a significant consideration in the benefit case for PTM will be the ability to have multiple, co-altitude, same track aircraft operating with different equipage levels and a PTM separation standard applied between aircraft. This is particularly beneficial when “loading” aircraft on fixed routes and organized track systems. This track loading occurs as aircraft transition from radar surveillance airspace to oceanic, non-radar airspace. The required spacing based on non-PTM separation distances often limits the number of aircraft that can enter a given track at a given altitude. There are times when aircraft must fly at less than optimal altitudes or fly different tracks. The reduced spacing due to PTM will mean that more aircraft will be able to fly where and when they want to for better aircraft and system performance.

This is illustrated in Figure 22. In this case, there are three aircraft that would like to operate on the same oceanic track at similar times. As seen in the left-hand graphic of Figure 22, without PTM, controllers would have to put the second aircraft on a different track or at a different altitude in order to prevent a traffic conflict. As seen in the right-hand graphic of Figure 22, using PTM, the second and third aircraft can be instructed to use PTM and all three aircraft can operate on their desired track at their desired altitude.

Figure 22. Example of how PTM could be used to improve track loading.

Intersecting Tracks

PTM is also applicable for intersecting track situations. In general, there will be restrictions on the maximum possible crossing angle permitted by PTM. As stated earlier, this is often due to limitations of the ADS-B signal range and the requirement that the controller resolve conflicts by some time or distance prior to the actual loss of separation. Typically, this will restrict the intersecting track angle to about 30 degrees.

Crossing Path Scenario

For the crossing path scenario shown in Figure 23, aircraft AC2 and AC1 are moving towards a loss of separation in an oceanic environment (30 NM minimum separation). The aircraft are both at FL310 and Mach 0.80. The ground automation system is reporting that a loss of separation will occur in 40 minutes, when the distance between the two aircraft will decrease to less than 30 NM. The controller may choose to use a PTM clearance to resolve the conflict.

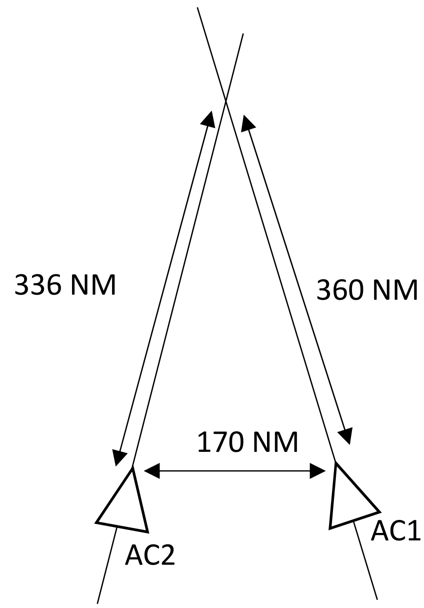


Figure 23. Example of PTM operations with intersecting tracks, time 1.

When the PTM clearance is received by AC2, the PTM clearance information would be loaded into the FIM equipment. The acceptability of the PTM clearance would be checked against associated criteria required for PTM operations. The FIM equipment uses data received from AC1 and the ground automation system to predict the time, location, and separation distance at the closest point of approach. This distance is called the projected closest distance (PCD). This displayed distance is a continuously updated value of the closest distance that the PTM aircraft will get to the position of the designated aircraft. It is computed based on the route and trajectory of the aircraft and on the current commanded speed of the PTM aircraft and the current speed of the designated aircraft. As such, when the flight crew changes the aircraft's commanded speed, the PCD will change immediately. If the traffic situation is such that the distance at the closest point of approach is less than the PTM- spacing distance, the FIM equipment displays, to the flight crew, Mach guidance (different from the aircraft's current commanded speed) that would ensure the required spacing between the PTM aircraft and the designated aircraft is satisfied during the PTM operation.

If the pending Mach guidance was acceptable, the flight crew would engage the FIM equipment and accept the clearance. It is likely that, while the aircraft will pass too close for a non-PTM separation standard, the aircraft will be significantly farther apart than required for the PTM separation standard. The flight crew follows the Mach guidance provided by the FIM equipment throughout PTM operations, as shown in Figure 24.

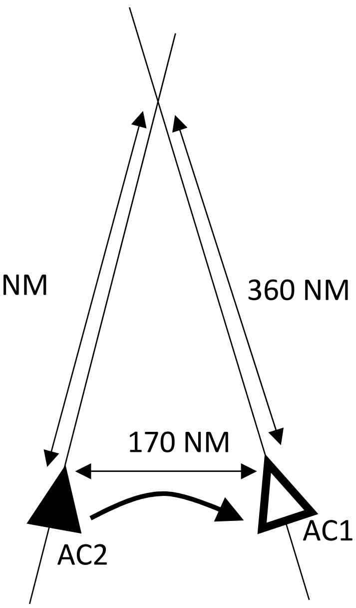


Figure 24. Example of PTM operations with intersecting tracks, time 2.

Once the aircraft have passed the closest point of approach and the controller determines that a non-PTM separation standard has been achieved (e.g., 30 NM), the controller may terminate the PTM procedure.

Merging Path Scenario

PTM can also be utilized when the paths of two aircraft merge. This could happen with an aircraft joining an organized route structure at a waypoint along the route as illustrated in Figure 25.

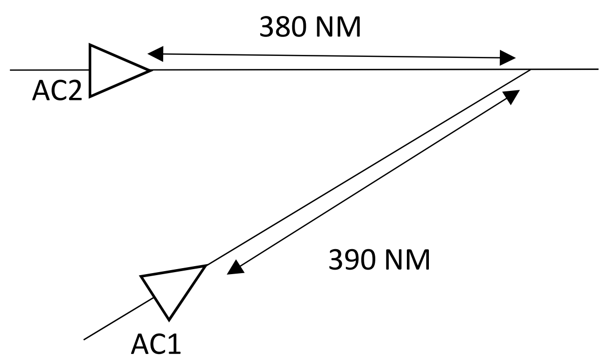


Figure 25. PTM merging track scenario, time 1.

In this scenario, the controller predicts there would be a loss of separation if AC1 joined the track of AC2 using non-PTM separation standards. Without PTM, the controller would normally have to change the altitude or significantly change the speed of either AC2 or AC1. However, using PTM, the controller can avoid the altitude or significant speed change and issue a PTM clearance to the PTM aircraft, as shown in Figure 26. The clearance message would include the expected relative position the controller is expecting for the operation (e.g., "ahead of" or "behind"). In the case above, the clearance to AC2 would be similar to "CLEARED PTM MACH, MERGE AHEAD OF AC1."

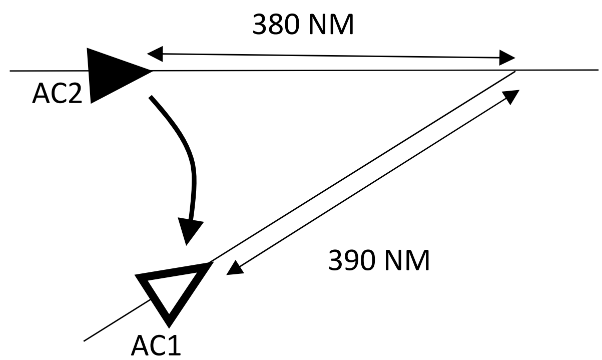


Figure 26. PTM merging track scenario, time 2.

While engaged, the FIM equipment compares the trajectory of the PTM aircraft with the location and planned trajectory of the designated aircraft and provides Mach guidance that is predicted to result in avoiding a loss of spacing.

In the above example, the Pair of aircraft will transition to an in-trail maneuver invoking use of the functionality described in earlier scenarios. Once established in the in-trail operation, the FIM equipment will continue to perform a PTM operation until a pair-specific terminate message is received from ATC. This could happen after route divergence, if vertical separation is established, or if a speed difference increases the distance between the PTM aircraft and the designated aircraft to a distance where a non-PTM separation standard can be applied.

Ground Automation and Air Traffic Controller Procedures

Ground Automation

Currently, US-controlled oceanic airspace is managed with the Advanced Technology and Oceanic Procedures (ATOP) system, which includes the Ocean 21 system and controller interface (ref. 6). This system gathers aircraft position information either through Automatic Dependent Surveillance-Contract (ADS-C) position reports or High Frequency (HF) voice position reports. Using this information and the aircraft's flight plan, the system projects the future position of each aircraft. The system includes a conflict probe that is used to identify potential traffic conflicts up to two hours in the future. The separation standard that is applied for conflict detection may vary by aircraft and is a function of the type, frequency, and/or quality of the position reports received from each aircraft as well as aircraft equipage.

Losses of separation (traffic conflicts) that are projected to occur within two hours but greater than 30 minutes into the future are displayed to the controller with an advisory conflict alert indication. Conflicts displayed to the controller that will not be resolved within 30 minutes prior to loss of separation are given a higher level of alerting on their display. The ATOP system displays a list of all active (unresolved) conflicts.

The Ocean 21 system uses intent information on all aircraft (via the flight plan) to predict future trajectories. It also provides a method of communication between the controller and flight crew. Finally, as appropriate clearances are input into the system, it removes resolved conflicts from the conflict list. All three of these capabilities will be utilized in supporting PTM operations.

Many other automation systems used throughout the world to manage oceanic airspace have similar characteristics. PTM operations will require significant integration with the controller's ground automation system. Some of the anticipated ground system functionality should include:

- Identify potential PTM situations.
- Formulate clearances for the controller to issue.
- Send intended flight path information of designated aircraft to PTM aircraft.
- Recognize accepted PTM clearances (and provide indications of conflicts that are resolved by the acceptance of PTM clearances).
- Identify when non-PTM separation is re-established.
- Notify the controller that PTM is no longer required, and be able to send a pair-specific PTM cancellation message to the FIM equipment.

Air Traffic Controller

Within the current oceanic system, the controller is tasked with maintaining separation between all participating aircraft in their assigned airspace. This is accomplished by having a method of determining aircraft position and projected positions (position reports and ground automation support), and applying rules, techniques, and skill to identify conflicts in a timely manner and resolve them prior to a loss of separation.

PTM operations begin once a controller has identified that a traffic conflict will exist and when a controller determines that the PTM separation standard is applicable and beneficial for the safe and efficient operation of the airspace. The ground automation system identifies the traffic conflict, and the controller determines which separation standard is most applicable.

If PTM is the most applicable or preferred option, the controller will issue a PTM clearance. Once accepted, the flight crew is then required to manage speeds based on information provided by the FIM equipment.

The controller also has the option of assigning additional designated aircraft to aircraft already conducting PTM operations. The controller accomplishes this by sending a new clearance to the PTM aircraft. This new clearance instructs the flight crew to continue doing PTM on the aircraft already assigned to them and includes instructions to conduct PTM on the additional designated aircraft.

Similarly, if the controller no longer prefers to use PTM between the PTM aircraft and a subset of the already designated aircraft, the controller will send a new clearance to the PTM aircraft. This clearance will identify which PTM operations should be continued and which are no longer required or desired.

To make use of the PTM clearance, the controller is responsible for:

- Determining if a PTM clearance is suitable, including the presence of operational FIM equipment.

- Determining and verifying the PTM aircraft and the designated aircraft call signs.
- Ensuring separation between the PTM aircraft and all other aircraft, excluding the designated aircraft.
- Ensuring that the designated aircraft is not authorized to deviate from its cleared flight plan during the duration of the PTM operation.
- Terminating the PTM operation after non-PTM separation is re-established and when the controller no longer desires to apply the PTM clearance.

Controller Monitoring of Procedure Compliance

During the development of the PTM concept, a one-way data link between the ground automation and the FIM equipment was assumed. In other words, the ground automation has the ability to communicate with the FIM equipment, but the FIM equipment has no means of sending data link messages to ground automation. If it were possible and practical to remove that constraining assumption, so that the FIM equipment could have a two-way data link with the ground system, then there are some possible benefits that could be realized.

Due to communications and surveillance limitations, ATC currently uses procedural separation in oceanic airspace. However, in airspace in which aircraft spacing is guaranteed with procedural separation, the controller is required to monitor the aircraft compliance with the procedure. A very common example of this is ground system alerting to deviations from an assigned altitude and route. Whether or not there is an associated loss of aircraft separation, the controller monitors and reacts to deviations from the assigned procedural clearance. This same concept could be valuable in PTM operations.

When a PTM clearance is issued and accepted, the ground system could receive reports on the FIM equipment health, the status (engaged in a PTM operation vs. not engaged in a PTM operation), target status (loss of ADS-B signal), and certain flight crew alerts that the flight crew has not responded to within an appropriate interval. This monitoring would improve the PTM overall safety performance by reducing the impact of any flight crew training and performance issues and by providing ground monitoring of avionics system health.

Actual and projected aircraft spacing information would not be data linked to the controller. The controller is neither trained nor capable of applying tactical separation with aircraft involved in PTM.

This down link data channel could include the following standard message from the FIM equipment:

- PTM state [Pending PTM operation, Pending PTM operation/Engaged PTM operation, Engaged PTM operation, no activity]
- Designated aircraft status
- Call sign of all PTM aircraft engaged in a PTM operation
- Any (and all) alerts of a moderate to high severity level that are displayed to the flight crew

A new message would be sent to the controller if there is a change in any of the fields.

Flight Deck Automation and Flight Crew Procedures

Flight Deck Automation

The FIM equipment will need numerous functions certified by the Federal Aviation Administration (FAA). Anticipated functions requiring certification include:

- The ability to receive PTM clearance data from the ground system.
- Status monitoring and appropriate notification of status of the FIM equipment.
- Interface with the flight crew to enable the flight crew to follow Mach guidance to support PTM operations.
- Adequate alerting to the flight crew of failure to comply with Mach guidance.
- Alerting to the flight crew of an imminent loss of spacing or loss of spacing.
- Alerting to the flight crew of a loss of separation.

Flight Crew Procedures

In non-PTM operations, the flight crew's responsibility (role) in maintaining traffic separation is to comply with the assigned route, altitude, and speed (as necessary). The change with PTM is that the Mach guidance is generated by on-board FIM equipment rather than provided by the controller. The significant job responsibility change (or addition) is the requirement for the flight crew to be familiar with and able to execute responses to PTM alerts and equipment failures.

When a controller issues a PTM clearance to a flight crew, the flight crew of the PTM aircraft will use their ADS-B-enabled on-board FIM equipment to manage their speed to achieve spacing relative to the aircraft designated by the controller. The flight crew task of flying the assigned altitude, route, and speed does not change, with the exception that the required speed (Mach) is determined by the FIM equipment and authorized by the PTM clearance. Regarding speed, the flight crew is responsible for the task of following Mach guidance from a new source (FIM equipment vs. controller).

The PTM Mach guidance (along with suitable alerting) will be provided to the flight crew through an interface that either resides within current aircraft displays or is presented using one or more auxiliary displays.

During a PTM operation, additional responsibilities required of the PTM aircraft's flight crew include:

- Validating the operational status of the FIM equipment.
- Rejecting the PTM clearance if, at the discretion of the flight crew, the outcome will be operationally undesirable.
- Being familiar with and prepared to execute appropriate procedures should the FIM equipment fail (e.g., in the event that the designated aircraft's ADS-B transmitter fails).
- Being familiar with and able to execute responses to PTM alerts generated by the FIM equipment.
- Complying with PTM Mach guidance displayed by the FIM equipment.
- Acknowledging instructions from the controller that terminate the PTM operation and resuming normal operations.

Airborne Human-Machine Interface for PTM

Flight crews authorized to conduct PTM operations will require the use of an HMI capable of providing enhanced situation awareness of surrounding traffic, enabling interactions with on-board FIM equipment, and presenting Mach guidance (and any required alerts) that the flight crew must follow (or respond to) in order to achieve spacing relative to aircraft designated by the controller. Future implementations of an airborne HMI that will support PTM operations may be fully integrated, for example, with an aircraft's primary flight display, navigation display, and multifunction control display unit. However, another possible implementation involves the flight crew HMI operating independently of other flight guidance and navigation displays. A non-integrated implementation of this type, which may be considered for retrofit installations, was designed and investigated at the NASA Langley Research Center.

NASA Langley's airborne PTM HMI consists of two primary hardware components – a side mounted display with a touchscreen interface and a 7.62 cm x 7.62 cm Configurable Graphics Display (CGD) located in the flight crew's primary field-of-view (FOV). (As mentioned previously, CPDLC is assumed to be in use during PTM operations.) Possible locations for left-seat PTM HMI components within the flight deck are shown in Figure 27.

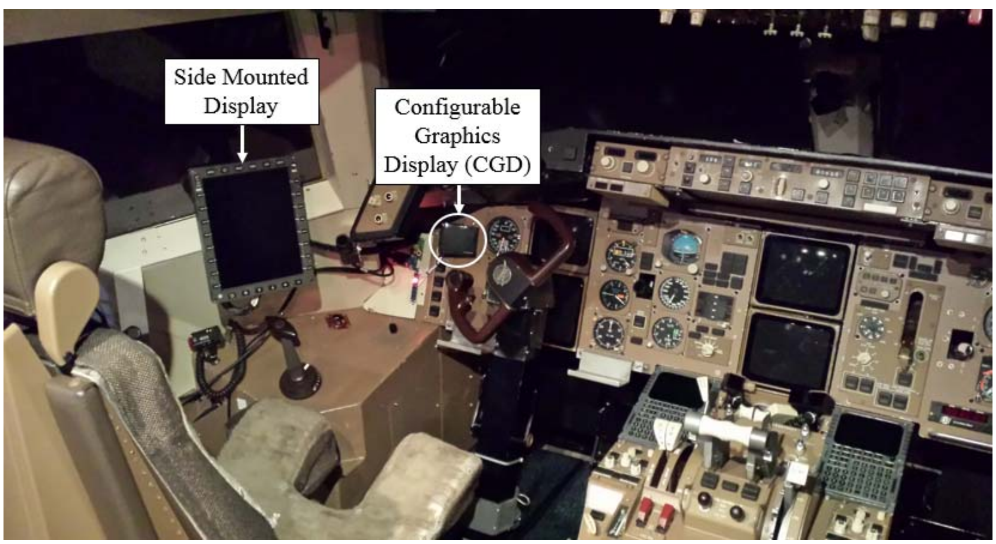


Figure 27. Possible locations for left-seat PTM HMI components within the flight deck.

Side Mounted Display

Each side mounted display used during PTM operations must present a cockpit display of traffic information (CDTI) in accordance with requirements associated with applications supported by an Aircraft Surveillance Applications (ASA) System (RTCA, 2014). Ownship data acquired from aircraft sensors and aircraft systems as well as surveillance data received from traffic aircraft via ADS-B messages must be available for the CDTI to be populated with required information elements. In addition to providing enhanced situation awareness of surrounding traffic through the presentation of its CDTI, the side mounted display will also enable the flight crew to interact with the FIM equipment in response to PTM clearances received from ATC. The FIM equipment and PTM HMI interact with the PTM algorithm which, as described above and in detail in

Appendix H, generates commanded Mach guidance and provides flight crew messages, indications, and alerts when the Mach guidance changes or is not being followed.

Examples of the PTM HMI designed for use with a side mounted display are shown in Figure 28 and Figure 29, and descriptions of the HMI's functions and informational content are provided in Table 2. Information regarding the design, development, and initial evaluations of the proposed flight crew HMI is included in Appendices I and J, and a complete PTM Pilot Guide is included in Appendix L.

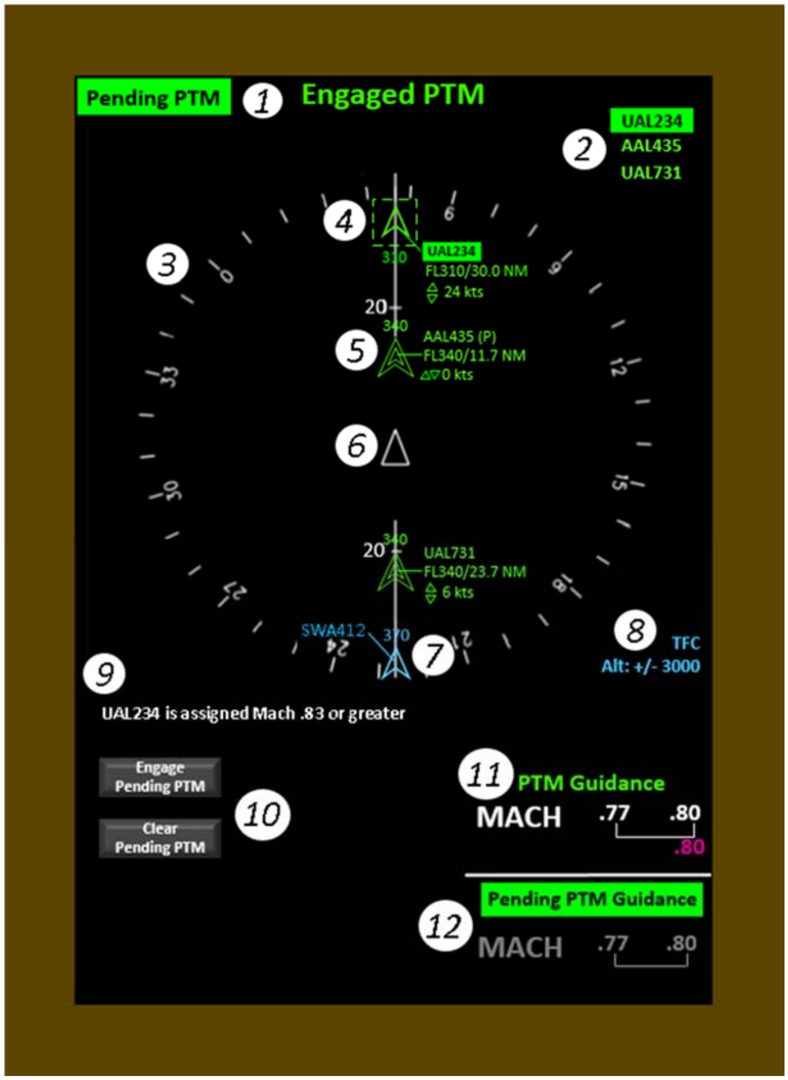


Figure 28. Airborne PTM HMI presented on a side mounted display.

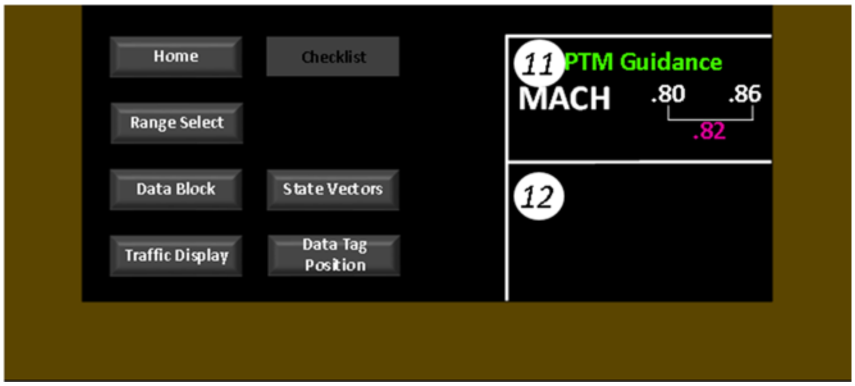


Figure 29. Multi-use information area included on the airborne PTM HMI's side mounted display.

Table 2. Descriptions of display areas included in the airborne PTM HMI presented on a side mounted display.

Numerical identifier included on HMI graphics shown in Figure 28 and Figure 29	Name of HMI component or display screen area	Description of informational content and/or function of HMI display area
1	PTM Mode Indicator	Displays current status of PTM. Can display one of the following five modes: • "Pending PTM" • "Engaged PTM" • "Pending PTM" & "Engaged PTM" • "Cancelled PTM" • "NO PTM"
2	Flight Identification (ID) List	Displays flight ID of all aircraft that are or may become engaged in a PTM operation with the ownship. Normal text indicates designated aircraft. Reverse video text indicates pending aircraft. Aircraft flight ID's are listed in the order that aircraft symbols appear on the CDTI, from top to bottom.
3	Cockpit Display of Traffic Information (CDTI)	Displays ownship symbol and ADS-B traffic that is within ADS-B signal range. Current heading is shown in the compass rose located around the perimeter of the CDTI. Distance is shown by the tick marks on the center lubber line. Various range scales may be selected.

4	Pending Aircraft Symbol and Data Tag	Each pending aircraft is displayed as a single green chevron surrounded by a dashed box. Flight ID is shown in reverse video text. The rest of the data tag is shown in green text.
5	Designated Aircraft Symbol and Data Tag	Each designated aircraft is displayed as a double green chevron. The information in data tags associated with designated aircraft can be reduced by the pilot, leaving only the flight ID.
6	Ownship Aircraft Symbol	Ownship is displayed as a hollow white triangle.
7	Background Aircraft Symbol and Data Tag	Each ADS-B Out aircraft not being used by ownship as pending or designated aircraft in a PTM operation is displayed as a single cyan chevron. Only the flight ID is included in a background aircraft's data tag, and the flight ID can be removed by the pilot.
8	Background Traffic Indicator	Shows the altitude filter applied to determine which background aircraft are displayed. The setting for the Altitude Filter is changed within the Traffic Display menu. The Background Traffic Indicator serves as a selectable area of the display screen and may be used to toggle background traffic off/on. When background traffic is off, TFC OFF is displayed.
9	Message Area	PTM related messages are displayed in this area. White text is associated with information and indications; amber text is associated with cautions; and white text with red highlighting is associated with warnings.
10	Selectable Buttons	Various buttons, used to interact with the FIM equipment, are displayed depending on the PTM mode. Two columns of buttons are displayed during the "Engaged PTM" mode (in contrast to the combined "Pending PTM / Engaged PTM" mode shown above). During an engaged PTM operation, additional data associated with a flight crew selected aircraft may be displayed in a data block that replaces the right column of buttons. The right column of buttons can also be replaced with a checklist during rare non-normal events.

11	PTM Guidance	Displays Mach guidance (in white) that ownship is allowed to fly during Engaged PTM mode. Flight crew commanded Mach for ownship is shown in magenta. During Engaged PTM mode, this area “repeats” the PTM Mach guidance shown on the CGD. When areas 11 and 12 display the exact same information as that shown on the CGD, areas 11 and 12 of the side mounted display are segregated by white border lines on the top and left.
12	Multi-Use Information Area	Displays information pertaining to PTM, but is normally blank. During the Pending PTM mode, “Pending PTM Mach guidance” is displayed (in grey) to show the flight crew the PTM Mach guidance that the PTM aircraft will be required to fly if a pending PTM clearance is accepted. There are times, when the FIM equipment determines that PTM conditions are not met when ATC issues a PTM clearance. When this occurs, the words “Unable Pending PTM” are shown (in white) since the option to accept the PTM clearance is not available to the flight crew. Other than in a Pending PTM mode, the word “Message” is displayed in area 12 when a message is shown in the Message Area. Additionally, when areas 11 and 12 display the exact same information as that shown on the CGD, areas 11 and 12 of the side mounted display are segregated by white border lines on the top and left (as shown below in Figure 29).

Configurable Graphics Display (CGD)

The CGD located in the flight crew’s primary FOV serves two purposes. It will provide indications that direct the flight crew’s attention to important information elements located on the side mounted display, and it will present Mach guidance issued by the PTM algorithm that the flight crew must follow to maintain spacing from controller assigned aircraft.

An example of the PTM HMI designed for use with the CGD is shown in Figure 30, and descriptions of the display areas included in the airborne PTM HMI presented on the CGD are provided in Table 3.

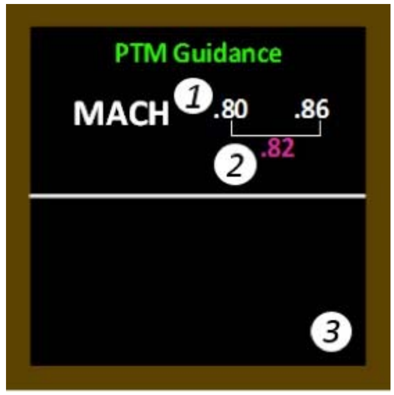


Figure 30. Airborne PTM HMI presented on a configurable graphics display.

Table 3. Descriptions of display areas included in the airborne PTM HMI presented on a CGD.

Numerical identifier included on HMI graphic shown in Figure 30	Name of HMI component or display screen area	Description of informational content and/or function of HMI display area
1	PTM Guidance	Displays Mach guidance (in white) that ownship is allowed to fly during Engaged PTM mode.
2	Flight Crew Selected Mach	Flight crew commanded Mach for ownship (shown in magenta) may be from the mode control panel (MCP) or an available mode of the flight management computer (FMC). When the flight crew selected Mach is set at a PTM Mach guidance range limit, at one end or the other, the flight crew selected Mach will be displayed under that limit. Otherwise, the flight crew selected Mach will be displayed under the center of the range (as shown in Figure 30).
3	Multi-Use Information Area	Displays information pertaining to PTM operations, but is normally blank. “Pending PTM” will be displayed in green reverse video during a Pending PTM mode. “Message” will appear whenever a message is present on the side mounted display in the message area. The color of the “Message” notification will match the color of the message displayed.

As shown in Figure 31, the CGD presents PTM Mach guidance within the flight crew’s primary FOV and presents notifications that direct flight crew attention to information located on the side mounted display. Descriptions of the display areas included in the airborne PTM HMI are provided in Table 4.

Figure 31. Relationship between the side mounted display and the CGD.

Table 4. Descriptions of information and display areas included in the airborne PTM HMI presented on the side mounted display and the CGD.

Numerical identifier included on HMI graphics shown in Figure 31	Name of HMI component or display screen area	Description of informational content and/or function of HMI display area
1	PTM Guidance	Mach guidance (in white) that ownship is allowed to fly during Engaged PTM mode is presented on the CGD and on the side mounted display.
2	“Pending PTM”	This text (in reverse video) is shown on the CGD to direct attention to the side mounted display’s presentation of Pending PTM Mach guidance.

3	Pending PTM Guidance	Mach guidance (in grey) that ownship will be required to fly if the pending PTM clearance is accepted by the flight crew. Pending PTM Mach guidance is presented only on the side mounted display. To avoid any confusion over the Pending PTM Mach guidance being a command to follow, it is never presented in the primary FOV.
4	“Message”	This text appears on the bottom of the CGD any time there is information presented in the side mounted display’s Message Area.
5	Message Area	This area of the side mounted display is used to provide information and indications to the flight crew.

As mentioned previously, Appendixes I and J provide much more detail regarding the design, development, and initial evaluations of the flight crew HMI.

Benefits Analysis

Experiment Design

A fast-time experiment to support the development and evaluation of the PTM concept of operations was conducted at the NASA Langley Research Center. The focus of this experiment was to evaluate the benefits of PTM in the Central East Pacific (CEP) oceanic airspace region. This experiment considered the parameters of ADS-B In equipage, FIM equipment, PTM separation standard and airspace separation standard. ADS-B In equipage was varied as a percentage of the aircraft in the airspace, with the settings of 10%, 20%, 45%, 70%, and 80% being used. It was assumed that all aircraft in the airspace would be equipped with ADS-B Out, given the FAA mandate on ADS-B Out equipment being installed by 2020. The PTM separation standard distance, which was set to 5 or 10 NM in the experiment, was only applied to aircraft that were equipped with PTM. The final parameter of airspace separation standard, which was applied to non-PTM equipped aircraft, was 15, 30, or 50 NM. To model the density and distribution of aircraft within the CEP, recorded traffic data were received from the FAA and converted into scenario files that could be used in the simulation. This allowed for the experiment to use traffic patterns that are comparable to what aircraft in real operations would experience. A nominal unconstrained airspace was also examined, in which every aircraft was able to fly the exact altitudes that were desired at all times. This provided an upper bound to the maximum benefits possible in the CEP airspace region.

Sample Results

The data from this experiment were analyzed to observe the benefits experienced by unequipped aircraft and by PTM equipped aircraft. Several measures were compared between the current day airspace, PTM test case airspace, and the unconstrained airspace to quantify the benefit of PTM. Aircraft equipped with PTM resolved more conflicts which led to improvements in fuel efficiency and increased time on optimum flight level.

A primary interest during this study was the difference in fuel efficiency, expressed in nautical miles per thousand pounds of fuel as well as percent difference. It is a measure of change in fuel performance between corresponding aircraft in different airspaces. Table 5 shows the average percent differences in fuel efficiency above current day for PTM equipped aircraft, unequipped aircraft in the PTM airspace, and the unconstrained airspace. Unequipped aircraft average essentially no difference over current day while unconstrained and PTM aircraft see improvements. In fact, PTM equipped aircraft see improvements that nearly reach the values gained by unconstrained aircraft. PTM equipped aircraft are predicted to experience a 0.93% increase in fuel efficiency over current day airspace operations (assuming a 50NM non-PTM separation standard distance).

Table 5. Mean percent difference in fuel efficiency of experimental conditions over current day by airspace.

Airspace	**Current Day, non-PTM separation**		
	15 NM	**30 NM**	**50 NM**
	Mean (%)	Mean (%)	Mean (%)
PTM Airspace: Unequipped Aircraft	0.02	0.04	0.06
PTM Airspace: Equipped Aircraft	0.84	0.88	0.93
Unconstrained	0.88	0.92	0.97

For more detailed information regarding this experiment and the results obtained, see ref. 7.

Summary

PTM is an IM concept that utilizes airborne and ground-based capabilities to enable the implementation of an airborne pairwise spacing capabilities in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage an “at or greater than” inter-aircraft spacing. Due to the accuracy of ADS-B information and the use of airborne spacing guidance (speed commands), the minimum PTM spacing distance will be less than distances a controller can support with current automation systems utilized in oceanic operations. Ground tools assist the controller in evaluating the traffic conditions and determining appropriate PTM clearances to be issued. Avionics systems provide Mach guidance information that allows the flight crew to conform to the PTM clearance issued by the controller. The combination of a reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace.

This paper provided an overview of the proposed application, description of several key scenarios, and a high-level discussion of expected air and ground equipment and procedure changes. A description of a proposed flight crew HMI and initial benefits analyses were also presented. A more detailed description of the PTM concept of operations, in the form of an OSED document, and a companion “Future Considerations for the Pairwise Trajectory Management Concept: Potential Future Updates for the PTM OSED” paper is included in Appendices A and B. Furthermore, a detailed description of the PTM algorithm and PTM Limit Mach rules, initial PTM safety requirements and safety assessment documents, a detailed description of the design, development, and initial evaluation of the proposed flight crew HMI, an overview of the methodology and results of PTM pilot training requirements focus group and HITL testing activities, and the HMI Pilot Guide are included in Appendices C through L.

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[7] Chartrand, R. and Ballard, K., “Benefits of using Pairwise Trajectory Management in the Central East Pacific,” AIAA Aviation and Aeronautics Forum and Exposition (Aviation 2017), Denver, CO, June 2017.

Appendix A: Interval Management (IM) Pairwise Trajectory Management (PTM) Operational Services and Environment Description (OSED)

Version 3.0
February 2017

ANNEX A - OPERATIONAL SERVICES AND ENVIRONMENT DEFINITION

A.1 INTRODUCTION

Interval Management (IM) describes a set of capabilities designed to support a range of IM Operations whose goal is precise inter-aircraft spacing. IM is defined as the overall system, including both ground and airborne domains, that enables improved means for managing traffic flows, aircraft spacing and separation assurance. This includes both the use of ground and airborne tools, where ground tools assist the controller in evaluating the traffic picture and determining appropriate clearances to space aircraft efficiently and safely, and airborne tools that allow the flight crew to conform to the clearance. Interval Management-Pairwise Trajectory Management (IM-PTM) is an Interval Management concept that utilizes airborne and ground-based capabilities to enable airborne pairwise distance spacing capabilities in procedural airspace regions.

This document specifies only the surveillance and avionics requirements needed by the airborne domain to support PTM operations. Detailed system requirements for ground automation systems that support PTM operations are outside the scope of this document. However, since PTM relies on significant coordination between the airborne and ground domains, to analyze and derive requirements for PTM, assumptions and operational requirements are made concerning associated ground system capabilities. These could lead to operational requirements in ground system development. The areas that may be affected include surveillance of the entire traffic picture, and decision-making criteria to ensure that issued clearances are safe and appropriate for the overall traffic flow and the specific aircraft involved in the operation.

The key addition to current operations is the provision of precise guidance within the flight deck to enable the flight crew to actively manage the spacing relative to designated aircraft. During PTM operations, the flight crew is responsible for using the FIM Equipment[1] to manage inter-aircraft spacing.

PTM uses airborne surveillance and tools to manage inter-aircraft spacing with the goal of improving operations that can occur in a variety of oceanic environments and situations. These oceanic regions are characterized by reduced surveillance and limited communication capabilities. In such airspace, air traffic is managed procedurally with reliance on specified navigation performance, periodic position reports to the ground, and large separation standards. These airspace regions also involve a variety of route structures including fixed routes, organized track system routes, and user preferred routes. Details for these regions can be found in section A.6. This document describes a number of generic PTM operations and scenarios. These scenarios were developed to determine operational requirements and form the basis for safety and performance analyses.

This document provides high-level requirements for supporting services, systems, technologies, tools, procedures, and airspace changes. Section A.2 provides a high-level description of the OSED objectives. Section A.3 contains a high-level description of PTM operations including two representative operational examples. Section A.4 contains a summary of key PTM assumptions and constraints. Section A.5 provides a set of operational scenarios used to illustrate PTM operations. In Section A.6, the airspace

[1] The term "FIM Equipment" in this document is used to refer to any avionics on board the IM Aircraft that supports the FIM application. The term "FIM Equipment" does not imply any dedicated avionics or a specific avionics architecture.

characteristics and supporting systems are described. Section A.7 includes the scope of PTM operations considered as well as controller and flight crew roles and responsibilities. Section A.8 summarizes the procedural flow of PTM operations while Sections A.9 and A.10 contain the phase diagrams and tables, respectively. Section A.11 lists Abnormal Events and their expected responses, and Section A.12 contains a list of definitions of unique terms used in this document.

A.2 OBJECTIVE

Studies indicate there will be continued growth in oceanic air traffic operations. Even with recent improvements to oceanic surveillance and communications systems, required separation standards in oceanic airspace are still large enough to cause aircraft operational inefficiencies. These inefficiencies include flights being unable to operate at their desired altitude and speeds for extended periods of time, flights being unable to operate on their desired routes, and flights required to change altitudes for crossing traffic. These system inefficiencies can increase flight time and fuel burn.

The goal of PTM is to use airborne surveillance and tools to manage inter-aircraft spacing. Due to the accuracy of ADS-B information and the use of real-time flight deck avionics guidance, the PTM minimum spacing distance will be less than distances a controller can support with current automation systems that support procedural airspace operations (which typically characterize operations in oceanic regions). Ground tools assist the controller in evaluating the traffic picture and determining appropriate PTM clearances to be issued. FIM equipment provides guidance information that allow the flight crew to conform to the PTM clearance issued by the controller. The combination of a reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace.

A.3 OPERATIONAL DESCRIPTION

PTM utilizes airborne and ground-based capabilities to enable the implementation of an airborne-based spacing and distance monitoring in procedural airspace regions. Ground tools assist the controller in evaluating the traffic picture and determining appropriate PTM clearances to be issued. FIM equipment on-board the aircraft provides speed guidance information that allows the flight crew to conform to the PTM clearance issued by the controller. The combination of reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace.

This document describes a number of generic PTM operations and scenarios. These scenarios were used to explore the operational requirements needed to support PTM operations.

PTM is designed to enable operations that are not possible with current, non-PTM, separation standards. These operations will be enabled by more efficient spacing assignments issued by controllers and managed by aircraft. The controller, using ground-based decision-support automation, issues a pair-specific PTM clearance to a PTM-equipped aircraft. When accepted, this clearance will allow the PTM aircraft to operate on the same flight level and track of the designated aircraft (the paired aircraft), or to cross the track of the designated aircraft with reduced spacing as compared to current, non-PTM, separation standard minimums. The PTM clearance requires the flight crew of the PTM aircraft to use their ADS-B-enabled on-board FIM equipment to manage their spacing relative to the designated aircraft. The FIM equipment will provide speed guidance to ensure that the inter-aircraft spacing is no closer than the PTM minimum distance during the PTM operation. When the controller assesses (with ground automation system support) that a non-PTM separation standard has been achieved and the PTM operation is no longer required, the controller may terminate the PTM operation. The controller is not required to terminate the PTM operation as soon as non-PTM separation standards are available and may allow the PTM operation to continue for operational reasons.

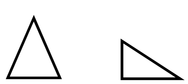
PTM will support same track operations (typically found in oceanic organized track systems) and crossing track operations (typically found with oceanic user preferred routes). Due to the reduced PTM minimum spacing distance, the PTM aircraft may not be required to modify their current speed in many traffic-crossing situations since what was a conflict when assessed using non-PTM separation standards may no longer be a conflict when PTM-supported separation is applied. PTM should save fuel and reduce delays by improving operations that increase time on an aircraft's optimal trajectory (track, speed and altitude). The airborne managed distance can allow for higher throughput and generally more efficient aircraft operations.

PTM is employed, depending on local constraints and traffic characteristics, to support several different types of operations. For example, a PTM clearance could be used for a short duration to allow an aircraft to climb through the altitude of another aircraft, or could be used for an extended period of time (e.g., same track, same altitude).

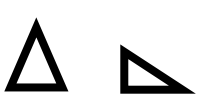
The availability of a PTM clearance in a given situation does not necessarily make it the preferred option for the controller. PTM is not intended to take away the controller's discretion in managing the traffic in their sector; PTM is an additional option for the controller to use as needed or desired.

There are also times when PTM is not an available option for the controller. One example of this is when the two aircraft are out of ADS-B range from each other (since the PTM aircraft must be receiving the ADS-B signal of the designated aircraft to accept the clearance and manage spacing). Additionally, other operational conditions may cause the flight crew to refuse the PTM clearance. This could include situations when PTM operations would require the flight crew to fly a speed that is faster or slower than the aircraft can maintain. In addition, certain traffic encounter geometries may prevent the availability of PTM to be used by either the controller or the flight crew (e.g., head on traffic encounter geometries).

The following sections include descriptions of two typical PTM scenarios that illustrate details of the PTM concept. For all graphic depictions in this document, the following applies:



These symbols are directional, and the color indicates background aircraft.



These symbols are directional, and the bold border indicates designated aircraft.

These symbols are directional, and the color indicates PTM aircraft.

These symbols are directional, and the color indicates the aircraft are PTM aircraft as well as serving as a designated aircraft for another PTM aircraft.

These symbols indicate aircraft 2 (AC2) is a PTM aircraft and aircraft 1 (AC1) is the designated aircraft for the PTM operation that AC2 is conducting.

A.3.1 Same-Track, Altitude Change Scenario

In this scenario, the PTM aircraft (AC2) is requesting a climb that would not be possible with current separation standards.

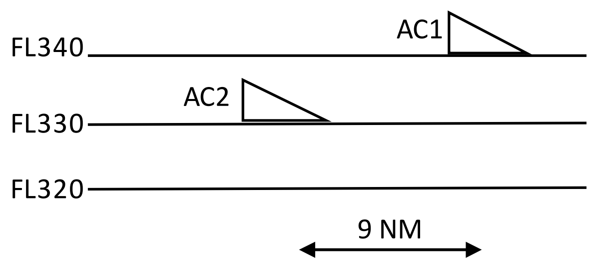


Figure A.1 Same-track, altitude change scenario.

Figure A.1 is a profile view representation of two aircraft (AC1 and AC2) operating at different altitudes on an identical track. In this scenario, the crew of AC2 has requested, for operational reasons, an altitude change from FL330 to FL340.

Using non-PTM separation distances the requested climb would be denied due to traffic (AC1) at FL340. However, because AC2 has indicated that it is PTM equipped in its flight plan, the ground automation system would indicate the possibility of issuing a PTM clearance, which if accepted, would allow the controller to subsequently issue a climb clearance.

If PTM is acceptable from a controller's perspective, the controller would issue a PTM clearance to AC2 instructing it to conduct PTM on AC1. Once the clearance is received by AC2 (the PTM aircraft), the PTM clearance information would be loaded into the FIM equipment. The FIM equipment would check the acceptability of the PTM clearance and display PTM speed guidance the flight crew would be expected to follow should they accept the clearance. The flight crew would review the proposed PTM speed guidance (fixed Mach speed or Mach speed range) to determine if the proposed guidance would be operationally acceptable. The flight crew would also review other information that could influence their decision to accept or reject the PTM clearance. This would include assessing potential future speed restrictions based on the current speeds of the designated aircraft (e.g., the eventual speed the PTM aircraft may be required to fly due to the speed of the designated aircraft). Other information that could influence the flight crew's decision would include aircraft performance, weather conditions, available ride information and general traffic situation awareness.

If the proposed guidance and clearance were acceptable, the flight crew would engage the FIM equipment and accept the clearance. With the PTM operation engaged, a single speed or a speed range is continuously displayed by the FIM equipment to the flight crew. If the proposed guidance or situation is unacceptable, the flight crew clears the proposed PTM guidance in the FIM equipment, rejects the clearance with ATC and continues normal operations.

Once the controller has received confirmation that the PTM clearance has been accepted, the controller would then clear AC2 to climb to and maintain FL340. The PTM aircraft would then start a normal climb to FL340. The flight crew follows the speed guidance provided by the FIM equipment throughout PTM operations. Figure A.2 below is an illustration of the situation once the climb to FL340 has been completed.

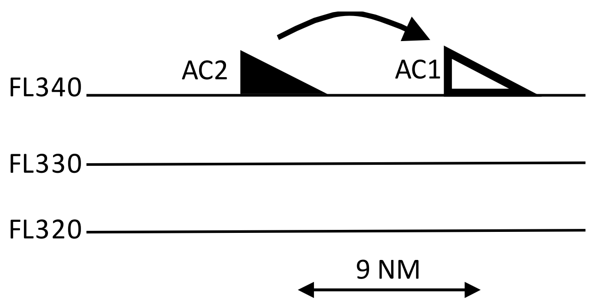


Figure A.2 Same-track, altitude change scenario.

Messages have been developed for PTM and are included in recently published versions of RTCA documents DO-350, DO-351 AND DO-352. These documents contain the standards that have been adopted for Baseline 2 ATS Data Communications. The combination of messages used to support PTM operations is called a message queue. The message queue consists of a list of CPDLC messages showing the destination, the sender, and the message.

Due to the complexity and importance of the structure of these messages, it is anticipated that the logic for these message queues would be built into ground automation systems used to support PTM operations. The rules for creating these message queues is documented and contained in the PTM Operational Performance Assessment (OPA) materials.

A sample of communications for this scenario are listed below. The format of these messages includes the recipient of the message (the destination) and who is sending the message (sender).

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.83
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.83
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

When the controller determines that a non-PTM separation standard has been achieved, the controller may terminate the procedure and instruct the crew to resume normal operations.

A.3.2 Intersecting Track Scenario

There will be cases where PTM will be used to support intersecting track situations. For the intersecting track situation shown in figure A.3 below, aircraft AC2 and AC1 are moving towards a loss of separation situation in an oceanic environment with a 30 NM minimum separation distance. The aircraft are both at FL310 and Mach 0.80. Without PTM, the controller would need to instruct one of the two aircraft to change its altitude or speed. However, because AC2 has indicated that it is PTM equipped in its flight plan, the ground automation system would indicate the possibility of issuing a PTM clearance for the controller. The controller can use a PTM clearance to resolve the conflict. If PTM is acceptable from the controller's perspective, the controller would issue a clearance to AC2 instructing it to conduct PTM on AC1.

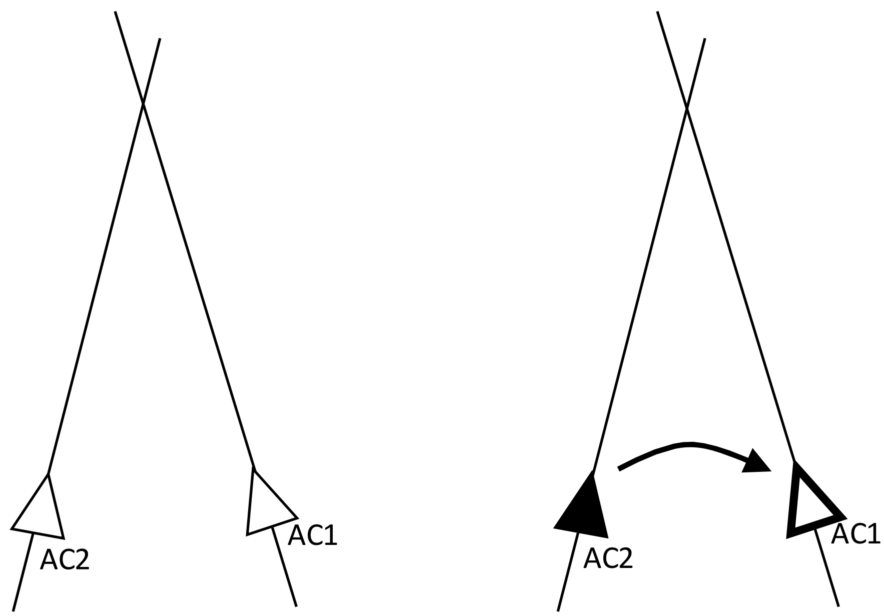


Figure A.3 Intersecting tracks scenario (prior to and after PTM is engaged).

When the PTM clearance is received by AC2, the PTM clearance information would be loaded into the FIM equipment. The acceptability of the PTM clearance would be checked against associated criteria required for PTM operations. The FIM equipment uses data received from AC1 and the ground automation system to predict the time, location, and separation distance at the closest point of approach. If the traffic situation is such that the distance at the closest point of approach is less than the PTM-enabled separation minima, the system displays Mach guidance to the flight crew that would ensure the required spacing between the PTM aircraft and the designated aircraft is satisfied during the PTM operation.

As before, the flight crew would review the proposed PTM speed guidance (fixed Mach speed or Mach speed range) to determine if the proposed guidance would be operationally acceptable. The flight crew would also review other information that could influence their decision to accept or reject the PTM clearance. This would include assessing potential future speed restrictions (e.g., the eventual speed the PTM aircraft may be required to fly due to the speed of the other aircraft) based on the current speed of the designated aircraft. Other information that could influence the flight crew's decision would include aircraft performance, weather conditions, available ride information and general traffic situation awareness.

If the proposed guidance was acceptable, the flight crew would engage the FIM equipment and accept the clearance. It is likely that, while the aircraft will pass too close for a non-PTM separation standard, the aircraft will be significantly farther apart than required for the PTM separation standard. The flight crew follows the speed guidance provided by the FIM equipment throughout PTM operations. A sample of the messages used for this scenario are listed below:

Message Queue [Destination, Sender]
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH CROSSING AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC2, ATC] CANCEL PTM, RESUME NORMAL MACH
[ATC, AC2] WILCO

Once the aircraft have passed the closest point of approach and the controller determines that a non-PTM separation standard has been achieved (e.g., 30 NM), the controller may terminate the PTM procedure.

A.4 ASSUMPTIONS AND CONSTRAINTS

There are several key assumptions and constraints associated with PTM operations. These are outlined below and then demonstrated in the PTM operational scenarios section (section A.5).

A.4.1 PTM Separation Standard and PTM Spacing Distance

A key component of PTM is a reduced minimum distance, referred to as the PTM separation standard distance, enabled by active ADS-B In monitoring and real-time, closed-loop interval management control. The PTM separation standard distance is a horizontal distance that the PTM aircraft must not get closer than during PTM operations. PTM aircraft can be at distances that are greater than this minimum distance but the horizontal distance between a PTM aircraft and all designated aircraft must never be less than the PTM separation standard distance while a PTM operation is in effect. The PTM separation standard distance is applicable in along-track scenarios as well as intersecting track operations. This PTM separation standard distance will be determined by safety and performance analyses. Initial analyses indicate this distance could be set at 5 NM.

The PTM spacing distance is the PTM separation standard distance plus a buffer. The size of the buffer is operation specific. The buffer is 1.5 NM for along-track operations and 3.5 NM for intersecting track operations. This results in a total PTM spacing distance of 6.5 or 8.5 NM. The intent of this buffer is not to imply precise management of the PTM spacing distance or to drive the PTM aircraft to a specific spacing objective, but to ensure that the PTM separation standard distance is not violated for wide-ranging operational behaviors and situations.

A.4.1.1 Along-track PTM spacing distance

When aircraft are on the same track, a spacing buffer must be applied to ensure that aircraft do not get closer than the PTM separation standard distance during normal operations. One typical scenario that demonstrates the importance of this buffer is when two aircraft are on the same route and the route includes a turn at a waypoint. In situations such as these, the along-track distance will remain the same but the absolute range will be reduced below the along-track range.

This is shown in figure A.4 below where the PTM separation standard distance is assumed to be 5 NM and the PTM spacing distance is 6.5 NM (i.e., a 1.5 NM buffer). Prior to the turn at the waypoint, both aircraft have an absolute range and along-track range of 6.5 NM. Once the aircraft are on opposite sides of the turn, the absolute range will be less than 6.5 NM but the along-track range will remain at 6.5 NM.

The extent of this buffer affects the acceptable geometries for feasible PTM operations, generally limiting turn angles to no greater than 45 degrees.

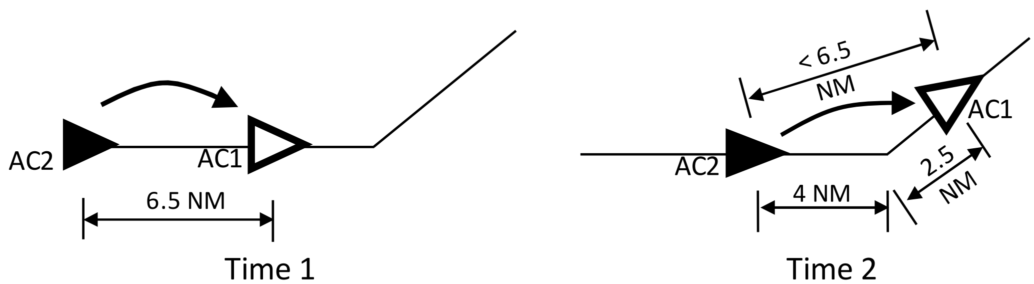


Figure A.4 Along-track PTM spacing distance.

A.4.1.2 Intersecting track PTM spacing distance

Similar to the same track scenario, the specific geometry of the operation must be considered when determining the PTM spacing distance needed to ensure the 5 NM PTM separation standard distance is not violated. The same nominal operations, such as turns, apply which would result in the buffer being set at 1.5 NM. However, the crossing case requires an additional buffer to account for the possibility of aircraft performing a Strategic Lateral Offset Procedure (SLOP). A lateral offset of up to 2 NM to the right can be performed by aircraft in oceanic operations, at any time, without clearance or notification to Air Traffic Control. Aircraft that are performing SLOP can also return to centerline without clearance or notification. The possible SLOP combinations could lead to an error in the position of the assumed crossing point as depicted in figure A.5 below.

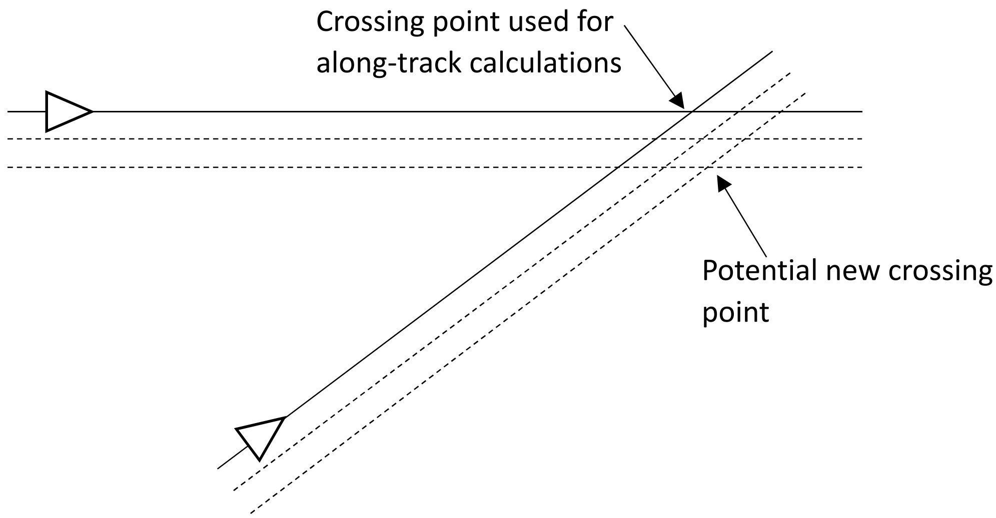


Figure A.5 Intersecting track PTM spacing distance considerations.

This error is accounted for by an additional 2 NM buffer bringing the total buffer to 3.5 NM and the total PTM spacing to 8.5 NM. It should be noted that the effect of SLOP in same-track operations is accounted for in the original 1.5 NM buffer, but the potential difference in path length from SLOP combinations is much smaller. Similar to the same-track scenario, the acceptability of this 8.5 NM PTM spacing is predicated on assumed geometries, such as intersection angles of no greater than 45 degrees.

Importantly, since ensuring this PTM separation is the operational intent, the PTM spacing objective is assessed as a horizontal range between the aircraft at an estimated point of closest approach.

A.4.1.3 PTM operations during altitude change maneuvers

There are scenarios (as demonstrated in section A.3.1 above) where PTM is used to enable altitude change maneuvers. These include situations where an aircraft desires a change to the same altitude of another aircraft or where an aircraft is flying “through” the altitude of another aircraft.

The first step in this procedure is to establish PTM operations with the designated aircraft. This is to ensure that during altitude change maneuvers, there is valid longitudinal and lateral separation between the PTM aircraft and the designated aircraft before vertical separation is lost and throughout the ensuing PTM operation. Once PTM is established the altitude change clearance can be issued.

It is important to point out that with PTM, FIM equipment will provide PTM Mach guidance to manage spacing with designated aircraft, even if those aircraft are at different altitudes. This is because the PTM separation standard is a longitudinal and lateral separation standard and takes no “credit” for vertical separation.

In the illustration below (figure A.6), for an aircraft climbing, PTM is first established between AC2 and AC1. Once engaged, the FIM equipment will provide PTM Mach guidance that will enable AC2 to manage spacing with AC1 even while AC2 remains at the original altitude. Once the controller has received a reply from the flight crew that

PTM has been established between AC2 and AC1, AC2 is cleared to climb. AC2 then climbs to the desired altitude and continues to follow the PTM Mach guidance.

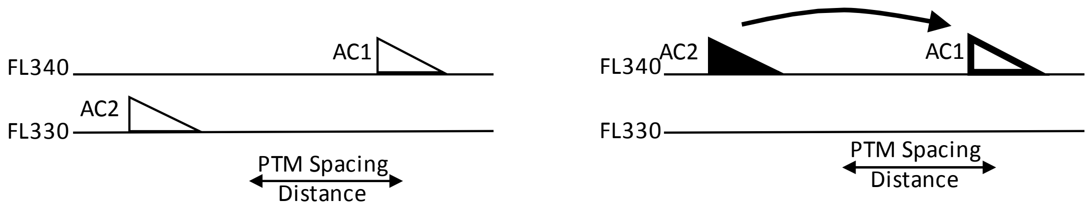


Figure A.6 PTM operations during altitude change maneuvers.

Messages supporting this operation are listed below:

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.83
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.83
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

A.4.2 Multiple PTM Operations within a non-PTM Separation Distance

When there are multiple aircraft performing PTM in a sequence within a non-PTM separation standard distance, some special rules apply. In this case, PTM must be conducted on all aircraft that are within the non-PTM separation standard distance. This ensures there is an appropriate separation standard being used between all pairs of aircraft.

In the illustration in figure A.7 below, PTM aircraft AC2 is conducting PTM on designated aircraft AC1. PTM aircraft AC3 is conducting PTM operations on AC2 (in the direction of the designated aircraft AC1). However, because AC3 and AC1 are within the minimum non-PTM separation standard distance, AC3 must also conduct PTM on the designated aircraft AC1. Without this addition, there is no applicable separation between AC3 and AC1.

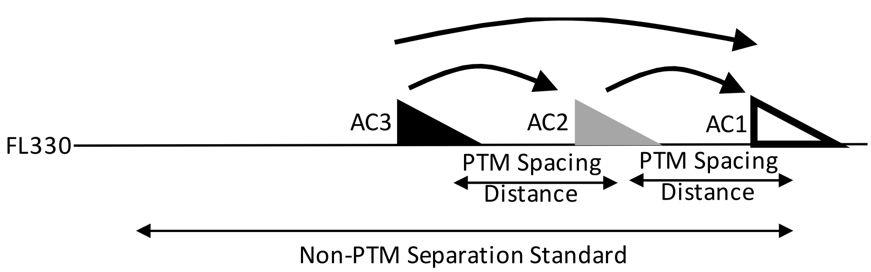


Figure A.7 Multiple PTM operations within a non-PTM separation distance.

A.4.3 Clearance Type

PTM operations involve many new features and behaviors when compared to other IM applications. These new features are not counter to the core capabilities of IM, which is to use ADS-B In data to actively manage aircraft intervals, but are suggestive of a specific operational intent. Since the operational intent of PTM is to ensure the PTM aircraft gets no closer than a minimum separation distance, while not performing to a precise spacing objective, PTM uses a new IM clearance type called “No Closer Than”.

A.4.4 PTM Algorithm Description

A PTM algorithm has been developed to provide part of the airborne functionality needed to perform PTM operations. There is a top-level module named the executive module. The executive module receives PTM clearances from ATC and using the PTM operations criteria and other information, advises the crew whether the PTM clearance should be accepted or rejected. If the flight crew accepts the PTM clearance, the executive module is invoked continuously to provide speed guidance to the flight crew to ensure appropriate spacing from the designated aircraft. The executive module also receives clearances to add designated aircraft to an existing PTM operation and to terminate PTM operations with existing designated aircraft.

Other modules and functions that comprise the airborne PTM algorithm include the Along-Track module, the Intent Speed Resolution module, and the Alert function. The Along-Track Module calculates the speed guidance using a state projection of the ownship and designated aircraft. The Intent Speed Resolution module calculates a speed guidance using the current location, the next waypoints, the next-plus-one waypoints, and the estimate time of arrivals to the waypoints of the ownship and designated aircraft. The alert function produces predicted, imminent, and actual loss of spacing alerts. The executive module selects between the Along-Track and Intent Speed Resolution modules to produce the speed guidance. Selection is determined by the type of clearance, geometry, waypoint locations, and other criteria.

A.4.4.1 Calculation of along-track PTM Mach guidance

The along-track algorithm generates Mach guidance that, if followed, will ensure that the inter-aircraft spacing is no closer than the PTM minimum distance during the PTM operation. The objective of the algorithm is for the PTM aircraft to manage spacing from the designated aircraft in a safe and efficient manner.

The spacing is the sum of a separation standard minimum distance and buffer distance. The algorithm gives speed guidance to achieve the spacing. If the along-track distance is greater than the spacing, the algorithm could give speed guidance such that the along-track distance can be reduced. When the along-track distance is at or near the spacing, the algorithm will give speed guidance to maintain the spacing.

An example of how this works can be seen in the following example. In figure A.8 below, AC1 is a designated aircraft for PTM aircraft AC2. AC1 is flying at a Mach speed of M=0.80. For operational reasons, in this example, AC2 can fly no slower than M=0.75 and it is currently 25 NM away from AC1. Since AC2 is behind AC1, the along-track algorithm will calculate an upper speed guidance that AC2 can fly. Details for determining this speed guidance can be found in the OPA materials.

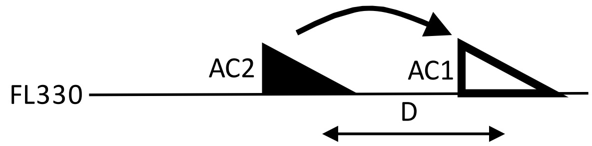


Figure A.8 Closing PTM aircraft behind a designated aircraft.

For this situation, the along-track algorithm will provide an upper guidance of M=0.86. At this distance, the flight crew would be provided a PTM Mach guidance range of M=0.75 (the lower bound) to M=0.86 (the current algorithm calculated upper bound). As a result, if the flight crew chose to fly at the upper bound of M=0.86, AC2 would close to a distance of 6.5 NM with AC1 in 30 minutes. However, as AC2 gets closer to AC1, the Mach guidance will change and the upper speed guidance will be less than M=0.86.

The Mach guidance will be updated as the operation continues. This is done in increments of M=0.01. At each update, the upper Mach guidance will ensure that it would take at least 30 minutes to close the distance to 6.5 NM. However, once the PTM Mach guidance is within M=0.01 of the designated aircraft's Mach (in this case M=0.80), the upper Mach guidance would stay M=0.01 above the designated aircraft Mach until the two aircraft are within 6.5 NM (with hysteresis effects built into the logic to minimize short-term fluctuations in the Mach guidance). Sample Mach guidance that could be provided to the crew for various distances between the two aircraft is shown below:

Distance	25 NM	7 NM	6.5 NM
Upper bound Mach guidance	M=0.86	M-0.81	M=0.80
Lower bound Mach guidance	M=0.75	M=0.75	M=0.75

A.4.4.2 Flight crew input of operating Mach number range

The default maximum and minimum possible values of Mach numbers provided to flight crews during operations would be set based on the maximum and minimum possible values the aircraft is capable of flying. During initial studies, flight crews have expressed a desire to have a method to input the operating Mach range they are able and/or willing to fly at a given time. The algorithm is designed in such a way that it would permit the flight crew to enter minimum and maximum possible values at any time during the flight. If the flight crew is currently conducting PTM operations, the current PTM Mach guidance provided by the PTM algorithm will be contained within the minimum and maximum bounds set by the flight crew.

Additional details of the PTM algorithm are included with the PTM OPA materials.

A.4.5 ADS-B Signal Range Impact on PTM Operations

For oceanic operations, there are widely varying separation standards applicable for the controller to use with a specific aircraft pair. These typically vary from as small as 30 NM to as long as 15 minutes (approximately 120 NM in distance) between the aircraft (it should be noted that there is other work being done to further reduce these standards and these should be considered as they are approved). During normal operations, most ground automation systems report projected losses of separation (traffic conflicts) and often display which separation standards may be available to the controller to solve the traffic conflict. If the ground automation system reports that the conflict is with a PTM aircraft and a suitable designated aircraft, PTM would be one of the potential options listed to the controller.

It is possible that at the time the conflict is reported by the ground system, the onboard FIM equipment may not have the designated aircraft ADS-B signal identified due to ADS-B signal range limitations. Typically, ADS-B signals are received up to an average of 180 NM away. If the two aircraft are at a distance that is greater than a nominal ADS-B signal range at the time the PTM clearance were issued, it is likely that the flight crew would not be able to identify the designated aircraft and it would be necessary for the flight crew to refuse the clearance.

To maximize acceptance of PTM clearances, the controller should wait until the ground automation system computes that the two aircraft are close enough to each other (within an expected ADS-B range) so that there is a high probability that the FIM equipment will be able to identify the designated aircraft and enable acceptance of the PTM clearance. This expected ADS-B range could be a facility configurable parameter that could be adjusted as experience with ADS-B signal range is obtained.

Another aspect of operations that would go into this decision-making process is the time or distance prior to a predicted loss of separation when the controller needs to issue a clearance. This is often determined either by local policy and/or controller comfort levels. For example, in most US managed oceanic airspace, controllers are notified by ground automation of a conflict two hours prior to the loss of separation and should be in the process of resolving the conflict at least 30 minutes prior to the predicted loss of separation.

As a result, the nominal ADS-B range (approximately 180 NM) and time prior to loss of separation that traffic conflicts are resolved impacts the use of PTM operations. This is particularly true for intersecting track geometries.

If a controller has a conflict with two aircraft with a 30 NM separation standard, and the controller wants to issue a clearance 40 minutes prior to the predicted loss of separation in an environment with a 180 NM expected ADS-B range, the crossing angle for PTM would be limited to approximately 30 degrees. This can be illustrated in the following example.

In figure A.9 (below) the two aircraft are about 40 minutes away from a loss of separation (both flying at M=0.80). With a 30-degree crossing angle the range of the two aircraft would be approximately 170 NM 40 minutes prior to the loss of separation.

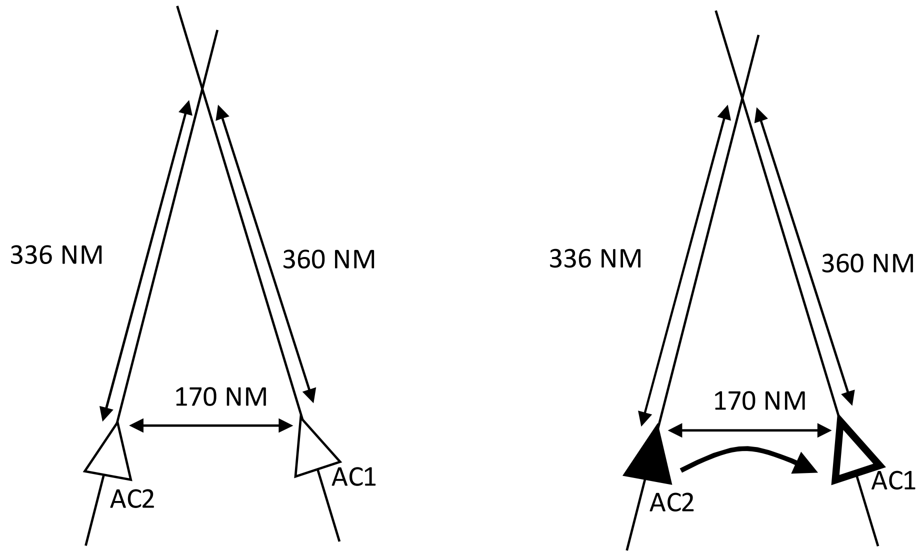


Figure A.9 Impact of ADS-B range on intersection track operations.

In this example, it is assumed that the current minimum separation available with the ATC automation system is 30 NM. The ground automation will report a traffic conflict between these two aircraft. The controller will review the situation to determine the best resolution to the conflict, including whether PTM is a suitable solution. An important part of that decision will be determining when it will be possible to issue the PTM clearance. The ATC automation system will indicate whether PTM is available now or at some later time. With a 30-degree crossing geometry, the earliest time to issue a PTM clearance would be approximately 40 minutes prior to the predicted loss of separation. The controller could then issue a PTM clearance.

If the aircraft are currently further away from the predicted loss of separation (e.g., 60 minutes from the predicted loss of separation), the ground system would indicate to the controller that PTM is not available at that moment but will be available in 20 minutes. The controller would then have the freedom to either wait for 20 minutes before issuing the clearance or decide to use a different approach for resolving the traffic conflict (e.g., issue a flight level change to one of the aircraft if that was available).

Messages to support intersecting track scenarios are similar to the along-track scenarios messages. A sample of messages to support the PTM operation depicted in figure A.9 is listed below:

Message Queue [Destination, Sender]
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH CROSSING AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC2, ATC] CANCEL PTM, RESUME NORMAL MACH
[ATC, AC2] WILCO

A.4.6 Aircraft Sequence Geometries

PTM operations can involve a number of different geometric configurations. These are based on the number of PTM aircraft and designated aircraft. The most basic PTM geometry is between two aircraft, a PTM aircraft and one designated aircraft. These two aircraft together form a PTM Pair.

When there are more than two PTM aircraft in a sequence and only one designated aircraft at either end of the sequence, these aircraft form a PTM String. Finally, if there are two designated aircraft at either end of a sequence with one or more PTM aircraft between them, that situation is called a PTM Chain. A more detailed description of these geometries is contained below.

A.4.6.1 PTM Pairs – single target geometries

A PTM Pair is formed when:

- There are two aircraft in a sequence,
- The separation standard between the two aircraft is PTM separation
- There is one PTM aircraft and one designated aircraft.
-

Figured A.10 shows examples of PTM Pairs.

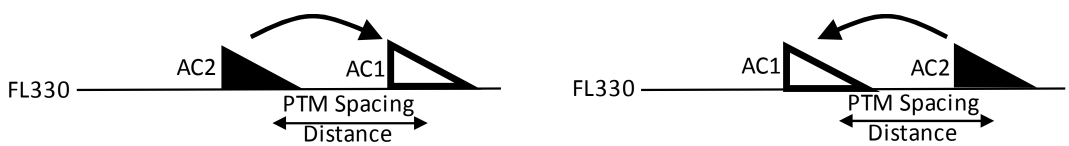


Figure A.10 PTM Pairs – single target geometries.

PTM aircraft can be ahead of or behind a designated aircraft and any combination of ahead of and behind when there are multiple designated aircraft. Figure A.10 is an example of two these different situations. It is important to point out that a designated non-PTM aircraft could be PTM equipped, but it has not been cleared and it is not conducting a PTM operation.

In the figure on the left, the PTM aircraft is behind the non-PTM (designated) aircraft. For the diagram on the right, the PTM aircraft is ahead of the non-PTM (designated) aircraft. The arrow shows the “direction” of the PTM operation.

The obvious effect here is that the behavior of the speed guidance bounds would be reversed. With the PTM aircraft behind the designated traffic, the upper bound would be based on the speed of the designated aircraft; while if the PTM aircraft were ahead of the designated traffic, the lower bound would be based on the speed of the designated aircraft.

This position behavior also applies to other PTM sequences detailed below.

A.4.6.2 PTM Strings

A PTM String is formed when:

- There are more than two aircraft in a sequence
- There is only one designated aircraft in the sequence
- The designated aircraft is leading or trailing the sequence

Figure A.11 illustrates two types of PTM Strings. The arrows illustrate the direction of the PTM operation.

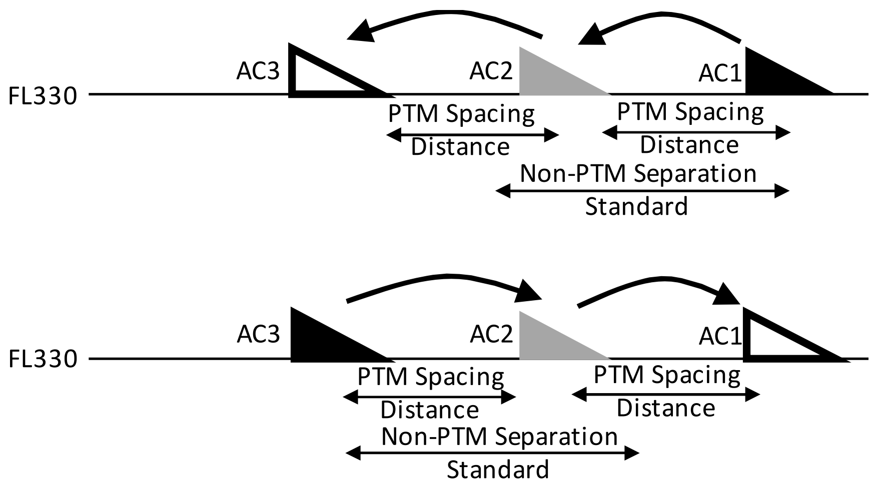


Figure A.11 PTM Strings – multiple PTM aircraft, one designated aircraft.

In the diagram on the top, within figure A.11, aircraft AC3 is the designated aircraft in the String. Aircraft AC2 is conducting PTM operations with aircraft AC3. Aircraft AC1 is conducting PTM operations on aircraft AC2. In the diagram on the bottom, aircraft AC1 is the designated aircraft in the string, aircraft AC2 is conducting PTM operations with AC1, and aircraft AC3 is conducting PTM operations with AC2.

A.4.6.3 PTM Chains

A PTM Chain is formed when:

- There are more than two aircraft in a sequence,
- There are two designated aircraft in the sequence, one leading and one trailing,
- The separation standard between the two designated aircraft is a non-PTM separation standard,
- All PTM aircraft in the sequence must be assigned and maintain PTM separation from all designated aircraft in front of and all designated aircraft behind the PTM aircraft

See figure A.12 below.

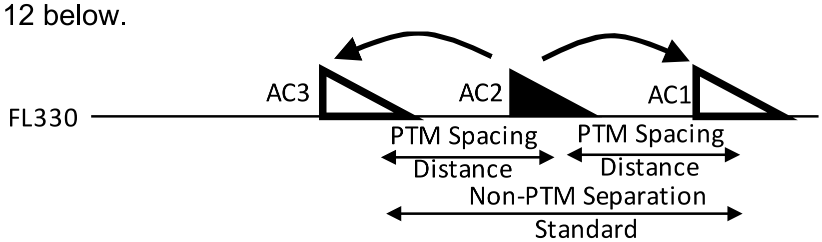


Figure A.12 Example of a PTM Chain.

A.4.6.4 PTM Strings and Chains Application and Rules

A common PTM clearance that is enabled by strings and chains occurs when an aircraft on the same track requests a climb that would occur between two aircraft that are flying at the desired altitude in trail of each other with less than twice the minimum standard separation between them. If that is the case, there is no room between them to insert an additional aircraft based on current non-PTM separation standards. If, however, the additional aircraft is PTM equipped, it would be possible to clear the additional aircraft into this otherwise unusable airspace, and thus permit more efficient operations. This is illustrated in figures A.13 and A.14 below.

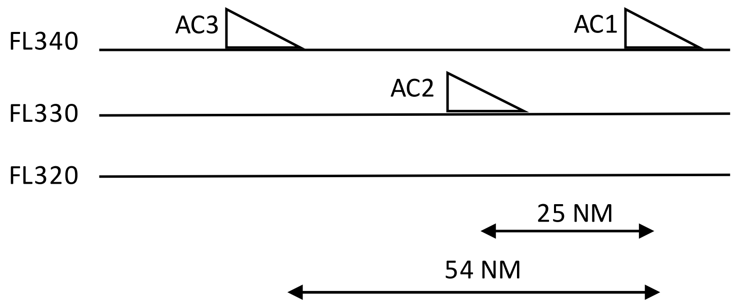


Figure A.13 Initial condition prior to a climb into a PTM Chain.

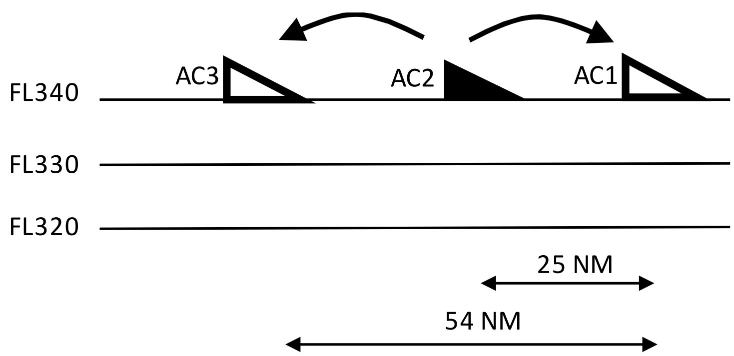


Figure A.14 Geometry once the climb into a PTM Chain has been completed.

Messages that would support this operation are listed below:

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.83
[AC3, ATC] MAINTAIN MACH 0.83
[ATC, AC3] WILCO
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, AHEAD of AC3, LIMIT MACH FOR PTM OPERATION 0.83
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

Speed guidance would be provided by the FIM equipment to keep the PTM aircraft at a distance greater than the PTM minimum from both aircraft. ATC will ensure that non-PTM separation will be maintained between AC3 and AC1.

A complete set of rules for pairs, strings and chains has been developed and is included in Appendix A-1. Because of the complexity of the rules necessary for strings and chains, it is anticipated that they will be included in the ground automation system, as well as in the airborne equipment (as needed). A rule that must be enforced by the ground automation is the independence of PTM operations. That is, the PTM concept does not allow for “interacting” PTM operations. For purposes of interacting operations, a PTM operation is represented by the aircraft contained in a pair, string, or chain. Interacting operations are defined to be when a single designated aircraft is involved in two different PTM operations. For example, an intersecting track PTM operation cannot be performed with an aircraft in a string if at least one of the aircraft would be a designated aircraft for the string and the intersecting track operation. Additionally, when conducting along-track operations, no aircraft can be involved in separate PTM operations both in front and behind them.

A.4.7 Impact of a non-PTM aircraft behind a string

In figure A.15 below, AC2 is conducting PTM operations with AC1 as the designated aircraft. AC3 is also conducting PTM operations with AC2 and AC1 as designated aircraft. All three aircraft are currently flying at M=0.80. AC4 is currently flying at M=0.82 and is slowly getting closer to the AC3 (but is far enough away that the controller is responsible for maintaining separation from the string of aircraft).

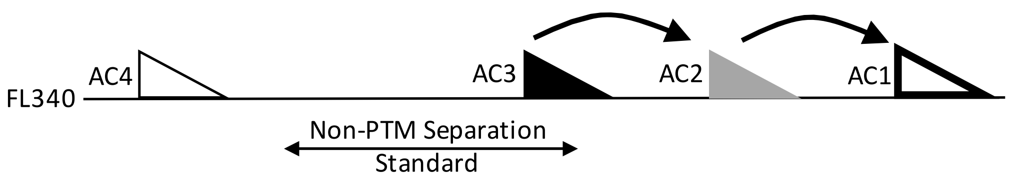


Figure A.15 Example of an aircraft closing on a PTM String.

As AC4 approaches the string, the ground automation system will alert the controller to a conflict. The controller has three potential approaches to solve this conflict. The controller could consider slowing AC4. If a different altitude is available, the controller could clear AC4 to a different altitude. Finally, if AC4 is PTM equipped, the controller could send the required clearances to add AC4 to the existing PTM String resulting in the configuration shown in figure A.16.

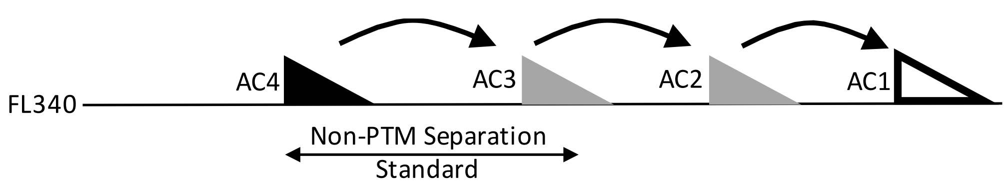


Figure A.16 Example of the situation after an aircraft has been added to a PTM String.

Messages associated with this operation are as follows:

Message Queue [Destination, Sender]
[AC4, ATC] CLEARED PTM MACH BEHIND AC3, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC3, ATC] DESIGNATED PTM TRAFFIC FOR AC4

A.4.8 Limit Mach

As part of a PTM clearance, PTM aircraft are assigned a Limit Mach by ATC. The objective of this Limit Mach is to ensure PTM flight crews are not directed to fly a Mach during a PTM operation that they are unwilling or unable to fly. For trailing operations (where the PTM aircraft is behind the designated aircraft), the Limit Mach would be a minimum Mach number the aircraft could be directed to fly by the FIM equipment. For leading operations (where the designated aircraft is behind the PTM aircraft), the Limit Mach is a maximum Mach number the aircraft could be directed to fly. Flight crews will be required to review the assigned Limit Mach and determine if it is acceptable. If the assigned Limit Mach is unacceptable, flight crews should refuse the PTM clearance.

Limit Mach is calculated by the ground automation system. There are a set of rules for determining limit Mach for clearances and PTM operations. These rules are documented and contained in the PTM OPA materials. The following figures help illustrate how limit Mach is calculated and used during PTM operations.

In figure A.17, AC1 is an ADS-B out aircraft flying at FL340 and M=0.80. AC2 is a PTM capable aircraft, flying at FL330 and M=0.79. AC2 sends a request to ATC for an altitude change from FL330 to FL340. ATC's ground automation indicates this climb can be supported using PTM. If AC1 does not have a current Mach assignment, ATC sends a Mach assignment clearance to AC1 to maintain 0.80 or greater.

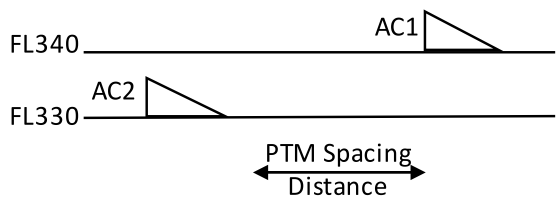


Figure A.17 Example of Limit Mach assignment scenario (trailing operation) prior to PTM clearance.

The ground automation then calculates the Limit Mach that would be assigned to AC2. Since this operation is a trailing operation (the designated aircraft AC1 is ahead of AC2) the Limit Mach is defined to be the minimum of the designated aircraft's assigned Mach or the PTM aircraft's current Mach. For this example, the Limit Mach would be the PTM aircraft's current Mach (M=0.79). ATC sends a PTM clearance to AC2 to follow behind AC1 (while AC2 is still at FL330). The Limit Mach is sent to the aircraft as part of the clearance message.

At the time the clearance is received, the FIM equipment and flight crew evaluate the clearance to determine if the clearance can be accepted. Part of this evaluation includes an evaluation of the ability of AC2 to fly the Limit Mach of 0.79. The flight crew determines if the clearance, including the Limit Mach, is acceptable. The flight crew for AC2 engages the FIM equipment and the speed guidance produced by the FIM equipment will have the lower bound limited to M=0.79. The upper bound of the speed guidance is determined by the PTM algorithm and is a function of the distance between the aircraft and the current speed of the designated aircraft. The flight crew then accepts the clearance and ATC clears AC2 to climb to FL340. Figure A.18 shows the result of receiving the appropriate clearances (which includes the Limit Mach number) and then climbing to FL340.

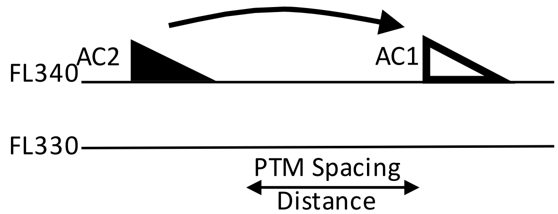


Figure A.18 Example of Limit Mach assignment scenario (trailing operation) after PTM clearance acceptance and climb to new altitude.

The messages used to support the PTM climb scenario are shown below:

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.79
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

An example of how Limit Mach is determined and used for a PTM operation in a leading operation is shown in figure A.19. AC1 is an ADS-B out aircraft flying at FL340 and M=0.80. AC2 is a PTM capable aircraft, flying at FL330 and M=0.79. AC2 sends a request to ATC for an altitude change from FL330 to FL340. ATC's ground automation indicates this climb can be supported using PTM. If AC1 does not have a current Mach assignment, ATC sends a Mach assignment clearance to AC1.

The ground automation then calculates the Limit Mach that would be assigned to AC2. Since this operation is a leading operation (the PTM aircraft is ahead of the designated aircraft) the Limit Mach is defined to be the maximum of the designated aircraft's assigned Mach or the PTM aircraft's current Mach. For this example, the Limit Mach would be the Mach of the designated aircraft's current Mach (M=0.80). ATC sends a PTM clearance to AC2 to conduct PTM ahead of AC1 (while AC2 is still at FL330). The Limit Mach is sent to the aircraft as part of the clearance message.

At the time the clearance is received, the FIM equipment and flight crew evaluate the clearance to determine if the clearance can be accepted, including the Limit Mach of 0.80. The flight crew for AC2 engages the PTM equipment and the speed guidance produced by the FIM equipment will have the upper bound limited to M=0.80. The lower bound of the speed guidance is determined by the PTM algorithm and is a function of the distance between the aircraft and the current speed of the designated aircraft. The flight crew then accepts the clearance and ATC clears AC2 to climb to FL340. Figure A.20 shows the result of receiving the appropriate clearances (which includes the Limit Mach number) and then climbing to FL340.

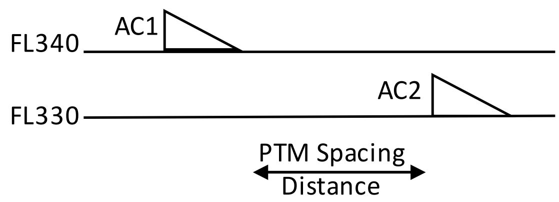


Figure A.19 Example of Limit Mach assignment scenario (leading operation) prior to PTM clearance.

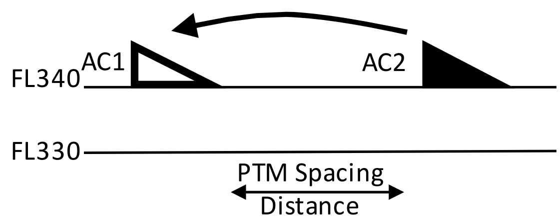


Figure A.20 Example of Limit Mach assignment scenario (leading operation) after PTM clearance acceptance and climb to new altitude.

The messages used to support the PTM climb scenario are shown below:

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

A.4.9 Flight Path Communication

The intended flight path of an oceanic flight can span thousands of miles in an environment with limited available means of communication. For ADS-C operations in this environment, an aircraft communicates an Extended Projected Profile (EPP) to ATC via CPDLC. This EPP consists of the sequence of waypoints and associated Estimated Time of Arrivals (ETAs) along the aircraft's flight path. For PTM, a set of this information is communicated to the PTM aircraft for the designated aircraft's Intended Flight Path Information (IFPI).

Additional IFPI may need to be communicated to the PTM aircraft during a PTM operation as IFPI is updated. For flight path construction, the PTM aircraft must, at a minimum, maintain awareness of the designated aircraft's current position, next waypoint, and waypoint after the next waypoint (and associated ETAs).

A.4.10 Point of Intersection and Traffic Intent

In a crossing scenario, it is worth noting that the actual point of intersection for the operation is unlikely to be a defined waypoint in the IFPI. For those situations, the FIM equipment will need to calculate the point of intersection based on the waypoint structure of both the PTM aircraft and the designated aircraft preceding and following an intersection. The potential errors in this calculation are included in the added buffer previously mentioned. Before the designated aircraft has sequenced the waypoint immediately preceding the calculated point of intersection, designated aircraft intent and subsequent range predications and speed guidance are based on the ETA to that waypoint. After the designated aircraft has sequenced the last waypoint prior to the calculated point of intersection, speed guidance is based on observed aircraft state.

This calculation of the point of intersection and intent behavior is true, whether the designated aircraft is crossing the intersection or merging at the point of intersection.

Generally, the behavior of PTM speed guidance in same track, crossing, and merging is the same. It bounds acceptable speeds based on operational development, provides these bounds as guidance, and will only present a singular commanded speed if PTM aircraft behavior is outside of these bounds or if the upper and lower limit are the same.

A.4.11 Future Items

While this document addresses many aspect of the PTM concept, there are still a few areas remaining to be developed. Some of those key areas include weather deviations, wake hazards and mitigations and oceanic airspace entry and exit (and coordination with radar sectors). These will be addressed in future versions of this document.

A.5 OPERATIONAL SCENARIOS

The following scenarios are included to illustrate the concept but are not intended to represent the complete range of possible PTM geometries or supporting systems' functionalities. Each scenario description gives an overview of the operation that is being performed, and what aspects of PTM each scenario is stressing.

A.5.1 Same-Track, Co-Altitude Scenario

In this first scenario, the PTM aircraft, operating at FL 330, is overtaking a co-altitude ADS-B Out aircraft on the same route. See Figure A.21 below.

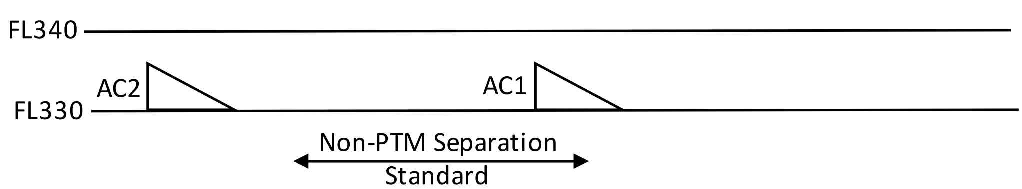


Figure A.21 Same-track, co-altitude scenario.

When the controller determines that a conflict exists and intervention action is required, the controller might issue the overtaking aircraft (AC2) a speed restriction to eliminate the overtake and ensure that AC2 gets no closer than a non-PTM separation standard distance.

However, if the ground automation indicates that a PTM clearance is available, the controller would have the option to issue a clearance to AC2 to conduct PTM on AC1 and maintain the current flight level. This clearance would allow AC2 to close to and maintain a distance greater than or equal to the PTM minimum distance with AC1 (figure A.22). Since this minimum distance is significantly less than the non-PTM separation distance, AC2 will be able to operate at the desired speed for a longer period of time, increasing the aircraft's overall performance.

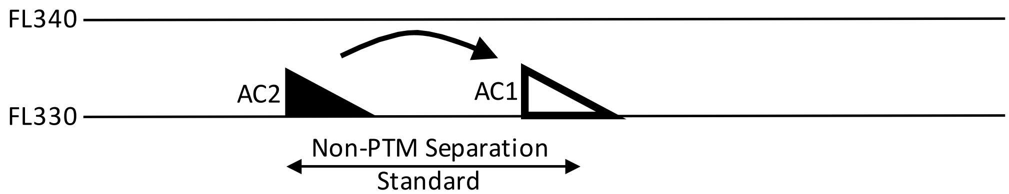


Figure A.22 Same-Track, co-altitude scenario.

Messages supporting this scenario are shown below:

Message Queue [Destination, Sender]
[AC1, ATC] MAINTAIN MACH 0.82
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.82
[ATC, AC2] WILCO

A.5.2 Same-Track, Altitude Change Scenario

In this scenario, the PTM aircraft is requesting a climb that would cause a conflict with an ADS-B out aircraft. Initially, it is possible that this will be the most common application of PTM.

General conditions:

- Aircraft are currently vertically separated
- Aircraft are on the same route

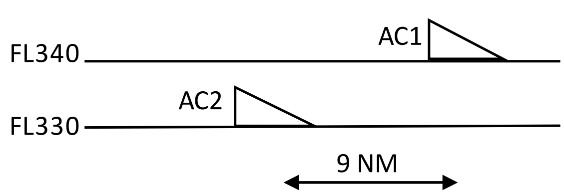


Figure A.23 Same-track, altitude change scenario.

Figure A.23 shows two aircraft (AC1 and AC2) operating on the same identical track. In this scenario, the crew of AC2 has requested, for operational reasons, an altitude change from FL330 to FL340.

The controller receiving the request would observe that the climb would result in an immediate conflict with AC1 at FL340 using non-PTM separation standard distances.

However, because AC2 has indicated that it is PTM equipped (on the flight plan), the ground automation system would indicate the possibility of a PTM clearance (for the controller to issue) that would provide a separation standard that would authorize a climb. The controller would issue a clearance to AC2 instructing it to conduct PTM on AC1.

The clearance information would be loaded into the FIM equipment and the flight crew would confirm acceptability of the PTM clearance. If acceptable, the flight crew engages the FIM equipment, follows the PTM guidance and accepts the clearance with ATC. With the PTM operation engaged, a speed (or speed range) will be commanded by the FIM equipment.

Once the controller has received confirmation that the PTM clearance has been accepted, the controller would then clear AC2 to climb to and maintain FL340. The PTM aircraft would then start a normal climb to FL340. The flight crew follows the speed guidance provided by the FIM equipment throughout PTM operations (figure A.24).

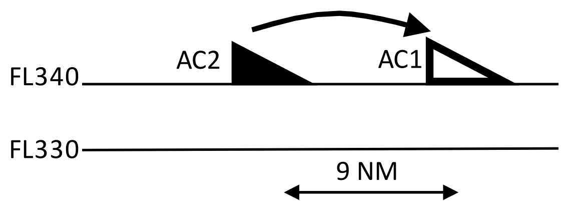


Figure A.24 Same-track, altitude change scenario.

Messages supporting this scenario are shown below:

Message Queue [Destination, Sender]
[ATC, AC2] REQUEST CLIMB TO FL340
[AC1, ATC] MAINTAIN MACH 0.83
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH BEHIND AC1, LIMIT MACH FOR PTM OPERATION 0.83
[ATC, AC2] WILCO
[AC2, ATC] CLIMB TO AND MAINTAIN FL340, REPORT REACHING FL340
[ATC, AC2] WILCO
[ATC, AC2] LEVEL FL340

A.5.3 Same-Track, Multiple Aircraft Interactions (Track Loading)

It is anticipated that a significant consideration in the benefit case will be the ability to have multiple, co-altitude, same identical track aircraft operating with different equipage levels and a PTM separation standard applied between aircraft. This is particularly beneficial when “loading” aircraft on fixed routes and organized track systems. This track loading occurs as aircraft transition from radar surveillance airspace to oceanic, non-radar airspace. The required spacing based on non-PTM separation distances often limits the number of aircraft that can enter a given track at a given altitude. There are times when aircraft must fly at less than optimal altitudes or fly different tracks. The reduced spacing due to PTM will mean that more aircraft will be able to fly where and when they want to for better aircraft and system performance. This is illustrated in figure A.25 below.

Figure A.25 Example of how PTM could be used to improve track loading.

A.5.4 Intersecting Tracks

PTM is also applicable for intersecting track situations. In general, there will be restrictions on the maximum possible crossing angle permitted by PTM. As stated earlier, this is often due to limitations of the ADS-B signal range, and the requirement that the controller resolve conflicts by some time or distance prior to the actual loss of separation. Typically, this will restrict the intersecting track angle to about 30 degrees.

For the crossing shown in figure A.26, aircraft AC2 and AC1 are moving towards a loss of separation in an oceanic environment (30 NM minimum separation). The aircraft are both at FL310, and Mach 0.80. The ground automation system is reporting that a loss of separation will occur in 38 minutes, when the distance between the two aircraft will decrease to less than 30 NM. The controller may choose to use a PTM clearance to resolve the conflict.

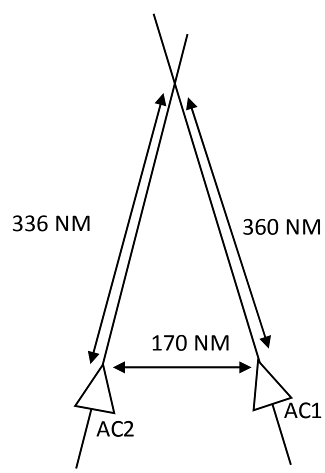


Figure A.26 Example of PTM operations with intersecting tracks.

When the PTM clearance is received by AC2, the PTM clearance information would be loaded into the FIM equipment. The acceptability of the PTM clearance would be checked against associated criteria required for PTM operations. The FIM equipment uses data received from AC1 and the ground automation system to predict the time, location, and range (horizontal distance) at the closest point of approach. This distance is called the projected closest distance (PCD). This displayed distance is a continuously updated value of the closest distance that ownship will get to the position of the designated aircraft. It is computed based on the current commanded speed of ownship and the current speed of the designated aircraft. As such, when the pilot changes his command speed, the PCD should show an immediate change in the PCD. If the traffic situation is such that the distance at the closest point of approach is less than the PTM-enabled separation minima, the system displays, to the flight crew, speed guidance (different from the current speed) that would ensure the required spacing between the PTM aircraft and the designated aircraft is satisfied during the PTM operation.

If the proposed guidance was acceptable, the flight crew would engage the FIM equipment and accept the clearance. It is likely that, while the aircraft will pass too close for a non-PTM separation standard, the aircraft will be significantly farther apart than required for the PTM separation standard. The flight crew follows the speed guidance provided by the FIM equipment throughout PTM operations (figure A.27).

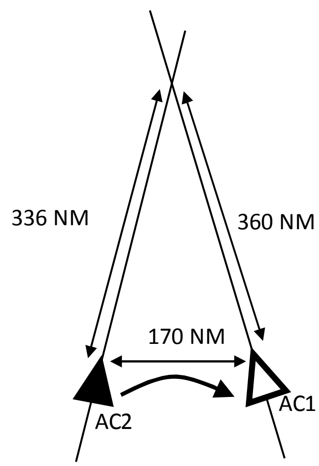


Figure A.27   Example of PTM operations with intersecting tracks.

Messages supporting this operation would be as follows:

Message Queue [Destination, Sender]
[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH CROSSING AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO
[AC2, ATC] CANCEL PTM, RESUME NORMAL MACH
[ATC, AC2] WILCO

Once the aircraft have passed the closest point of approach and the controller determines that a non-PTM separation standard has been achieved (e.g., 30 NM), the controller may terminate the PTM procedure.

A.5.5 Merging Tracks

PTM can also be utilized when the paths of two aircraft merge. This could happen with an aircraft joining an organized route structure at a waypoint along the route as illustrated in figure A.28 below.

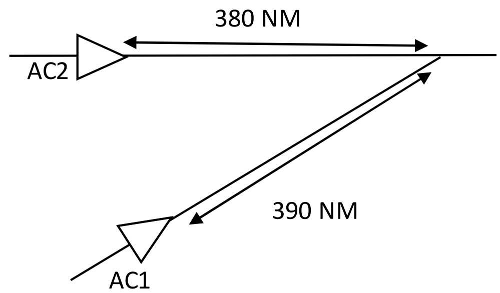


Figure A.28 PTM merging track scenario.

In this scenario, the controller predicts there would be a loss of separation if AC1 joined the track of AC2 using non-PTM separation standards. Without PTM, the controller would normally have to change the altitude or significantly change the speed of either AC2 or AC1. However, using PTM, the controller can avoid the altitude or significant speed change, and issue a PTM clearance to the PTM aircraft (figure A.29). The clearance message would include the expected relative position the controller is expecting for the operation (e.g., “ahead of” or “behind”). In the case above, the clearance to AC2 would be similar to “Cleared PTM MACH, merge ahead of AC1”.

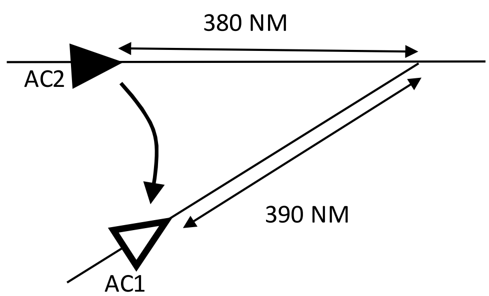


Figure A.29 PTM merging track scenario.

Messages supporting this operation would be as follows:

[AC1, ATC] MAINTAIN MACH 0.80
[ATC, AC1] WILCO
[AC2, ATC] CLEARED PTM MACH MERGE AHEAD OF AC1, LIMIT MACH FOR PTM OPERATION 0.80
[ATC, AC2] WILCO

While engaged, the FIM equipment compares ownship trajectory with the location and planned trajectory of the designated aircraft, and provides speed commands that are predicted to avoid a loss of spacing.

In the above example, the pair of aircraft will transition to an in-trail maneuver invoking use of the functionality described in earlier scenarios. Once established in the in-trail operation, the FIM equipment will continue to perform a PTM operation on all designated aircraft until a pair-specific terminate message is received from ATC. This could happen after route divergence, if vertical separation is established, or if a speed difference increases the distance between the PTM aircraft and the designated aircraft to a distance where a non-PTM separation standard can be applied.

A.5.6 Maximum Designated Aircraft Scenario

There is no conceptually dictated maximum number of designated aircraft that can be part of a PTM operation. However, taking into consideration common, non-PTM separation standard distances (e.g., 50 NM), it is assumed eight designated aircraft would be the practical maximum number of aircraft a PTM aircraft could encounter. These situations would likely involve aircraft that are transitioning from one PTM operation to another.

An example of one of these eight aircraft operations is show in figure A.30 below. In this example, AC5 is at the end of a PTM String. AC5 is conducting PTM on four designated aircraft and desires to climb to FL340. For ATC to clear AC5 up to FL340, ATC must first issue PTM clearance to AC5 to conduct PTM on the four aircraft currently at FL340, since they are all within the current non-PTM separation standard. Once AC5 accepts the modified PTM clearance and is performing PTM on all eight-designated aircraft, then ATC is able to issue the climb clearance. Once AC5 reports level at FL340, then ATC is able to remove the four designated aircraft at FL330 from AC5's PTM clearance.

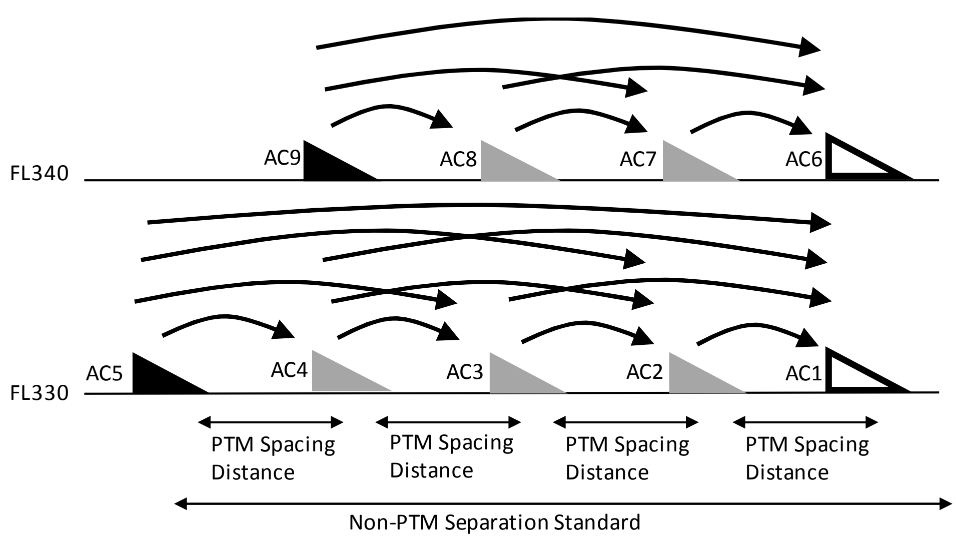


Figure A.30 PTM eight aircraft scenario.

It is anticipated that there will be very few PTM operations that will require eight designated aircraft. However, in rare situations, this scenario could occur and FIM equipment designed to support PTM operations should consider this scenario.

The messages required to support this operation are listed below. Although the figure looks complicated, the number of messages required is not significantly greater than the number of PTM clearances required for PTM operations consisting of fewer designated aircraft.

Message Queue [Destination, Sender]
[ATC, AC5] Request climb to FL340
[AC5, ATC] Continue PTM following AC1, following AC2, following AC3, following AC4, Add PTM MACH following AC6, following AC7, following AC8, following AC9
[ATC, AC5] WILCO
[AC5, ATC] Climb to and maintain FL340, Report reaching FL340
[ATC, AC5] WILCO
[ATC, AC5] Level FL340
[AC5, ATC] Continue PTM following AC6, following AC7, following AC8, following AC9, Remove PTM AC1, AC2, AC3, AC4
[ATC, AC5] WILCO

A.6 AIRSPACE CHARACTERISTICS, SUPPORTING SYSTEMS AND OPERATIONAL ENVIRONMENT

This section emphasizes the airspace characteristics and supporting systems that are envisioned for the use of PTM. These characteristics can be used as a foundation for the PTM safety review.

A.6.1 Airspace System

The oceanic airspace system is composed of fixed routes, organized track system routes, and user preferred routes.

Fixed routes are similar to routes employed in domestic airway structures. They consist of a set of fixed waypoints. These routes can support significant traffic densities while often not requiring significant airborne equipage. Some examples of fixed route systems are the Central East Pacific (CEP) routes between the West coast of the United States and Hawaii and the Northern Pacific (NOPAC) routes from Alaska to Asia.

Organized track systems are flexible routes that are dynamically adjusted based on weather conditions (e.g., routes that are adjusted to take advantage of favorable winds or routes that are adjusted to avoid adverse winds and weather). They are often used in locations where traffic densities are high and wind or weather changes can be significant. These routes are often generated twice a day to account for changes in weather. Examples of these organized track systems are found in the North Atlantic region (North Atlantic Organized Track System or NATOTS) and the Northern Central Pacific area between the United States and Asia (Pacific Organized Track System or PACOTS).

Air Navigation Service Providers (ANSP) are working on oceanic airspace redesigns that will allow more aircraft to operate on random or user preferred routes (UPRs). These are routes that are requested by the airline operator that are tailored for weather and city pair great circle routing. Aircraft on UPRs fly at optimal cruise trajectories (altitude and route) resulting in improved fuel efficiency, increased predictability of fuel usage and payload capacity.

In the past, these routes were typically only used for low density traffic flows. As separation standards have decreased, ANSPs are able to offer more UPRs to aircraft operators.

These routes will often result in crossing or intersecting routes with other aircraft that are also flying UPRs. User preferred routes may cross each other at a variety of angles depending on city pairs served by the flights and on forecast winds. User preferred routes may also merge with each other. Aircraft flying in the South Pacific (SOPAC) region (between the United States and Australia/New Zealand) have successfully flown UPRs for many years.

There are also oceanic, airspace regions where aircraft spend most of the flight in non-radar airspace but occasionally transition through radar airspace (e.g., non-radar airspace to radar airspace and then back into non-radar airspace). An example of this would include the Northern Pacific (NOPAC) routes. If an aircraft that is conducting PTM operations in non-radar airspace is about to transition a section of radar airspace for a short period of time, controllers may determine that it would be operationally desirable to allow the aircraft to continue conducting PTM operations even during the time the aircraft is transiting radar airspace.

A.6.2 Oceanic Procedural Separation Control

For safe and efficient flight operations, an airspace environment relies on the synergy afforded by the combination of three systems; communication, navigation, and surveillance (CNS). The performance of these systems has a direct bearing on airspace capacity, throughput, and efficiency.

Air traffic management over the ocean and in remote land areas is characterized by reduced surveillance and limited communication capabilities. In such airspace, air traffic is managed procedurally with reliance on specified navigation performance, periodic position reports to the ground, and large separation standards. Depending on aircraft equipage, longitudinal separation requirements range from 30 NM to 15 minutes (approximately 120 NM).

A.6.2.1 Position Reports

Surveillance is supported by periodic position reports. The frequency and delivery of these reports varies depending on aircraft equipage, airspace region (and supporting ground infrastructure) and the separation standard being applied. These position reports are often communicated to the ground via third-party High Frequency (HF) voice communication, or by satellite-based data link communication (Automatic Dependent Surveillance or ADS). These ADS reports can be single event or periodic, “contracted” reports (ADS-C).

A.6.2.2 Communication Means

The worst case of communication between controller and crew is by HF voice through a third-party radio operator. In such communications, crews pass requests in voice transactions with radio operators who then transcribe the crew request into a ground data link message, which is then sent to the controller. Once the controller has developed a suitable response, it is sent to the radio operator by the same ground data link, and the radio operator alerts the crew to the availability of a response by a selective calling function. The crew responds to the alert, and the clearance or other information is then passed by voice. The net result is latency between request and clearance that may be up to 12 minutes in duration.

Many modern oceanic aircraft use Controller Pilot Data Link Communication (CPDLC) to communicate between the controller and the flight crew. This satellite-based data link communication provides less error-prone and faster communication. It is assumed that CPDLC is required for PTM operations and no effort will be made in this document to assign probabilities of error associated with HF or VHF voice communication.

A.6.2.3 Equipment Impact on Separation Standards

Separation requirements between aircraft are a function of surveillance (e.g., position reports), communication (e.g., 3rd party HF Voice or CPDLC) and navigation (e.g., RNP-10, RNP-4, etc.) systems. Better equipped aircraft are eligible for separation standards with lower minimum distances. However, it is the least equipped aircraft that determines the separation standard that is applied between the aircraft that make up the pair. To illustrate, reference the figure below, which summarizes how separation standards between two aircraft are determined in FAA-controlled Pacific airspace. In the figure below the first number represent the lateral separation minimum and the second number the longitudinal separation minimum. Aircraft equipped with FANS 1/A (aircraft that are FANS 1/A compliant have ADS-C and CPDLC) and RNP4 avionics are eligible for 30/30 NM separation (30 miles lateral/30 miles longitudinal). However, if separation is maintained from an aircraft with HF Voice Communication and no RNP, the separation standard will be 10 minutes longitudinally and 100 NM laterally on same tracks or 15 minutes when crossing.

Aircraft A

Aircraft B	HF Voice No RNP	HF Voice RNP- 10	FANS 1/A RNP- 10	FANS 1/A RNP- 4
HF Voice No RNP	100/80 NM	100/80 NM	100/80 NM	100/80 NM
HF Voice RNP- 10	100/80 NM	50/80 NM	50/80 NM	50/80 NM
FANS 1/A RNP- 10	100/80 NM	50/80 NM	50/50 NM	50/50 NM
FANS 1/A RNP- 4	100/80 NM	50/80 NM	50/50 NM	30/30 NM

Figure A.31 Equipment impact on separation standards, separation standard minimum lateral/longitudinal.

A.6.2.4 Vertical Separation Minimum

Vertical separation minimum is:

- 2000 ft. below FL290 or above FL410;
- 1000 ft. at or above FL290 between RVSM capable aircraft
- 2000 ft. at or above FL 290 between a non−RVSM aircraft and all other aircraft at or above FL 290.

A.6.3 Ground equipment

Currently, US-controlled oceanic airspace is managed with the Advanced Technology and Oceanic Procedures (ATOP) system (which includes the Ocean 21 system and controller interface). This system gathers aircraft position information through either ADS-C position reports or HF voice position reports. Where available, the system can also accept aircraft position information from radar and ADS-B sources. Using this information and the aircraft's flight plan, the system projects the future position of each aircraft. The system includes a conflict probe that is used to identify potential traffic conflicts up to two hours in the future. The separation standard that is applied for conflict detection may vary by aircraft pair, and is a function of the type, frequency, and/or quality of the position reports received from each aircraft as well as other aircraft equipage.

Losses of separation that are projected to occur (conflicts) between 120 and 30 minutes in the future are displayed to the controller with an advisory conflict alert indication. Conflicts displayed to the controller that are not resolved within 30 minutes prior to loss of separation are given a higher level of alerting in their display. The ATOP system displays a list of all active (unresolved) conflicts.

The Ocean 21 system uses intent information on all aircraft (via the flight plan) to predict future trajectories. It also provides a method of communication between the controller and flight crew. Finally, as appropriate clearances are input into the system, it removes resolved conflicts from the conflict list. All three of these capabilities will be utilized in supporting PTM operations.

Many other automation systems used throughout the world to manage oceanic airspace have similar characteristics.

PTM operations will require significant integration with the controller's ground automation system. Some of the anticipated ground system functionality should include:

- Identify potential PTM situations
- Formulate clearances for the controller to issue
- Send intended flight path information of designated aircraft to PTM aircraft for crossing track operations
- Recognize accepted PTM clearances (and consider designated conflicts resolved).
- Identify when non-PTM separation is re-established
- Notify the controller that PTM is no longer required, and be able to send a pair-specific PTM cancellation message to the FIM equipment
- Coordination with adjacent and other down-stream FIRs

A.6.4 Airborne Equipment

The FIM equipment will need numerous functions certified. Some of the anticipated functions include:

- The ability to receive PTM clearance data from the ground system.
- Status monitoring and appropriate notification of status of PTM system elements.
- Interface with the flight crew to enable the flight crew to follow Mach guidance to support PTM operations.
- Adequate alerting to crew of failure to comply with Mach guidance
- Alerting to the flight crew for an imminent loss of spacing or loss of spacing.
- Alerting to the flight crew for a loss of separation

A.7 GENERAL APPLICATION CONTEXT

A.7.1 Scope

The goal of PTM is to use airborne surveillance and tools to manage a “no closer than” inter-aircraft spacing. PTM is an application that enables controllers to resolve a specific traffic conflict (or conflicts), identified by the ground system, with a potentially more efficient spacing assignment managed by the aircraft. The controller, using ground-based decision-support automation, issues pair-specific PTM clearances to FIM-equipped aircraft. The PTM clearance, once accepted by the flight crew, allows the flight crew of the PTM aircraft to use their on-board FIM equipment to manage their spacing relative to the designated aircraft using speed commands provided by the FIM equipment. The speed guidance ensures that a minimum spacing distance is assured throughout the PTM operation (i.e., the inter-aircraft spacing is no closer than the PTM minimum distance at any time). When the controller assesses (with ground automation system support) that the PTM clearance is no longer desired, the controller may terminate the PTM operation.

A.7.2 Roles and Responsibilities

Two participants are identified for a PTM operation: the controllers and the flight crew of the PTM aircraft. The sections below contain a high-level description of the roles and responsibilities of controllers and flight crews of PTM aircraft when performing PTM.

A.7.3 Roles and Responsibilities of the Controller

The controller is tasked with maintaining separation between all participating aircraft in their assigned airspace. This is accomplished by having a method of determining aircraft position and projected positions (position reports and ground automation support), and applying rules, techniques, and skill to identify conflicts in a timely manner and resolve them prior to a loss of separation.

PTM operations begin once a controller has identified that a traffic conflict will exist and when a controller determines that the PTM separation standard is applicable and beneficial for the safe and efficient operation of the airspace. The ground automation system identifies the traffic conflict and the controller determines which separation standard is most applicable.

If PTM is the most applicable or preferred option, the controller will issue a PTM clearance. Once accepted, the flight crew is then required to manage speeds based on information provided by the FIM equipment.

The controller also has the option of assigning additional designated aircraft to aircraft already conducting PTM operations. The controller accomplishes this by sending a new clearance to the PTM aircraft. This new clearance instructs the flight crew to continue doing PTM on the aircraft already assigned to it and includes instructions to conduct PTM on the additional designated aircraft.

Similarly, if the controller no longer prefers to use PTM between the PTM aircraft and a subset of the already designated aircraft, the controller will send a new clearance to the PTM aircraft. This clearance will identify which designated aircraft PTM operations should be continued and identify which aircraft for which PTM is no longer required or desired.

In summary, the controller is responsible for:

- Determining if a PTM clearance is suitable, including PTM equipage
- Determining and verifying the PTM aircraft and the designated aircraft call signs
- Ensuring separation between the PTM aircraft and all other aircraft, excluding the designated aircraft
- Assuring that the designated aircraft is not authorized to deviate from its cleared flight plan during the duration of the PTM maneuver
- Terminating the PTM operation when a non-PTM separation is available and is the preferred option

A.7.4 Roles and Responsibilities of the PTM Aircraft's Flight Crew

In non-PTM operations, the pilot's responsibility (role) in maintaining traffic separation is to comply with the assigned route, altitude, and speed (as necessary). The change with PTM is that the Mach guidance is generated by on board FIM equipment rather than provided by the controller. The significant job responsibility change (or addition) is the requirement for the flight crew to be familiar with and able to execute responses to PTM alerts and equipment failures.

When a controller issues a PTM clearance to a flight crew, the flight crew of the PTM aircraft will use their ADS-B-enabled onboard equipment to manage their speed to achieve spacing relative to the aircraft designated by the controller. The flight crew task of flying the assigned altitude, route, and speed does not change, with the exception that the required speed (Mach) is determined by the FIM equipment and authorized by the PTM Mach clearance. Regarding speed, the flight crew is responsible for the task of following speed guidance from a new source (FIM equipment vs. controller).

When the flight crew receives any PTM clearance, the flight crew is responsible for reviewing the proposed PTM Mach guidance (fixed Mach speed or Mach speed range) to determine if the proposed guidance would be operationally acceptable. The flight crew would also review other information that could influence their decision to accept or reject the PTM clearance. This would include assessing potential future speed restrictions (e.g., the eventual speed the PTM aircraft may be required to fly due to the speed of the other aircraft) based on the assigned speeds of the designated aircraft. Other information that could influence the flight crew's decision would include aircraft performance, weather conditions, available ride information, and general traffic situation awareness.

The guidance (along with suitable alerting) will be provided to the flight crew with an interface function that resides either within the current displays, or through an auxiliary display function.

The PTM operation puts additional responsibilities on the flight crew of the PTM aircraft. They include:

- Validating the operational status of the FIM equipment.

- Rejecting the PTM clearance if, in their sole discretion, the outcome will be operationally undesirable.
- Being familiar with and prepared to execute appropriate maneuvers should the FIM equipment fail (failure could include the designated aircraft's ADS-B transmitter failing).
- Being familiar with and able to execute responses to PTM alerts.
- Complying with guidance displayed by the PTM system.
- Acknowledging instructions from the controller that terminate the PTM operation and resuming normal operations.

A.8 PROCEDURAL FLOW

Any PTM operation is based on the following procedural flow:

Pre-Initiation Phase:

- The ground automation system determines there is a traffic conflict and identifies PTM as a solution option. This situation could arise from a flight crew initiated altitude change request or co-altitude aircraft whose trajectories would result in a traffic conflict.
- The controller determines that the use of PTM operations would be beneficial and viable. This includes determining if the PTM aircraft and designated aircraft are suitably equipped and capable, including having sufficient data quality. The controller also determines that the aircraft are within a facility set range (so that it is likely that the PTM aircraft will be able to detect the aircraft named in the PTM clearance).
- The ground automation system develops the PTM clearance information for the controller to transmit to the PTM aircraft.

Initiation Phase:

- The controller sends the PTM clearance to the PTM aircraft.
- The PTM aircraft receives the PTM clearance and the flight crew reviews the PTM clearance information
- The flight crew loads the information into the FIM equipment (if needed) and reviews the pending PTM guidance provided by the FIM equipment. This review includes ensuring the clearance information is valid and determining if the flight crew is comfortable with the proposed speed guidance and the potential speeds the PTM operation may require the aircraft to fly.
- If the flight crew finds the PTM situation acceptable, the flight crew engages PTM operation on the FIM equipment and transmits acceptance of the clearance to ATC.
- If there are multiple PTM aircraft involved in the operation, the controller sends appropriate PTM clearances to the other PTM aircraft once the first PTM aircraft responds to its clearance.

Execution Phase:

- The controller receives the acceptance of the PTM clearance and continues to monitor for additional conflicts.
- The ground also monitors the aircraft involved in the PTM operation to see if a non-PTM operation would be viable and desirable.
- The flight crew monitors the PTM Mach guidance provided by the FIM equipment and executes any speed changes required.
- The flight crew may receive additional PTM related clearances during the execution phase of the operation. The flight crew evaluates and responds to these clearances in a similar manner as with the initial PTM clearance.

Termination Phase:

- When the ground determines PTM operations are no longer required, the ground transmits a clearance canceling the PTM operation. The clearance also includes the new speed assignment the flight crew must follow.
- The flight crew acknowledges the termination of the PTM operation and resumes non-PTM operations.

A.9 PHASE DIAGRAMS

The following flowcharts describe graphically the process to be executed during a PTM operation. The specific actions or decisions are assigned to either the aircraft (A/C) or ground (Gnd) domains. Where applicable, further specificity is achieved for flight crew (A/C-FC), avionics (A/C-Av), controller (Gnd-ATC) and ground processing equipment (Gnd-Pro). Assignment to just the ground domain or aircraft domain means that either the human or their supporting automation could perform the action or make the decision.

The different steps within each phase are numbered. The first digit is the phase, “1” for Pre-Initiation, “2” for Initiation, “3” for Execution and finally “4” for the Termination phase. The second digit identifies whether the step is a ground action or an airborne action, “1” for ground and “2” for airborne. Finally, the third digit connotes the step within the phase. For example, box 3.2.1 is the first step for the aircraft in the execution phase (i.e., step 1 of Execution Airborne).

It should be noted that although there is a ground initiation phase (typically numbered 2.1.x), this phase is called “Process Message Queue” in these phase diagrams. The process message queue phase of PTM is when the ground (a combination of steps supported by the controller and the ground automation) initiates the process of sending messages required to support a PTM operation. This could be when a unique PTM operation is being initiated or when an existing PTM operation is being modified (by adding or removing aircraft to that unique operation).

The phase diagrams also contain dashed lines. These dashed lines indicate communication elements that “leave” or “enter” a phase diagram in the middle of the phase. An example of this can be seen in Process Message queue, step number 2 (box 2.1.2). The action in this box (by the ground automation system) is to transmit the next clearance or notification in the PTM message queue to an aircraft. As indicated by the dashed line, this message goes either to the start of Initiation Airborne or to Execution Airborne box number 3.2.11, depending on the operation being conducted. This then enables a series of actions in the aircraft (contained in Initiation Airborne or Execution Airborne). From a ground perspective, however, once this message is transmitted, the next step for the ground is step 2.1.3.

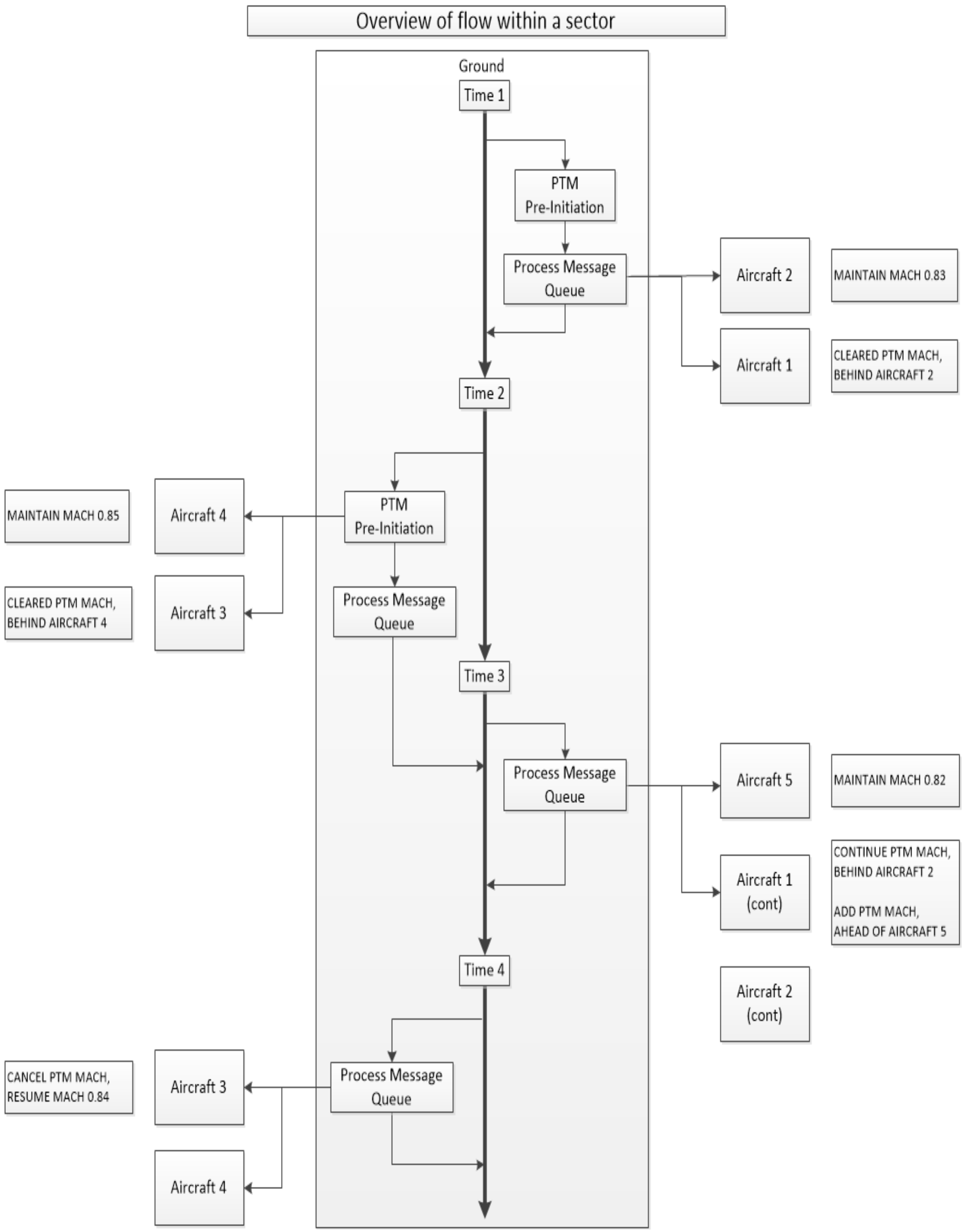
Another aspect of PTM operations can be seen in the very first diagram shown below which is entitled “Overview of flow within a sector”. As a part of normal sector management, the ground (controllers and ground automation) may need to support a number of unique PTM operations, which in turn may be modified as time progresses. This diagram illustrates how typical operations would be conducted. This is the same way current sector management is conducted but illustrates the broader picture of how PTM operations would be incorporated into today’s operations.

For example, at “time 1” the controller, as part of standard sector management, may desire to initiate a PTM operation between Aircraft 1 and Aircraft 2. The ground would first conduct the steps contained in “PTM Pre-Initiation”. Once those steps are complete, the ground performs the necessary steps contained in “Process Message Queue”. Some sample messages are shown in the boxes next to the specific aircraft boxes.

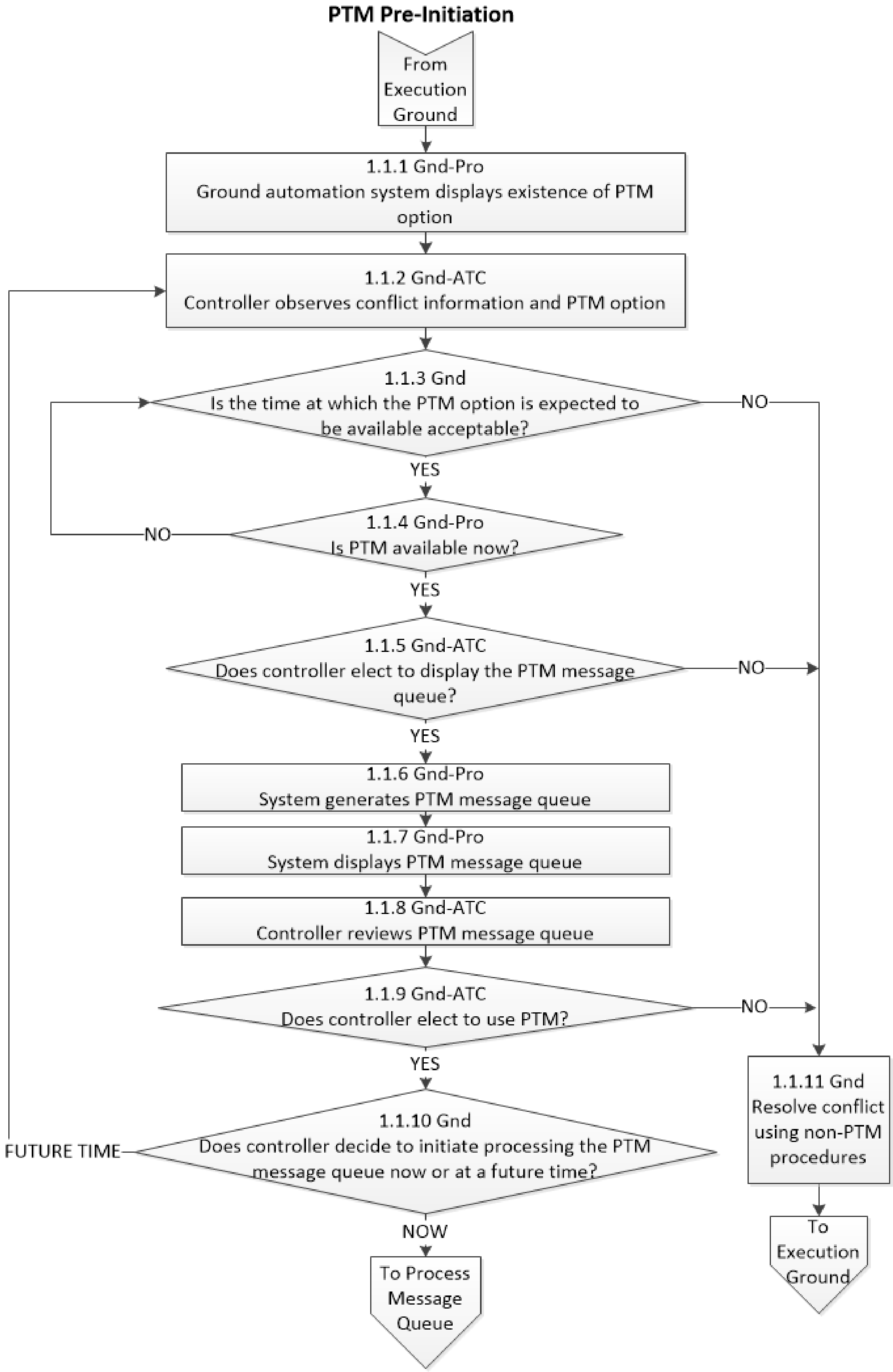
After some time has passed, at “time 2” the ground may desire to conduct PTM operations on another pair of aircraft (Aircraft 4 and Aircraft 5). As before, the ground would follow steps contained in the “PTM Pre-Initiation” and “Process Message Queue” phases.

At “time 3”, while the steps required to initiate PTM between Aircraft 4 and Aircraft 5 are being processed, the ground may decide to modify the previous PTM operation that is being conducted between Aircraft 1 and Aircraft 2. At “time 3” the ground decides to add a second aircraft to the PTM operation being conducted between Aircraft 1 and 2.

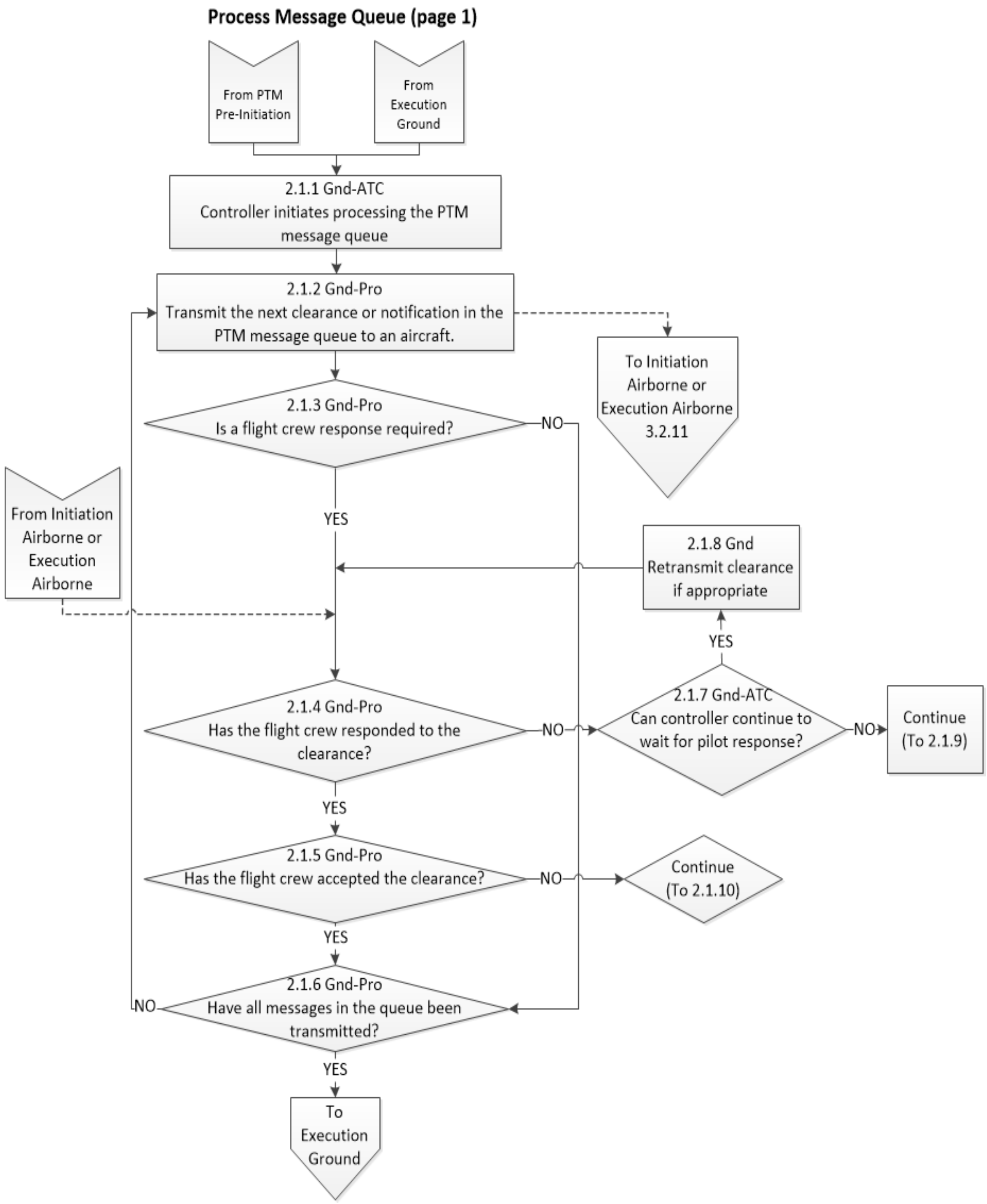
At “time 4” the ground decides to terminate the PTM operation between Aircraft 3 and Aircraft 4. The PTM operation between Aircraft 1, 2 and 5 remains ongoing.



Overview of flow within a sector
Ground
Time 1
PTM Pre-Initiation
Process Message Queue
Aircraft 2
MAINTAIN MACH 0.83
Aircraft 1
CLEARED PTM MACH, BEHIND AIRCRAFT 2
Time 2
MAINTAIN MACH 0.85
Aircraft 4
PTM Pre-Initiation
CLEARED PTM MACH, BEHIND AIRCRAFT 4
Aircraft 3
Process Message Queue
Time 3
Process Message Queue
Aircraft 5
MAINTAIN MACH 0.82
Aircraft 1 (cont)
CONTINUE PTM MACH, BEHIND AIRCRAFT 2
ADD PTM MACH, AHEAD OF AIRCRAFT 5
Time 4
Aircraft 2 (cont)
CANCEL PTM MACH, RESUME MACH 0.84
Aircraft 3
Process Message Queue
Aircraft 4

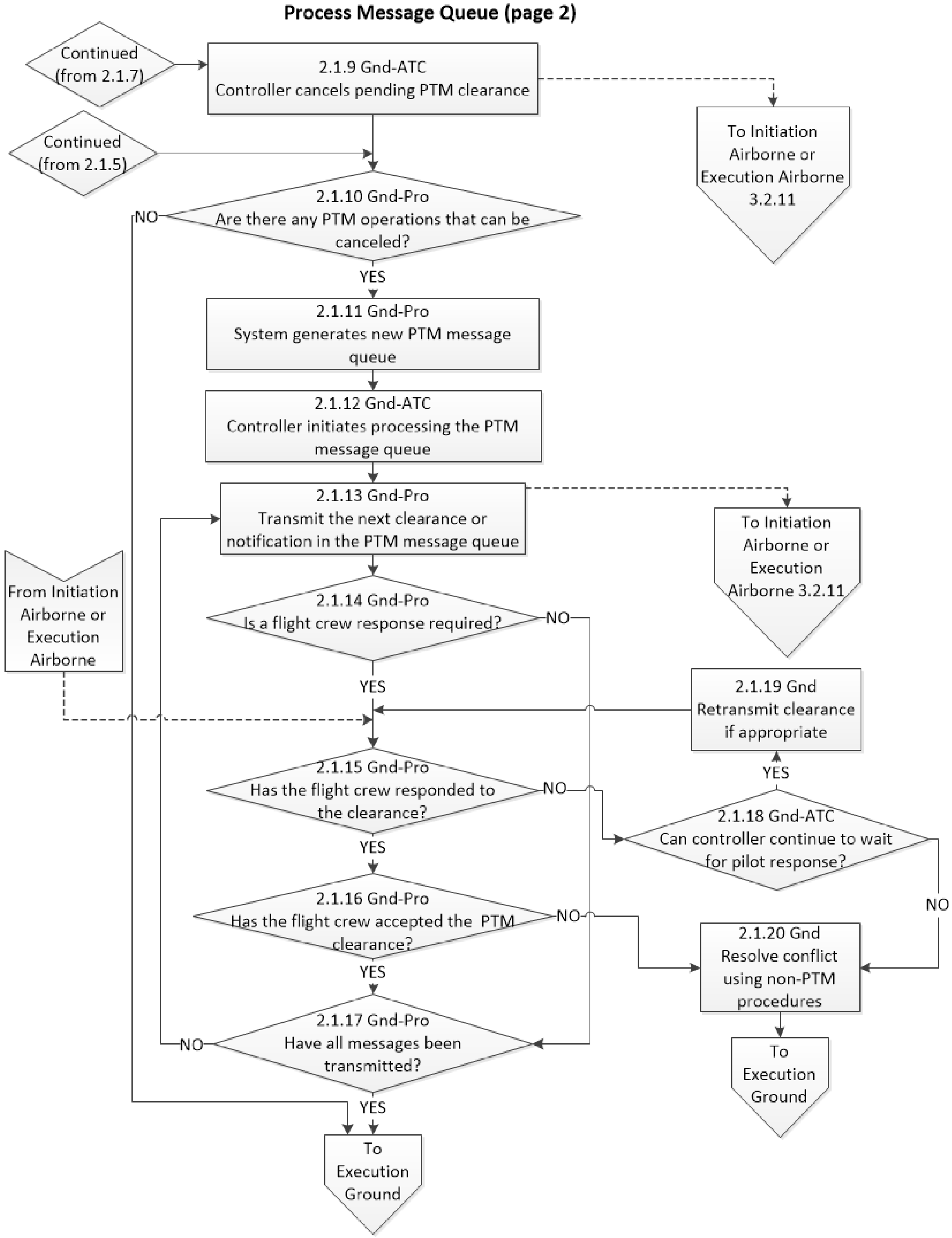


PTM Pre-Initiation
From Execution Ground
1.1.1 Gnd-Pro
Ground automation system displays existence of PTM option
1.1.2 Gnd-ATC
Controller observes conflict information and PTM option
1.1.3 Gnd
Is the time at which the PTM option is expected to be available acceptable?
NO
YES
1.1.4 Gnd-Pro
Is PTM available now?
NO
YES
1.1.5 Gnd-ATC
Does controller elect to display the PTM message queue?
NO
YES
1.1.6 Gnd-Pro
System generates PTM message queue
1.1.7 Gnd-Pro
System displays PTM message queue
1.1.8 Gnd-ATC
Controller reviews PTM message queue
1.1.9 Gnd-ATC
Does controller elect to use PTM?
NO
YES
1.1.10 Gnd
Does controller decide to initiate processing the PTM message queue now or at a future time?
FUTURE TIME
NOW
To Process Message Queue
1.1.11 Gnd
Resolve conflict using non-PTM procedures
To Execution Ground

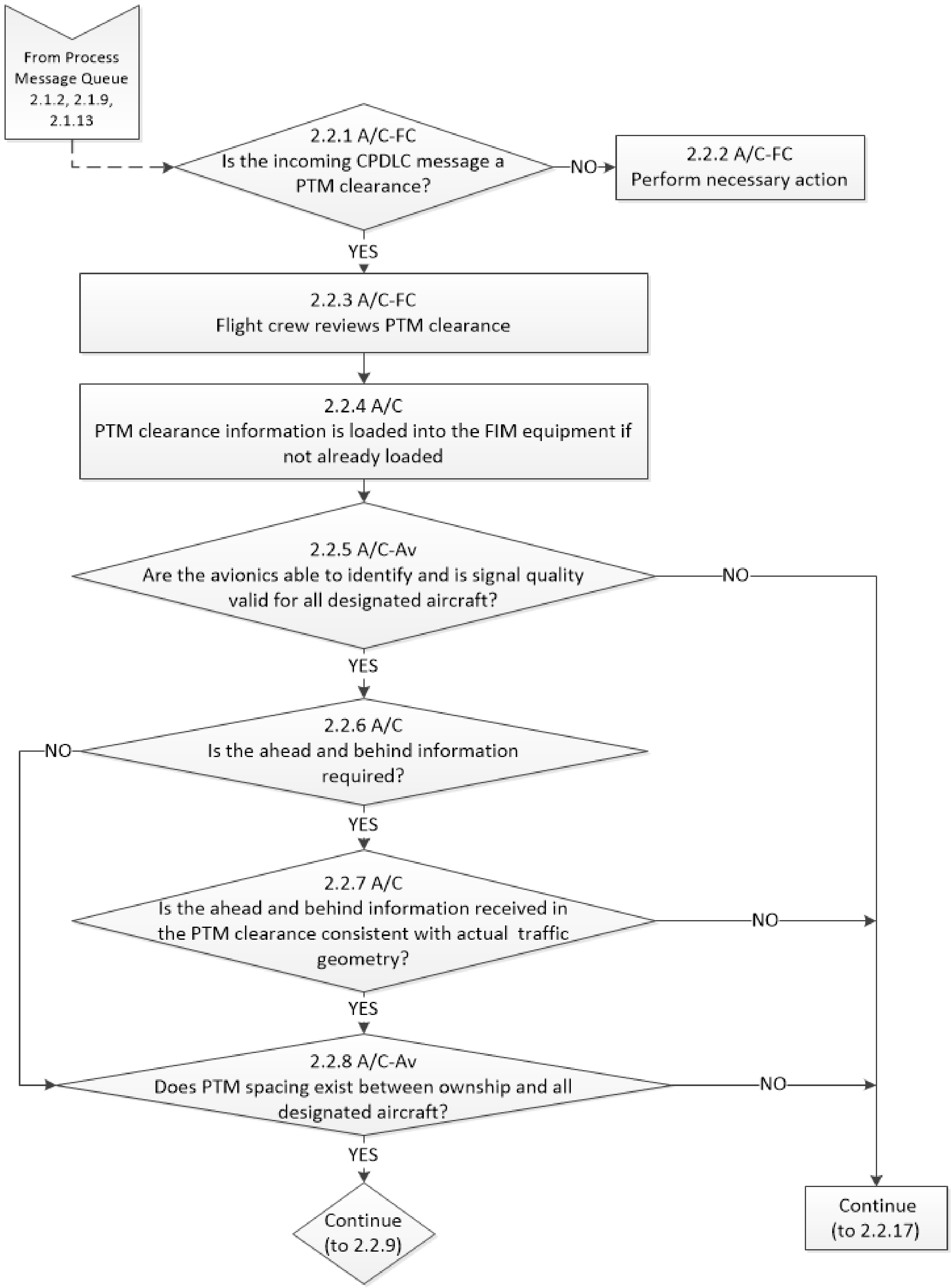


Process Message Queue (page 1)
From PTM Pre-Initiation
From Execution Ground
2.1.1 Gnd-ATC Controller initiates processing the PTM message queue
2.1.2 Gnd-Pro Transmit the next clearance or notification in the PTM message queue to an aircraft.
To Initiation Airborne or Execution Airborne 3.2.11
2.1.3 Gnd-Pro Is a flight crew response required?
NO
YES
From Initiation Airborne or Execution Airborne
2.1.8 Gnd Retransmit clearance if appropriate
YES
2.1.4 Gnd-Pro Has the flight crew responded to the clearance?
NO
2.1.7 Gnd-ATC Can controller continue to wait for pilot response?
NO
Continue (To 2.1.9)
YES
2.1.5 Gnd-Pro Has the flight crew accepted the clearance?
NO
Continue (To 2.1.10)
YES
2.1.6 Gnd-Pro Have all messages in the queue been transmitted?
NO
YES
To Execution Ground

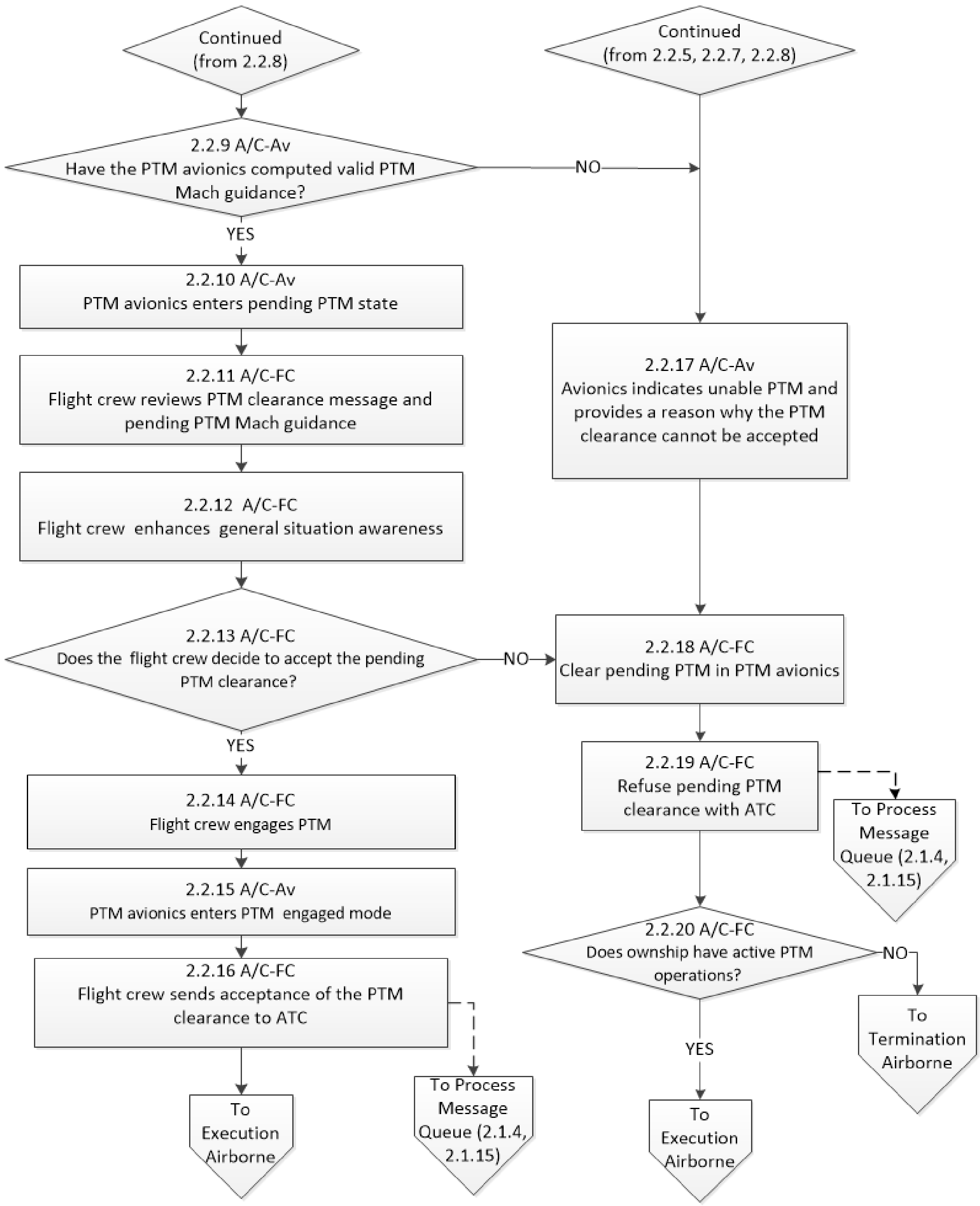
Process Message Queue (page 2)



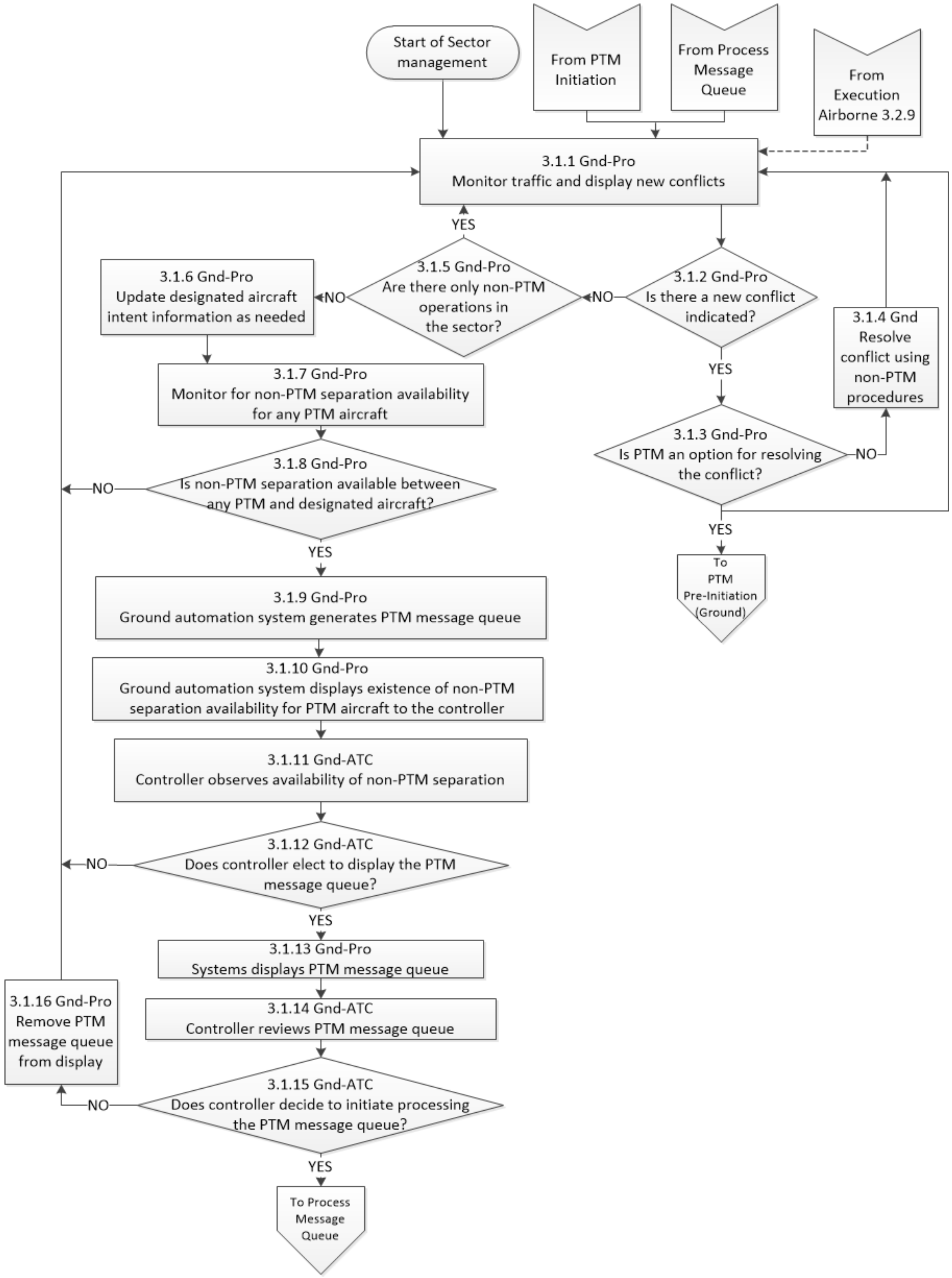
Initiation Airborne (page 1)

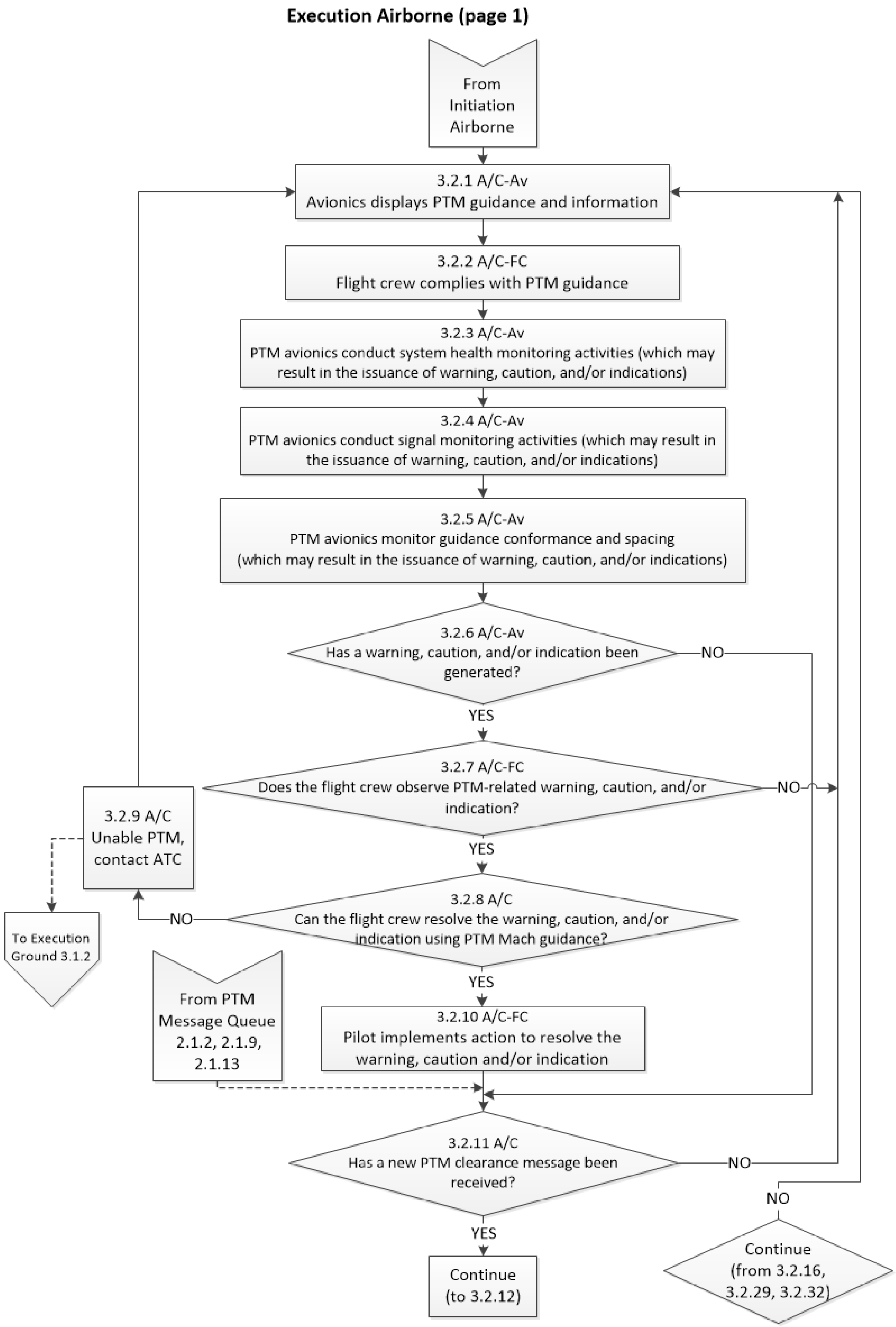


Initiation Airborne (page 2)



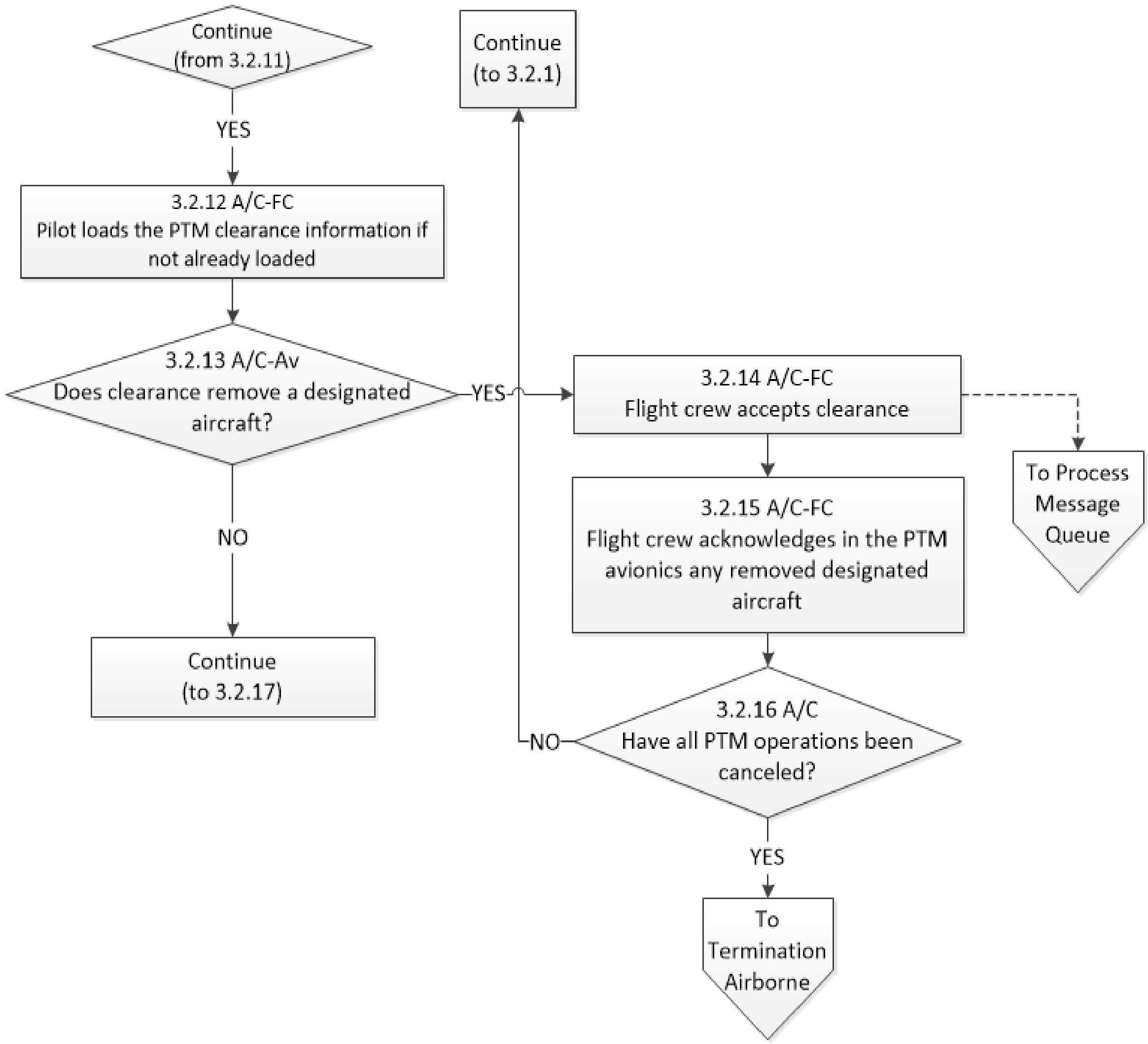
Execution Ground



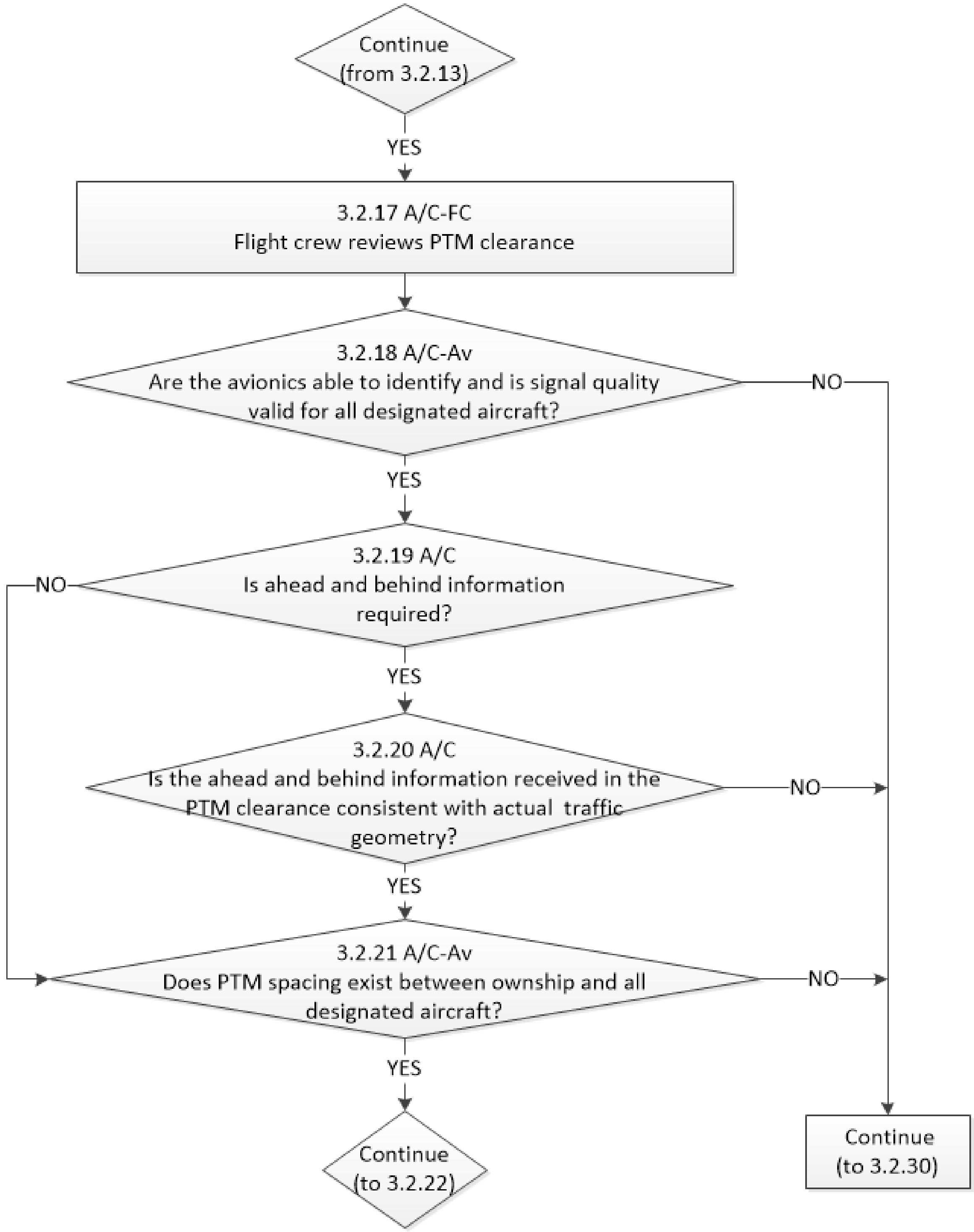


Execution Airborne (page 1)
From Initiation Airborne
3.2.1 A/C-Av
Avionics displays PTM guidance and information
3.2.2 A/C-FC
Flight crew complies with PTM guidance
3.2.3 A/C-Av
PTM avionics conduct system health monitoring activities (which may result in the issuance of warning, caution, and/or indications)
3.2.4 A/C-Av
PTM avionics conduct signal monitoring activities (which may result in the issuance of warning, caution, and/or indications)
3.2.5 A/C-Av
PTM avionics monitor guidance conformance and spacing (which may result in the issuance of warning, caution, and/or indications)
3.2.6 A/C-Av
Has a warning, caution, and/or indication been generated?
NO
YES
3.2.7 A/C-FC
Does the flight crew observe PTM-related warning, caution, and/or indication?
NO
YES
3.2.9 A/C
Unable PTM, contact ATC
To Execution Ground 3.1.2
3.2.8 A/C
Can the flight crew resolve the warning, caution, and/or indication using PTM Mach guidance?
NO
YES
From PTM Message Queue 2.1.2, 2.1.9, 2.1.13
3.2.10 A/C-FC
Pilot implements action to resolve the warning, caution and/or indication
3.2.11 A/C
Has a new PTM clearance message been received?
NO
YES
NO
Continue (to 3.2.12)
Continue (from 3.2.16, 3.2.29, 3.2.32)

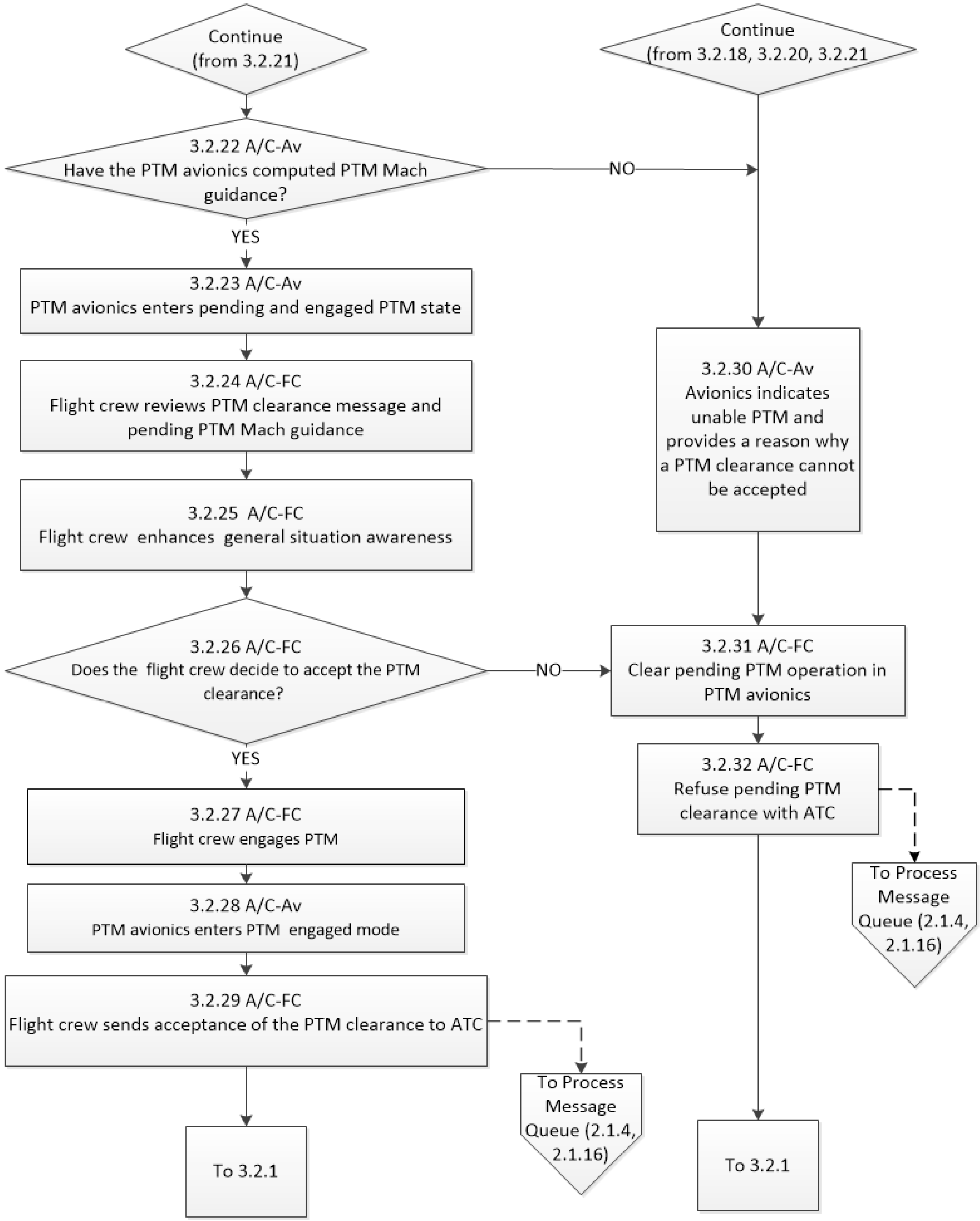
Execution Airborne (page 2)



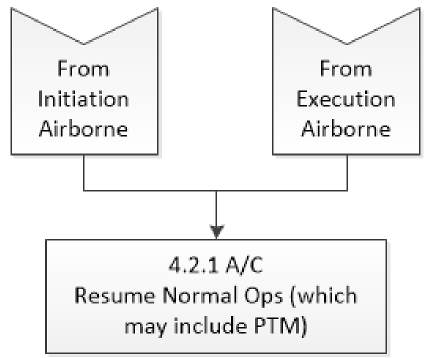
Execution Airborne (page 3)



Execution Airborne (page 4)



Termination Airborne



A.10 PHASE TABLES

The following tables describe the information needs by PTM Phase.

ID	Domain	Function	Required Information	Criteria for Transfer	Next
PTM Pre-Initiation (Ground) (page 1)					
1.1.1	Gnd-Pro	Ground automation system displays conflict and existence of PTM option to the controller	Existence of a conflict, aircraft involved are PTM capable aircraft	Required information elements provided	1.1.2
1.1.2	Gnd-ATC	Controller observes conflict information and PTM option	Existence of a conflict and standard conflict information, aircraft involved are PTM capable aircraft, time of applicability	Required information elements provided	1.1.3
1.1.3	Gnd	Is the time at which the PTM option is expected to be available acceptable?	Existence of PTM option, time of applicability	Ground determines the time of availability is acceptable	1.1.4
				Ground determines the time of availability is not acceptable	1.1.11
1.1.4	Gnd-Pro	Is PTM available now?	Existence of PTM option, time of applicability	PTM is available at this time	1.1.5
				PTM is not available at this time	1.1.3
1.1.5	Gnd-ATC	Does controller elect to display the PTM message queue?	Existence of PTM option	Controller elects to display PTM message queue	1.1.6
				Controller does not elect to display PTM message queue	1.1.11
1.1.6	Gnd-Pro	System generates PTM message queue	PTM message set rules, information required to populate the PTM message queue	PTM message queue	1.1.7

ID	Domain	Function	Required Information	Criteria for Transfer	Next
PTM Pre-Initiation (Ground) (page 2)					
1.1.7	Gnd-Pro	System displays PTM message queue	PTM message queue	Display of PTM message queue	1.1.8
1.1.8	Gnd-ATC	Controller reviews PTM message queue	PTM message queue	Controller completes review of PTM message queue	1.1.9
1.1.9	Gnd-ATC	Does controller elect to use PTM?	PTM message queue, sector traffic management plan	Controller elects to use PTM	1.1.10
				Controller does not elect to use PTM	1.1.11
1.1.10	Gnd	Does the controller decide to initiate processing the PTM message queue now or at a future time?	PTM message queue, sector traffic management plan	Controller issues the PTM message queue now	Process Message Queue
				Controller elects to wait for a future time to issue the PTM message queue	1.1.2
1.1.11	Gnd	Resolve conflict using non-PTM procedures	Standard sector operations (non-PTM separation standards, sector traffic information, etc.)	Non-PTM procedures result	Execution Ground

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Process Message Queue (page 1)					
2.1.1	Gnd-ATC	Controller initiates processing the PTM message queue	Existence of PTM message queue	Required information elements provided	2.1.2
2.1.2	Gnd-Pro	Transmit the next clearance or notification in the PTM message queue to an aircraft.	Existence of PTM message queue	Transmission complete	2.1.3
2.1.3	Gnd-Pro	Is a flight crew response required?	Message queue elements	Flight crew response is required	2.1.4
				Flight crew response is not required	2.1.6
2.1.4	Gnd-Pro	Has the flight crew responded to the clearance?	Log of aircraft transmissions received	Flight crew has responded to the clearance	2.1.5
				Flight crew has not responded to the clearance	2.1.7
2.1.5	Gnd-Pro	Has the flight crew accepted the clearance?	Content of aircraft transmissions received	Flight crew has accepted the clearance	2.1.6
				Flight crew has not accepted the clearance	2.1.10
2.1.6	Gnd-Pro	Have all messages in the queue been transmitted?	Message queue, log of ground system transmissions	All clearances have been transmitted	Execution Ground
				All clearances have not been transmitted	2.1.2

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Process Message Queue (page 2)					
2.1.7	Gnd-ATC	Can controller continue to wait for pilot response?	Time since the last transmission was sent, sector air traffic management plan	Controller can continue to wait for pilot response	2.1.8
				Controller cannot continue to wait for pilot response	2.1.9
2.1.8	Gnd	Retransmit clearance if appropriate	Last ground transmission	Clearance sent (if appropriate)	2.1.4
2.1.9	Gnd-ATC	Controller cancels pending PTM clearance	Knowledge of PTM message queue	Controller sends transmission canceling pending PTM clearance	2.1.10
2.1.10	Gnd-Pro	Are there any PTM operations that can be canceled?	Traffic, routes, separation criteria, PTM separation criteria, list of PTM operations	There are PTM operations that can be canceled	2.1.11
				No PTM operations need to be canceled	Execution Ground
2.1.11	Gnd-Pro	System generates new PTM message queue	Rules for PTM message queue	Required information elements provided	2.1.12
2.1.12	Gnd-ATC	Controller initiates processing the PTM message queue	PTM message queue	Initiation of the PTM message queue	2.1.13
2.1.13	Gnd-Pro	Transmit the next clearance or notification in the PTM message queue	Existence of PTM message queue	Transmission complete	2.1.14

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Process Message Queue (page 3)					
2.1.14	Gnd-Pro	Is a flight crew response required?	Message queue elements	Flight crew response is required	2.1.15
				Flight crew response is not required	2.1.17
2.1.15	Gnd-Pro	Has the flight crew responded to the clearance?	Log of aircraft transmissions received	Flight crew has responded to the clearance	2.1.16
				Flight crew has not responded to the clearance	2.1.18
2.1.16	Gnd-Pro	Has the crew accepted the PTM clearance?	Content of aircraft transmissions received	Flight crew has accepted the clearance	2.1.17
				Flight crew has not accepted the clearance	2.1.20
2.1.17	Gnd-Pro	Have all messages been transmitted?	Message queue, log of ground system transmissions	All clearances have been transmitted	Execution Ground
				All clearances have not been transmitted	2.1.13
2.1.18	Gnd-ATC	Can controller continue to wait for pilot response?	Time since the last transmission was sent, sector air traffic management plan	Controller can continue to wait for pilot response	2.1.19
				Controller cannot continue to wait for pilot response	2.1.20
2.1.19	Gnd	Retransmit clearance if appropriate	Last ground transmission	Required information elements provided	2.1.15
2.1.20	Gnd	Resolve conflict using non-PTM procedures	Standard sector operations (non-PTM separation standards, sector traffic information, etc.)	Non-PTM procedures result	Execution Ground

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Initiation Airborne (page 1)					
2.2.1	A/C-FC	Is the incoming CPDLC message a PTM clearance?	CPDLC message	Incoming CPDLC message is a PTM clearance	2.2.3
				Incoming CPDLC message is not a PTM clearance	2.2.2
2.2.2	A/C-FC	Perform necessary action	CPDLC message, non-PTM standard operating procedures		
2.2.3	A/C-FC	Flight Crew reviews PTM clearance	PTM clearance	Required information elements provided	2.2.4
2.2.4	A/C	PTM clearance information is loaded into the FIM equipment if not already loaded	PTM clearance	Information loaded	2.2.5
2.2.5	A/C-Av	Are the avionics able to identify and is signal quality valid for all designated aircraft?	Designated aircraft flight ID(s) and ADS-B signal(s) for designated aircraft	Avionics are able to identify all named aircraft and signal quality is valid for PTM	2.2.6
				Avionics are not able to identify all named aircraft and/or signal quality is not valid for PTM	2.2.17
2.2.6	A/C	Is ahead and behind information required?	PTM operation rules	Ahead and behind information is required.	2.2.7
				Ahead and behind information is not required.	2.2.8

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Initiation Airborne (page 2)					
2.2.7	A/C	Is the ahead and behind information received in the PTM clearance consistent with actual traffic geometry?	PTM clearance and ADS-B signal for designated aircraft	The ahead and behind information is consistent with actual traffic geometry	2.2.8
				The ahead and behind information is not consistent with actual traffic geometry	2.2.17
2.2.8	A/C-Av	Does PTM spacing exist between ownship and all designated aircraft?	Position of ownship and designated aircraft, required PTM distance	PTM spacing between ownship and all designated aircraft exist	2.2.9
				PTM spacing between ownship and all designated aircraft does not exist	2.2.17
2.2.9	A/C-Av	Have the PTM avionics computed valid PTM Mach guidance?	Results of PTM Mach guidance calculation	Computation of valid PTM Mach guidance	2.2.10
				Unable to compute valid PTM Mach guidance	2.2.17
2.2.10	A/C-Av	PTM avionics enters pending PTM state	Pending PTM Mach guidance and related information	Required information elements provided	2.2.11
2.2.11	A/C-FC	Flight crew reviews PTM clearance message and pending PTM Mach guidance	PTM clearance message, pending PTM Mach guidance	Required information elements provided	2.2.12

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Initiation Airborne (page 3)					
2.2.12	A/C-FC	Flight crew enhances general situation awareness	Weather information, aircraft performance, wind information, traffic situation awareness, avionics status, available ride information, etc.	Required information elements provided	2.2.13
2.2.13	A/C-FC	Does the flight crew decide to accept the pending PTM clearance?	Information from 2.2.11 and 2.2.12	Flight crew decides to accept the pending PTM clearance	2.2.14
				Flight crew decides not to accept the pending PTM clearance	2.2.18
2.2.14	A/C-FC	Flight crew engages PTM	Knowledge of PTM avionics HMI	PTM avionics enters PTM engaged mode	2.2.15
2.2.15	A/C-Av	PTM avionics enters PTM engaged mode	valid criteria for PTM avionics engagement	Engaged mode indication	2.2.16
2.2.16	A/C-FC	Flight crew sends acceptance of the PTM clearance to ATC	PTM acceptance message	Transmission complete	To Execution Airborne
2.2.17	A/C-Av	Avionics indicates unable PTM and provides a reason why the PTM clearance cannot be accepted	Unable PTM message, plus a statement regarding the reason why a PTM clearance cannot be accepted.	Information displayed to flight crew	2.2.18
2.2.18	A/C-FC	Clear pending PTM in PTM avionics		PTM operation cleared in PTM avionics	2.2.19

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Initiation Airborne (page 4)					
2.2.19	A/C-FC	Refuse pending PTM clearance with ATC	Unable PTM message and the reason why a PTM clearance cannot be accepted.	Transmission complete	2.2.20
2.2.20	A/C-FC	Does ownship have active PTM operations?	List of ownship active PTM operations	Ownship has active PTM operations	To Execution Airborne
				Ownship does not have any active PTM operations	To Termination Airborne

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Ground (page 1)					
3.1.1	Gnd-Pro	Monitor traffic and display new conflicts	Output from PTM aware conflict probe	Output displayed to controller	3.1.2
3.1.2	Gnd-Pro	Is there a new conflict indicated?	Existence of conflict	Indication of new conflict	3.1.3
				No new conflict indicated	3.1.5
3.1.3	Gnd-Pro	Is PTM an option for resolving the conflict?	Existence of conflict, PTM criteria	PTM is an option to resolve the new conflict	To PTM Pre-Initiation (Ground), 3.1.1
				PTM is not an option to resolve the new conflict	3.1.4
3.1.4	Gnd	Resolve conflict using non-PTM procedures	Standard sector management procedures (non-PTM separation standards, sector traffic information)	Required information elements provided	3.1.1
3.1.5	Gnd-Pro	Are there only non-PTM operations in the sector?	List of PTM operations in the sector	Only non-PTM operations in the sector (no PTM operations in the sector)	3.1.1
				Existence of PTM operations in the sector	3.1.6
3.1.6	Gnd-Pro	Update designated aircraft intent information as needed	Designated aircraft intent information (if available)	Transmission complete	3.1.7

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Ground (page 2)					
3.1.7	Gnd-Pro	Monitor for non-PTM separation availability for any PTM aircraft	Output from PTM aware conflict probe	Results of PTM aware conflict probe check	3.1.8
3.1.8	Gnd-Pro	Is non-PTM separation available between any PTM and designated aircraft?	Existence of availability of non-PTM separation standard	Non-PTM separation available between any PTM and designated aircraft	3.1.9
				No non-PTM separation available between any PTM and designated aircraft	3.1.1
3.1.9	Gnd-Pro	Ground automation system generates PTM message queue	PTM message queue rules	PTM message queue	3.1.10
3.1.10	Gnd-Pro	Ground automation system displays existence of non-PTM separation availability for the PTM aircraft to the controller	Existence of non-PTM separation standard	Required information elements provided	3.1.11
3.1.11	Gnd-ATC	Controller observes availability of non-PTM separation	Existence of non-PTM separation standard	Required information elements provided	3.1.12

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Ground (page 3)					
3.1.12	Gnd-ATC	Does controller elect to display the PTM message queue?	Existence of non-PTM separation standard	Controller elects to display the PTM message queue	3.1.13
				Controller does not elect to display the PTM termination package	3.1.1
3.1.13	Gnd-Pro	Systems displays PTM message queue	PTM message queue	Required information elements provided	3.1.14
3.1.14	Gnd-ATC	Controller reviews PTM message queue	PTM message queue	Required information elements provided	3.1.15
3.1.15	Gnd-ATC	Does controller decide to initiate processing the PTM message queue?	PTM message queue, sector traffic management plan	Controller decides to initiate processing the PTM message queue	To PTM Pre-Initiation (Ground)
				Controller decides to not initiate processing the PTM message queue	3.1.16
3.1.16	Gnd-Pro	Remove PTM message queue from display		Required information elements provided	3.1.1

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 1)					
3.2.1	A/C-Av	Avionics displays PTM information and PTM Mach guidance	PTM Mach guidance	Display of PTM Mach guidance	3.2.2
3.2.2	A/C-FC	Flight crew complies with PTM Mach guidance	PTM Mach guidance	Flight crew complies with PTM Mach guidance	3.2.3
3.2.3	A/C-Av	PTM avionics conduct system health monitoring activities (which may result in the issuance of warning, caution, and/or indications)	Avionics internal health monitoring	Results from monitoring	3.2.4
3.2.4	A/C-Av	PTM avionics conduct signal monitoring activities (which may result in the issuance of warning, caution, and/or indications)	ADS-B signals from all aircraft, Standards of validity	Results from monitoring	3.2.5
3.2.5	A/C-Av	PTM avionics monitor PTM Mach guidance conformance and spacing (which may result in the issuance of warning, caution, and/or indications)	PTM Mach guidance, aircraft commanded Mach, PTM spacing criteria, actual aircraft spacing	Results from monitoring	3.2.6
3.2.6	A/C-Av	Has a warning, caution, and/or indication been generated?	Results from monitoring	Existence of a warning, caution, and/or indication	3.2.7
				No warning, caution, and/or indication exist	3.2.10

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 2)					
3.2.7	A/C-FC	Does the flight crew observe PTM-related warning, caution, and/or indication?	warning, caution, and/or indication	Flight crew observes PTM-related warning, caution, and/or indication	3.2.8
				Flight crew does not observe the PTM-related warning, caution, and/or advisory alert	3.2.1
3.2.8	A/C	Can the flight crew resolve the situation using PTM Mach guidance?	warning, caution, and/or advisory alert, PTM Mach guidance. Knowledge of normal and non-normal procedures	Flight crew is able to resolve the situation by following PTM Mach guidance	3.2.10
				Flight crew is not able to resolve the situation by following PTM Mach guidance	3.2.9
3.2.9	A/C	Unable PTM, contact ATC		Transmission complete	3.2.1
3.2.10	A/C-FC	Pilot implements action to resolve the warning, caution, and/or indication	warning, caution, and/or advisory alert, PTM Mach guidance	Warning, caution, and/or indication removed	3.2.11
3.2.11	A/C	Has a new PTM clearance message been received?	Existence of a new PTM clearance message	A new PTM clearance message has been received	3.2.12
				No new PTM clearance message has been received	3.2.1
3.2.12	A/C-FC	Pilot loads the PTM clearance information if not already loaded	PTM clearance	Information loaded	3.2.13

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 3)					
3.2.13	A/C-Av	Does clearance remove a designated aircraft?	PTM clearance message	Clearance removes designated aircraft	3.2.14
				Clearance does not remove designated aircraft	3.2.17
3.2.14	A/C-FC	Flight crew accepts clearance	PTM clearance message	Transmission complete	3.2.15
3.2.15	A/C-FC	Flight crew acknowledges in the PTM avionics any removed designated aircraft	Flight ID(s) of removed aircraft	Flight crew action completed	3.2.16
3.2.16	A/C	Have all PTM operations been canceled?	List of remaining designated aircraft	PTM has been canceled on all designated aircraft	Termination Airborne
				PTM is still being applied on some designated aircraft	3.2.1
3.2.17	A/C-FC	Flight crew reviews PTM clearance	PTM clearance	Flight crew action completed	3.2.18
3.2.18	A/C-Av	Are the avionics able to identify and is signal quality valid for all designated aircraft?	Designated aircraft flight ID(s) and ADS-B signal(s) for designated aircraft	Avionics are able to identify all named aircraft and signal quality is valid for PTM	3.2.19
				Avionics are not able to identify all named aircraft and/or signal quality is not valid for PTM	3.2.30

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 4)					
3.2.19	A/C	Is ahead and behind information required?	PTM operation rules	Ahead and behind information is required.	3.2.20
				Ahead and behind information is not required.	3.2.21
3.2.20	A/C	Is the ahead and behind information received in the PTM clearance consistent with actual traffic geometry?	PTM clearance and ADS-B signal for designated aircraft	The ahead and behind information is consistent with actual traffic geometry	3.2.21
				The ahead and behind information is not consistent with actual traffic geometry	3.2.30
3.2.21	A/C-Av	Does PTM spacing exist between ownship and all designated aircraft?	Position of ownship and designated aircraft, required PTM distance	PTM spacing between ownship and all designated aircraft exist	3.2.22
				PTM spacing between ownship and all designated aircraft does not exist	3.2.30
3.2.22	A/C-Av	Have the PTM avionics computed valid PTM Mach guidance?	Results of PTM Mach guidance calculation	Computation of valid PTM Mach guidance	3.2.23
				Unable to compute valid PTM Mach guidance	3.2.30
3.2.23	A/C-Av	PTM avionics enters pending and engaged PTM state	Pending PTM Mach guidance and related information	Required information elements provided	3.2.24

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 5)					
3.2.24	A/C-FC	Flight crew reviews PTM clearance message and pending PTM Mach guidance	PTM clearance message	Pilot action completed	3.2.25
3.2.25	A/C-FC	Flight crew enhances general situation awareness	Weather information, aircraft performance, wind information, traffic situation awareness, avionics status, available ride information, etc.	Pilot action completed	3.2.26
3.2.26	A/C-FC	Does the flight crew decide to accept the PTM clearance?	Information from 3.2.24 and 3.2.25	Flight crew decides to accept the PTM clearance	3.2.27
				Flight crew decides not to accept the PTM clearance	3.2.31
3.2.27	A/C-FC	Flight crew engages PTM	Knowledge of PTM avionics HMI	Pilot action completed	3.2.28
3.2.28	A/C-Av	PTM avionics enters PTM engaged mode	valid criteria for PTM avionics engagement	Engaged mode indication	3.2.29
3.2.29	A/C-FC	Flight crew sends acceptance of the PTM clearance to ATC	PTM acceptance message	Transmission complete	3.2.1
3.2.30	A/C-Av	Avionics indicates unable PTM and provides a reason why the PTM clearance cannot be accepted	Unable PTM message, plus a statement regarding the reason why a PTM clearance cannot be accepted.	Information displayed to flight crew	3.2.31

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Execution Airborne (page 6)					
3.2.31	A/C-FC	Clear pending PTM in PTM avionics		PTM operation cleared in PTM avionics	3.2.32
3.2.32	A/C-FC	Refuse PTM clearance with ATC	Unable PTM message and the reason why a PTM clearance cannot be accepted.	Transmission complete	3.2.1

ID	Domain	Function	Required Information	Criteria for Transfer	Next
Termination Airborne					
4.2.1	A/C	Resume Normal Ops (which may include PTM)			

A.11 ABNORMAL EVENTS

The following table lists expected Abnormal Events and the appropriate response to them.

Abnormal Event	Response
Failure of FIM equipment on-board PTM aircraft during PTM operations	Flight crew follows failure checklist to include notifying ATC, maintains last PTM Mach guidance, considers an offset in an appropriate direction, broadcasts intent, and attempts to contact designated aircraft.
Failure of ADS-B transponder / equipment on-board designated aircraft	Flight crew contacts ATC, maintain last PTM Mach guidance, reviews altitude distance and closure of all aircraft, attempts to contact designated aircraft (as appropriate) and performs contingency maneuver as appropriate.
Designated aircraft ahead of PTM aircraft slows down, not in compliance with its Mach assignment (for other than turbulence)	Flight crew follows new speed guidance generated by FIM equipment. If not able to follow the speed guidance, flight crew notifies ATC, considers an offset in an appropriate direction, broadcasts intent and attempts to contact designated aircraft.
Designated aircraft ahead of PTM aircraft slows down, not in compliance with its Mach assignment (for turbulence)	Flight crew follows new speed guidance generated by FIM equipment. If not able to follow the speed guidance, flight crew notifies ATC, considers an offset in an appropriate direction, broadcasts intent and attempts to contact designated aircraft.
Designated aircraft behind PTM aircraft speeds up, not in compliance with its Mach assignment	Flight crew follows new speed guidance generated by FIM equipment. If not able to follow the speed guidance, flight crew notifies ATC, considers an offset in an appropriate direction, broadcasts intent, and attempts to contact designated aircraft.

Abnormal Event	Response
PTM aircraft experiences in-flight emergency (e.g., engine failure, cabin depressurization)	Comply with standard oceanic contingency procedures
FIM equipment produces erroneous guidance	Maintain situation awareness and respond to PTM alerts received from the FIM equipment. Note: alerts are not based on guidance calculations
PTM aircraft performance does not allow the PTM aircraft to follow the PTM speed guidance	Attempt to follow PTM guidance, contact ATC, considers an offset in an appropriate direction, broadcasts intent, and attempts to contact designated aircraft.

A.12 DEFINITION OF KEY TERMS

The following is a list of definitions that are essential for the correct interpretation of this document.

Add PTM Mach: Clearance from ATC to increase the number of designated aircraft included in an ongoing PTM operation.

Ahead of: PTM clearance geometry in which the PTM equipped aircraft is physically located in front (ahead) of a designated aircraft.

Automatic Dependent Surveillance – Broadcast (ADS-B): A means by which aircraft, aerodrome vehicles, and other objects can automatically transmit and/or receive data such as identification, position, and additional data, as appropriate, in a broadcast mode via a data link.

Automatic Dependent Surveillance – Contract (ADS-C): A means by which the terms of an ADS-C agreement will be exchanged between the ground system and the aircraft, via a data link, specifying under what conditions ADS-C reports would be initiated, and what data would be contained in the reports.

Background aircraft: Any ADS-B Out aircraft, within ADS-B signal range, not serving as a pending or designated aircraft in the ownship's PTM operation.

Behind: PTM clearance geometry in which the PTM equipped aircraft is physically located behind a designated aircraft.

Cancelled PTM: A mode within the airborne FIM equipment that occurs when a Cancel PTM clearance is received.

Cleared PTM Mach: Clearance from ATC to initiate a PTM operation.

Continue PTM: Clearance from ATC requiring the PTM equipped aircraft to maintain a PTM operation with a specific designated aircraft.

Controller Pilot Data Link Communication: A means of communication between controller and pilot, using data link for ATC communications.

Crossing: PTM clearance geometry in which the PTM equipped aircraft and designated aircraft are not located in-trail of each other and their routes will intersect.

Designated aircraft: An aircraft from which the PTM equipped aircraft must get no closer than a set distance during a PTM operation.

Engaged PTM: A mode within the airborne FIM equipment that occurs when a PTM clearance has been accepted by the flight crew and PTM is being actively performed with one or more designated aircraft.

FIM equipment: The avionics on board the PTM Aircraft that supports FIM applications. This includes the hardware, software, and displays necessary to perform PTM operations. The term "FIM equipment" does not imply any specific avionics architecture.

Ground automation system: Computer automation that assists the controller by providing a means for communication, separation, and decision support.

Limit Mach: The limit Mach is calculated for each PTM operation and is sent to each PTM aircraft that enters a specific PTM operation. This is a Mach number the PTM aircraft may be required to fly at some point during the PTM operation.

Merge Ahead of: PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located in front (ahead) of the designated aircraft once both aircraft are on the same track.

Merge Behind: PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located behind the designated aircraft once both aircraft are on the same track.

No PTM: A mode within the airborne FIM equipment that occurs when either no PTM clearance has been received or after all PTM clearances have been cancelled.

Non-PTM aircraft: An aircraft that has not been cleared to conduct a PTM operation. A non-PTM aircraft may serve as a designated aircraft.

Non-PTM separation: Separation applied by ATC for a given airspace and aircraft equipage level. For example, 50 NM longitudinal and lateral separations can be applied with ADS-C reporting in intervals of 27 minutes and Required Navigation Performance 10 (RNP10) aircraft. Non-PTM separation specifically refers to a separation standard that is not associated with PTM separation.

Pending aircraft: An aircraft that has been included in a PTM clearance being reviewed by the flight crew. If the clearance is accepted, this aircraft will become a designated aircraft. If the clearance is rejected, this aircraft will become a background aircraft.

Pending PTM: A mode within the airborne FIM equipment that occurs when a PTM clearance has been received, but the flight crew has not yet engaged the FIM equipment and begun conducting the PTM operation with the aircraft included in the clearance.

Pending PTM guidance: Shown during a Pending PTM mode, it provides the flight crew with a preview of what the PTM Guidance will be if the PTM clearance is accepted.

Procedural control: Term used to indicate that information derived from an air traffic services surveillance system is not required for the provision of air traffic control service.

Procedural separation: The separation used when providing procedural control.

PTM Chain: A sequence of aircraft following the rules stated in the PTM Chain rules (see Appendix A-1).

PTM equipped aircraft: An aircraft that has FIM equipment installed on-board.

PTM Pair: A pair of aircraft where one aircraft is a designated non-PTM aircraft and one aircraft is a PTM aircraft with a clearance to get no closer than a set distance from the designated aircraft.

PTM guidance: A series of Mach commands and restrictions provided by the FIM equipment to ensure that PTM operations are maintained for a minimum of 30 minutes
PTM separation standard: A procedure that, when applied, allows for PTM operations to be conducted while ensuring the required PTM separation standard distance.

PTM separation standard distance: A horizontal distance (currently proposed to be 5 NM) that aircraft get no closer than during a PTM operation. The horizontal distance between a PTM equipped aircraft and a designated aircraft shall never be less than the PTM separation standard distance while a PTM operation is in effect.

PTM spacing: A distance comprising the PTM separation standard distance plus a distance buffer. The FIM equipment provides guidance to the flight crew to achieve the PTM spacing.

PTM String: A sequence of aircraft following the rules stated in the PTM String rules (see Appendix A-1).

Remove PTM: Clearance from ATC to stop performing PTM on a specific designated aircraft.

Same identical track: Two aircraft are on same identical tracks when they are on the same route and following the same waypoints along a track. Same identical tracks are a special case of same track (as defined in ICAO PANS-ATM Doc. 4444 and FAA JO 7110.65) where the angular difference is zero degrees.

Same track: (As defined in ICAO PANS-ATM Doc. 4444 and FAA JO 7110.65) – Same direction tracks and intersecting tracks or portions thereof, the angular difference of which is less than 45 degrees or more than 315 degrees, and whose protected airspaces overlap.

Separation standard: A procedure that ATC applies to aircraft traffic to ensure required separation between aircraft. When ATC is applying a separation standard, the distance between aircraft shall never be less than the separation standard distance.

Separation standard distance: A minimum distance that shall never be infringed upon during aircraft operations.

Sequence: An ordered series of aircraft operating on a common track.

Speed command: PTM guidance form used when a single Mach speed is required to achieve or maintain a minimum separation standard distance.

Speed restrictions: PTM guidance form used when more than one Mach speed will achieve separation.

APPENDIX A-1 RULES FOR PTM PAIRS, STRINGS, AND CHAINS

A-1.1 PTM PAIRS

A-1.1.1 Pairs Overview

A PTM Pair is formed when:

- There are two aircraft in a sequence,
- The separation standard between the two aircraft is PTM separation
- There is one PTM aircraft and one designated non-PTM aircraft.

Figures A-1.1 and A-1.2 show examples of PTM Pairs. In these figures, the black aircraft denote PTM aircraft and the white aircraft denote designated, non-PTM aircraft. The arrow denotes that the black aircraft is conducting a PTM operation with the white aircraft as a designated aircraft. The distance D between the aircraft is greater than or equal to the PTM separation standard distance. It should be noted that a designated non-PTM aircraft could be PTM equipped, but it has not been cleared and it is not conducting a PTM operation.

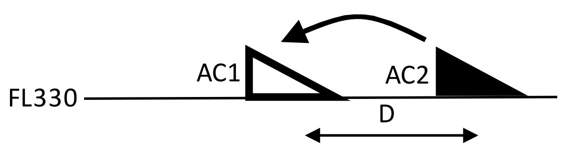


Figure A-1.1 PTM Pair with aircraft AC2 cleared for PTM separation from aircraft AC1.

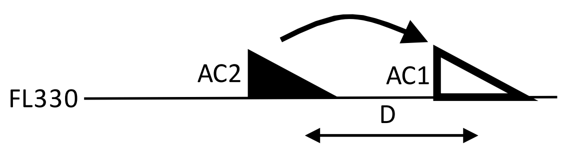


Figure A-1.2 PTM Pair with aircraft AC2 Cleared for PTM separation from aircraft AC1.

A-1.1.2 PTM Pair rules

- There is one PTM aircraft and one non-PTM aircraft. Either the PTM aircraft or the non-PTM aircraft could be leading.
- The non-PTM aircraft will be assigned a Mach speed.
- The non-PTM assigned Mach speed could be a fix value (e.g., 0.80 Mach) or a fix value or greater (e.g., 0.80 or greater) when the non-PTM aircraft is leading.
- The non-PTM assigned Mach speed could be a fix value (e.g., 0.80 Mach) or a fix value or less (e.g., 0.80 or less) when the non-PTM aircraft is trailing.
- The clearance will include a limit Mach. The limit Mach is calculated using the non-PTM aircraft assigned speed and the PTM aircraft's current speed. The limit Mach is a speed the PTM

aircraft may be required to fly at some point during the PTM operation.

- In an operation where the PTM aircraft is trailing, the limit Mach is the minimum of the PTM current Mach speed and the designated aircraft assigned speed. The limit Mach will become the lower bound of the speed guidance, except if a loss of spacing occurs.
- In an operation where the PTM aircraft is leading, the limit Mach is the maximum of the PTM current Mach speed and the designated aircraft assigned speed. The limit Mach will become the upper bound of the speed guidance, except if a loss of spacing occurs.
- The speed guidance for a PTM operation could be a fixed value (e.g., 0.79 Mach) or a range of speeds (e.g., 0.78 to 0.81).
- Lateral maneuvers (except SLOP[1]) are not authorized for any aircraft which is a designated aircraft in a PTM clearance. Turns at waypoints in a route are not considered lateral maneuvers.

A-1.2 PTM STRINGS

A-1.2.1 PTM Strings Overview

A PTM String is formed when:

- There are more than two aircraft in a sequence,
- There is a non-PTM designated aircraft leading or trailing the sequence,
- The separation standard between aircraft that do not have Non-PTM separation in the sequence is PTM separation,
- There is one (and only one) non-PTM aircraft in the sequence.

A PTM String can be formed in two different ways:

- The non-PTM aircraft is the leading aircraft (Figure A-1.3)
- The non-PTM aircraft is the trailing aircraft (Figure A-1.4)

Examples of PTM Strings are shown in figures A-1.3 and A-1.4. In these figures, the black aircraft denote PTM aircraft, the white aircraft denote non-PTM aircraft, and the grey aircraft denote a PTM aircraft that is also serving as a designated aircraft. Figure A-1.3 shows the case where the non-PTM aircraft is the leading aircraft. In this example, aircraft AC2 is conducting a PTM operation with AC1 as designated; Aircraft AC3 is conducting PTM operations with AC2 and AC1 as designated and; Aircraft AC4 is conducting PTM operations with AC3 and AC2. No PTM clearance is issued to aircraft AC4 to maintain separation from aircraft AC1 because Non-PTM separation exists. The ground automation (e.g., Advanced Technologies and Oceanic Procedures, ATOP) keeps track of what type of separation is being applied between which aircraft. If the distance between aircraft AC1 and AC4 is projected to be reduced to less than the Non-PTM separation standard minimum, the ground automation will signal a conflict and the controller could issue a PTM clearance between AC1 and AC4 or take other action.

[1] SLOP is the Strategic Lateral Offset Procedure that allows aircraft in Oceanic airspace to move 1 or 2 nautical miles to the right of the track centerline to reduce wake turbulence encounters and risk of collision.

Note that if aircraft AC4 is maintaining separation from aircraft AC3, it is, by the geometric condition that AC2 is in front of AC3, maintaining separation from AC2. However, a PTM clearance is issued to aircraft AC4 to maintain separation from AC2 because no legal separation standard exists between these two aircraft and in case a non-nominal condition or emergency occurs where aircraft AC3 is removed from the string.

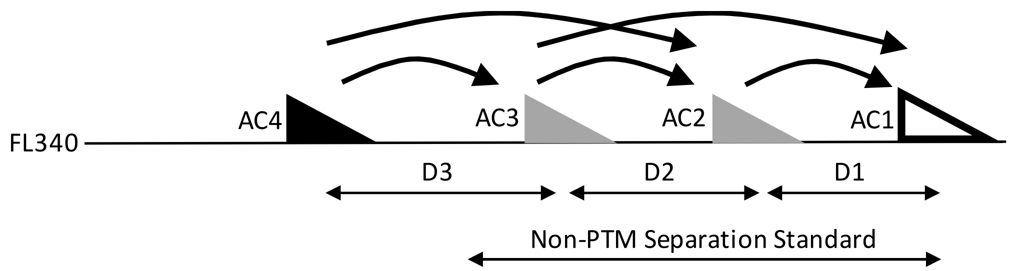


Figure A-1.3. PTM String with Non-PTM aircraft leading.

Figure A-1.4 shows the case where the non-PTM aircraft is the trailing aircraft. In this example, aircraft AC2 is performing a PTM operation with AC3 as designated and aircraft AC3 is performing a PTM operation with AC1 as designated.

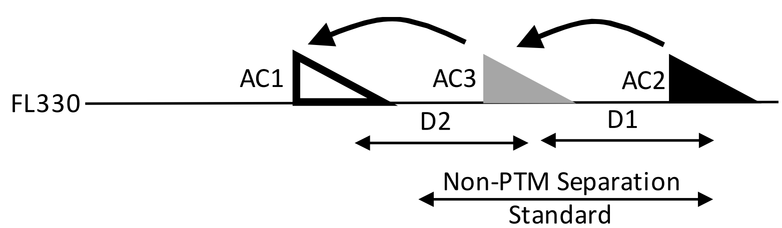


Figure A-1.4. PTM String with non-PTM aircraft trailing.

A-1.2.2 PTM String rules

- There can only be one non-PTM aircraft in a string. The non-PTM aircraft can be at the front of the string or at the end of the string.
- The non-PTM aircraft will be assigned a Mach speed.
- The non-PTM assigned Mach speed could be a fix value (e.g., 0.80 Mach) or a fix value or greater (e.g., 0.80 or greater) when the non-PTM aircraft is leading.
- The non-PTM assigned Mach speed could be a fix value (e.g., 0.80 Mach) or a fix value or less (e.g., 0.80 or less) when the non-PTM aircraft is trailing.
- The clearance will include a limit Mach.
- When the non-PTM aircraft is leading, the limit Mach is calculated using the assigned or limit Mach of the aircraft immediately in front and the PTM aircraft's current speed.

- When the non-PTM aircraft is trailing, the limit Mach is calculated using the assigned or limit Mach of the aircraft immediately behind and the PTM aircraft's current speed.
- In an operation where the non-PTM aircraft is leading, the limit Mach is the minimum of the PTM aircraft current Mach speed and the leading designated aircraft assigned Mach speed (non-PTM) or limit Mach (PTM aircraft). (In Figure A-1.3, the limit Mach of aircraft AC2 is the minimum of AC2's speed at the time of the clearance and AC1 assigned Mach speed. The limit Mach of aircraft AC3 is the minimum of AC3's speed at the time of the clearance and AC2's limit Mach). The limit Mach will become the lower bound of the speed guidance, except if a loss of spacing occurs.
- In an operation where the non-PTM aircraft is trailing, the limit Mach is the maximum of the PTM aircraft current Mach speed and the trailing designated aircraft assigned Mach speed (non-PTM) or limit Mach (PTM aircraft). The limit Mach will become the upper bound of the speed guidance, except if a loss of spacing occurs.
- In a PTM String, all PTM clearances will have the designated aircraft in the direction of the non-PTM aircraft.
- The string begins and ends with an interval of Non-PTM separation.
- Lateral maneuvers (except SLOP) are not authorized for any aircraft, which is a designated aircraft in a PTM clearance. Turns at waypoints in a route are not considered lateral maneuvers.

A-1.3 PTM CHAINS

A-1.3.1 PTM Chains Overview

A PTM Chain is formed when:

- There are more than two aircraft in a sequence,
- There are two non-PTM aircraft in the sequence, one leading and one trailing,
- The separation standard between the two non-PTM aircraft is Non-PTM separation,
- All PTM aircraft in the sequence must be assigned and maintain PTM separation from the aircraft in front and aircraft behind that do not have Non-PTM separation.

Figure A-1.5 shows an example of a PTM Chain. The black aircraft denotes a PTM aircraft and the white aircraft denote non-PTM aircraft.

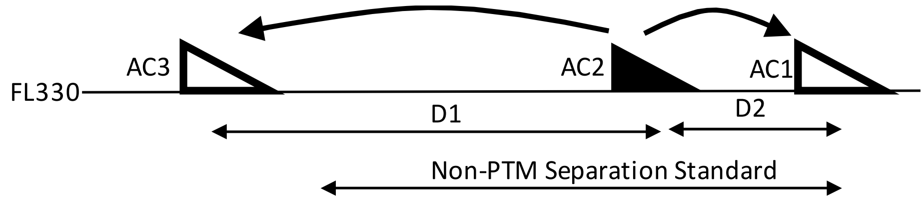


Figure A-1.5. PTM Chain, one PTM aircraft.

In the example of Figure A-1.5, ATC is implementing Non-PTM separation between aircraft AC1 and AC3. Aircraft AC2 is given a PTM clearance to maintain separation from aircraft AC1 and AC3.

Figure A-1.6 shows an example of a PTM chain with two PTM aircraft. Aircraft AC2 is maintaining separation from aircraft AC1, AC4, and AC3. Aircraft AC4 is maintaining separation from aircraft AC1, AC2, and AC3.

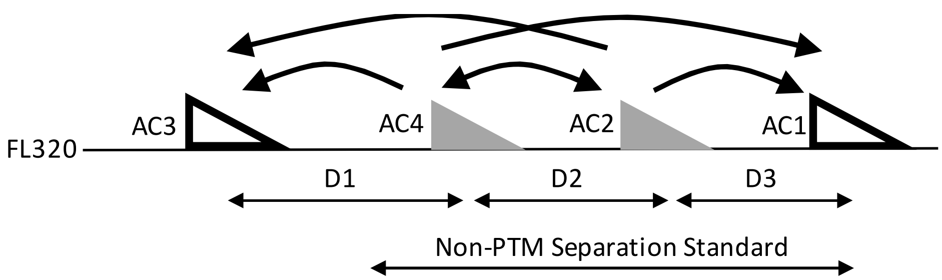


Figure A-1.6. PTM Chain, two PTM aircraft.

The maximum number of PTM aircraft in a chain is determined by the non-PTM separation distance, the PTM separation distance, and the buffers needed to maintain spacing, as shown in PTM Chain rule Equation A-1.1. For example, if the non-PTM separation distance is 30 NM, the Non-PTM separation buffer is 1 NM, the PTM separation distance is 5 NM, and the PTM distance buffer is 1.5 NM, then the maximum number of PTM aircraft in the chain is:

$$\left\lfloor \frac{30-1}{5+1.5} - 1 \right\rfloor = \lfloor 3.46 \rfloor = 3$$

A-1.3.2 PTM Chain rules

The maximum number of PTM aircraft in a chain is given by the following equation truncated to an integer:

$$\frac{\text{NonPTM separation} - \Delta_1}{\text{PTM separation} + \Delta_2} - 1$$

where Δ_1 and Δ_2 are separation buffers.

Equation A-1.1. PTM Chain rule.

Other chain rules include:

- All PTM aircraft in a chain must be assigned PTM separation with aircraft in the front and aircraft behind for which Non-PTM separation does not exist.
- The first and last aircraft in the chain, the non-PTM aircraft, will be assigned Mach speeds.
- If the Mach assignments to the non-PTM aircraft are fixed values, the Mach assignments to the first and last aircraft will be equal.
- If the Mach assignments to the non-PTM aircraft are ranges of speed, the lower bound of the leading aircraft will be equal to or greater than the upper bound of the trailing aircraft. (For example, in Figure A-1.5, aircraft AC3 has a Mach assignment of 0.8 or slower and aircraft AC1 has a Mach assignment of 0.81 or greater.)
- The clearance will include a limit Mach. The limit Mach is the average value of the leading aircraft lower bound Mach assignment and the trailing aircraft upper bound Mach assignment. For example, if the leading aircraft has a Mach assignment of [0.82 or greater] and the trailing aircraft has a Mach assignment of [0.80 to 0.80] (a fixed value), then the limit Mach is 0.81.
- The speed guidance received by an aircraft in a chain will be the limit Mach, unless there is a loss of spacing, in which case the guidance given will be to restore the spacing.
- Lateral maneuvers (except SLOP) are not authorized for any aircraft, which is a designated aircraft in a PTM clearance. Turns at waypoints in a route are not considered lateral maneuvers.

A-1.4 PROCESS FOR CREATING A PAIR

A PTM Pair is created when a clearance is given by ATC, to a PTM-capable aircraft, to maintain PTM separation from a non-PTM aircraft.

A-1.4.1 Rules for forming PTM Pairs

A-1.4.1.1 Case 1. Climb or descend, Figure A-1.7

- ATC assigns a Mach speed to the non-PTM aircraft (aircraft AC1).
- ATC (or ground automation) determines if the PTM capable aircraft is leading or trailing the non-PTM aircraft.
- ATC issues a PTM clearance to aircraft AC2, above or below the non-PTM aircraft (aircraft AC1), to maintain PTM separation from the non-PTM aircraft.
- If PTM spacing exists between aircraft AC2 and aircraft AC1 (and other criteria are compliant), aircraft AC2 accepts the clearance and maintains spacing/separation from AC1.
- ATC issues a climb or descent instruction to aircraft AC2 or to aircraft AC1. Both aircraft will be at the same flight level after the climb/descent.

- If PTM separation does not exist between aircraft AC2 and aircraft AC1 (or other conditions cannot be met), aircraft AC2 informs ATC “unable PTM.”

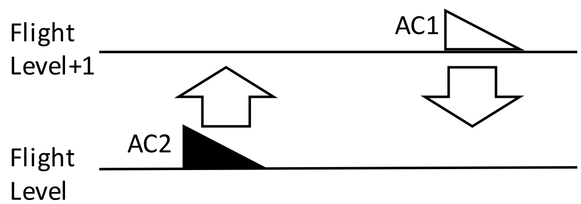


Figure A-1.7. Case 1. Forming a PTM Pair by climb or descent.

A-1.4.1.2 Case 2. Same flight level, Figure A-1.8

- Non-PTM non-radar separation exists between aircraft AC1 and AC2. Aircraft could be on the same track, identical same track, or merge.
- ATC assigns a Mach speed to the non-PTM aircraft (aircraft AC1).
- ATC (or ground automation) determines if the PTM capable aircraft is leading or trailing the non-PTM aircraft.
- ATC issued a PTM clearance to aircraft AC2 to maintain PTM separation from aircraft AC1, leading or trailing.
- Aircraft AC2 accepts or rejects PTM clearance.
- If aircraft AC2 accepts the PTM clearance, Non-PTM separation no longer needs to be maintained by ATC between aircraft AC1 and AC2.
- If aircraft AC2 is unable to accept the clearance, ATC must continue to maintain Non-PTM separation.

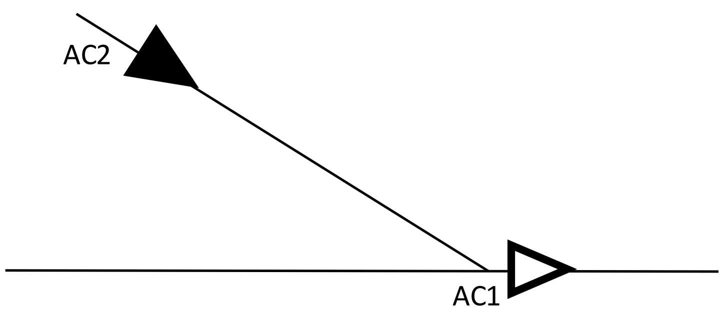


Figure A-1.8. Case 2. Forming a PTM Pair on same flight level.

A-1.4.1.3 Case 3. Same flight level, transition from radar to non-radar airspace, Figure A-1.9

- Radar separation exists between aircraft AC1 and AC2.
- ATC assigns a Mach speed to the non-PTM aircraft (aircraft AC1).
- ATC (or ground automation) determines if the PTM capable aircraft is leading or trailing the non-PTM aircraft.

- ATC issued a PTM clearance to aircraft AC2 to maintain PTM separation from aircraft AC1, leading or trailing.
- Aircraft AC2 accepts or rejects PTM clearance.
- If aircraft AC2 accepts the PTM clearance, ATC does not have to establish Non-PTM non-radar separation before aircraft AC2 is loaded into the non-radar track.
- If aircraft AC2 is unable to accept the clearance, ATC must establish Non-PTM non-radar separation before aircraft AC2 is loaded into the non-radar track.

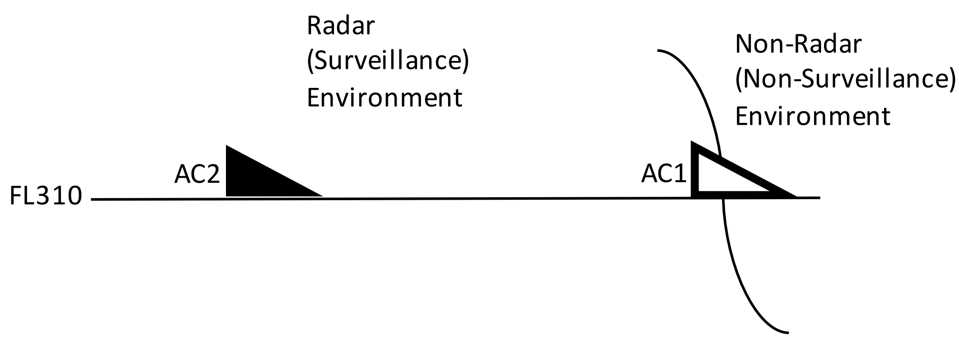


Figure A-1.9. Case 3. Forming a PTM Pair same flight level, transition from radar to non-radar airspace.

A-1.5 PROCESSES FOR CREATING PTM STRINGS

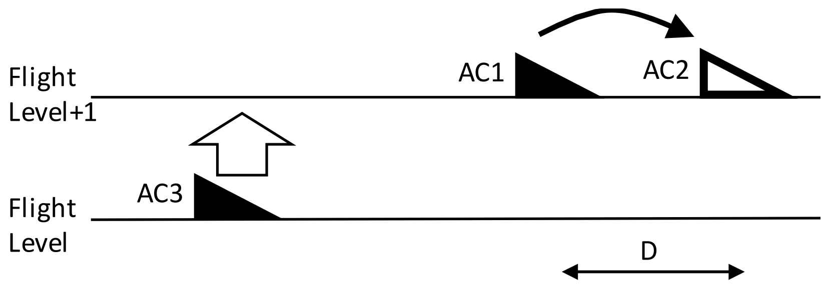
A string is created when a clearance is given to a PTM-capable aircraft to maintain PTM separation with an aircraft that is already part of a PTM Pair. The new aircraft joining the aircraft pair to form the PTM String could climb or descend to the flight level of the PTM Pair or it could join the pair horizontally.

A-1.5.1 Rules for Forming PTM Strings

A-1.5.1.1 Case 1. Climb or descend to PTM Pair flight level, trailing or leading the PTM Pair, Figures A-1.10 and A-1.11.

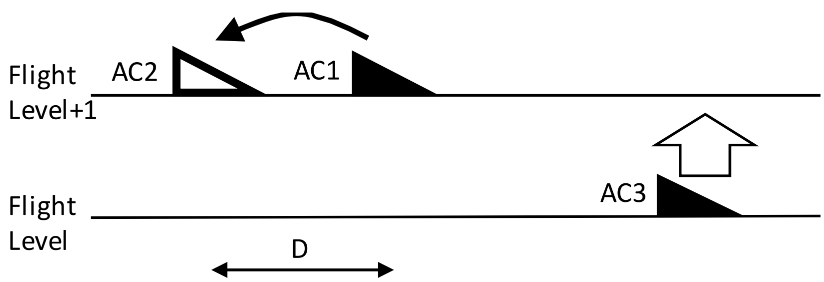
- ATC (or ground automation) must determine if the aircraft to join the PTM Pair is trailing, in between or leading the PTM Pair. If the aircraft to join the pair is trailing or leading the pair, Case 1 applies.
- ATC issues a PTM clearance to aircraft AC3, above or below the PTM Pair, to maintain PTM separation from aircraft AC1 (and from aircraft AC2 if distance between AC2 and AC3 is less than Non-PTM separation distance).
- If PTM spacing exists between aircraft AC3 and aircraft AC1, aircraft AC3 accepts the clearance and maintains spacing/separation from AC1.
- ATC issues a climb or descent instruction to aircraft AC3.

- If PTM spacing does not exist between aircraft AC3 and aircraft AC1, aircraft AC3 informs ATC “unable PTM.”



D ≥ PTM separation standard distance

Figure A-1.10. Case 1. Formation of a PTM String by climbing or descending to the PTM Pair flight level, trailing.



D ≥ PTM separation standard distance

Figure A-1.11. Case 1. Formation of a PTM String by climbing or descending to the PTM Pair flight level, leading.

A-1.5.1.2 Case 2. Climb or descend to PTM Pair flight level, between the aircraft in the PTM Pair, Figure A-1.12.

- ATC (or ground automation) must determine if the aircraft to join the PTM Pair is trailing, in between or leading the PTM Pair. If the aircraft to join the pair is between the aircraft in the pair, Case 2 applies.
- ATC gives clearance to aircraft AC3 to maintain separation from aircraft AC2.
- If PTM spacing exists between aircraft AC3 and aircraft AC2, aircraft AC3 accepts the clearance.
- ATC gives clearance to aircraft AC1 to maintain separation from aircraft AC3.
- If PTM spacing exists between aircraft AC1 and aircraft AC3, aircraft AC1 accepts the clearance.
- ATC issues a climb or descent instruction to aircraft AC3.

- If PTM spacing does not exist between aircraft AC3 and AC2 and/or aircraft AC1 and AC3, the flight crew of AC3 and/or the flight crew of AC1 inform ATC “unable PTM.”

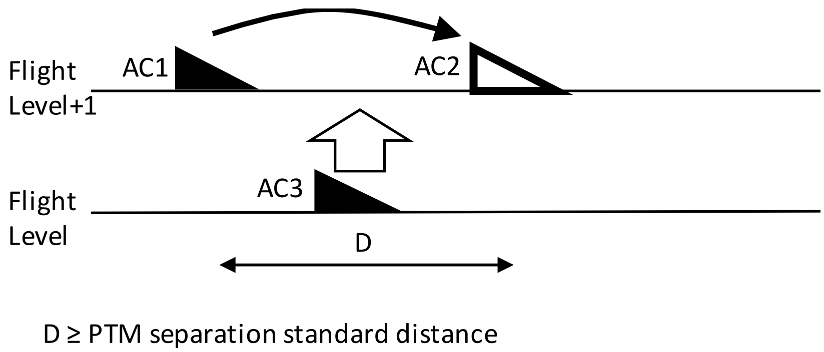


Figure A-1.12. Case 2. Formation of a PTM String by climbing or descending to the PTM Pair flight level, between the aircraft.

A-1.5.1.3 Case 3. Join PTM Pair horizontally, same track, same identical track, or merge, Figure A-1.13.

- ATC determines if the aircraft to join the PTM Pair is joining or merging behind or in front of the pair.
- Aircraft AC3 is at the same flight level as aircraft AC1 and AC2.
- Aircraft AC1 is maintaining PTM separation from aircraft AC2.
- Aircraft AC3 has Non-PTM separation from aircraft AC1 and AC2.
- ATC issues a PTM clearance to aircraft AC3 to maintain separation from aircraft AC1.
- Aircraft AC3 accepts or rejects PTM clearance.
- If aircraft AC3 accepts the PTM clearance, Non-PTM separation no longer needs to be maintained by ATC between aircraft AC1 and AC3.
- If aircraft AC3 is unable to accept the clearance, ATC must continue to maintain Non-PTM separation.

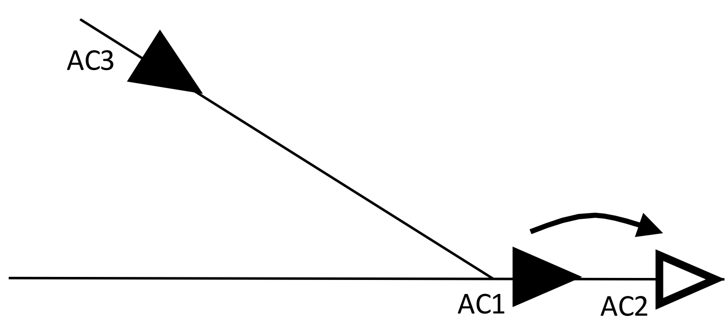


Figure A-1.13. Case 3. Formation of a PTM String Horizontally, same identical track, same track or merge.

A-1.5.1.4 Case 4. Join PTM Pair horizontally, transition from radar to non-radar, Figure A-1.14.

- Radar separation exists between aircraft AC2 and AC3.
- Aircraft AC3 is maintaining PTM separation from aircraft AC1.
- ATC issue a clearance to aircraft AC2 to maintain PTM separation from aircraft AC3.
- If oceanic non-radar Non-PTM separation does not exist between aircraft AC1 and AC2, ATC must also issue a PTM clearance between aircraft AC1 and AC2.
- If PTM spacing exists between aircraft AC2 and AC3, aircraft AC2 accepts the clearance.
- If PTM spacing does not exist between aircraft AC2 and AC3, aircraft AC2 informs ATC "unable PTM" and ATC must establish Non-PTM non-radar separation between AC3 and AC2 before aircraft AC2 is loaded into the non-radar track.

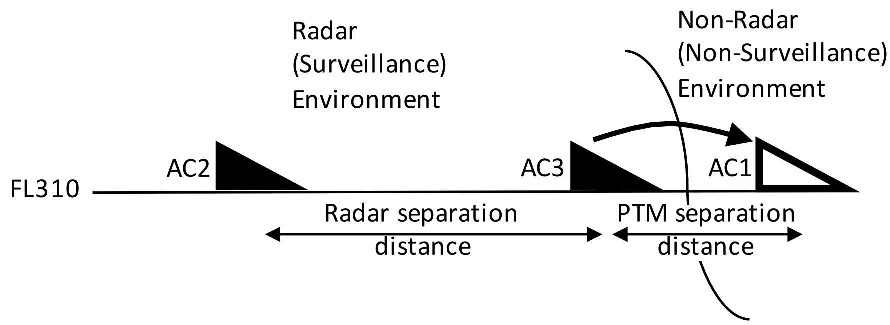


Figure A-1.14. Case 4. Formation of a PTM String horizontally, transition from radar to non-radar environment.

A-1.6 PROCESSES FOR CREATING PTM CHAINS

A chain can be formed by inserting a PTM aircraft between two designated aircraft or by adding a designated aircraft to a PTM Pair. The chain can be formed vertically or horizontally.

A-1.6.1 Rules for forming PTM Chains

A-1.6.1.1 Case 1. PTM aircraft climbs or descends to flight level between two designated aircraft, Figure A-1.15.

- ATC (or ground automation) must determine if the aircraft that will be given the PTM clearance is between the two aircraft that will become the designated non-PTM aircraft.
- Aircraft AC1 and AC2 are at the same flight level and have non-PTM horizontal separation.
- ATC or automation determines if Equation A-1.1, under PTM Chain rules Section A-1.3.2, is satisfied.
- ATC assigns Mach speeds to aircraft AC1 and AC2 (if they do not already have Mach assignments).
- ATC clears aircraft AC3 to maintain PTM separation from aircraft AC1 and AC2.

- If PTM spacing exists between aircraft AC3 and aircraft AC1 and AC2, aircraft AC3 accepts the clearance.
- ATC climbs/descends aircraft AC3.
- If PTM spacing does not exist between aircraft AC3 and aircraft AC1 or AC2, aircraft AC3 informs ATC “unable PTM.”

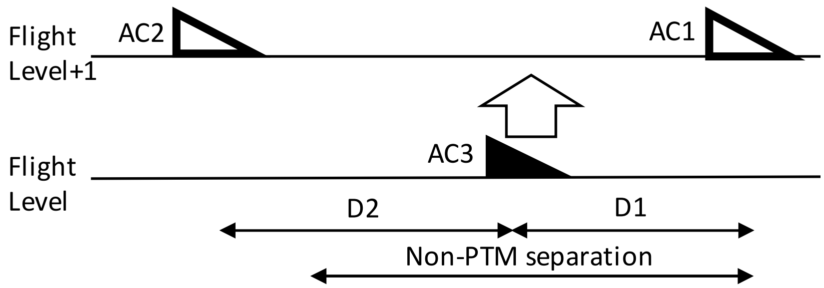
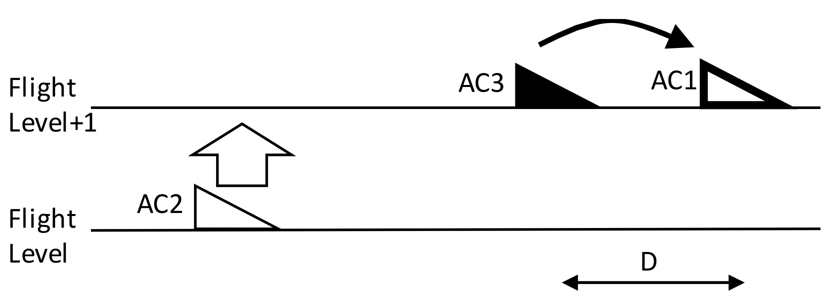


Figure A-1.15. Case 1. Formation of a PTM Chain by climbing or descending between designated aircraft.

A-1.6.1.2 Case 2. Designated aircraft climbs or descends to flight level of PTM Pair, Figure A-1.16.

- ATC (or ground automation) must determine if the aircraft that will become the designated aircraft is trailing or leading the PTM Pair.
- ATC (or ground automation) must determine if horizontal Non-PTM separation exists between aircraft AC1 and AC2.
- ATC or automation determines if Equation A-1.1, under PTM Chain rules Section A-1.3.2, is satisfied.
- If Non-PTM separation exists between aircraft AC1 and AC2 and Equation A-1.1 is satisfied, ATC issues PTM clearance to aircraft AC3 to maintain PTM separation from aircraft AC2.
- If PTM spacing exists between aircraft AC3 and aircraft AC2, aircraft AC3 accepts the clearance.
- ATC climbs/descends aircraft AC2.
- If PTM spacing does not exist between aircraft AC3 and aircraft AC2, aircraft AC3 informs ATC “unable PTM.”



D ≥ PTM separation standard distance

Figure A-1.16. Case 2. Designated aircraft climbs or descend to the flight level of the PTM Pair.

A-1.6.1.3 Case 3. PTM aircraft in a PTM Pair is cleared to maintain separation with a designated aircraft at the same flight level, Figure A-1.17.

- ATC must maintain Non-PTM (oceanic non-radar) separation between aircraft AC1 and AC2.
- ATC or automation determines if Equation A-1.1, under PTM Chain rules Section A-1.3.2, is satisfied.
- ATC issues PTM clearance to aircraft AC3 to maintain separation from aircraft AC2.
- If PTM spacing exists between aircraft AC3 and AC2, aircraft AC3 accepts the clearance.
- If PTM spacing does not exist between aircraft AC3 and AC2, aircraft AC3 informs ATC "unable PTM." ATC must establish Non-PTM non-radar separation before aircraft AC2 is loaded into the non-radar track.

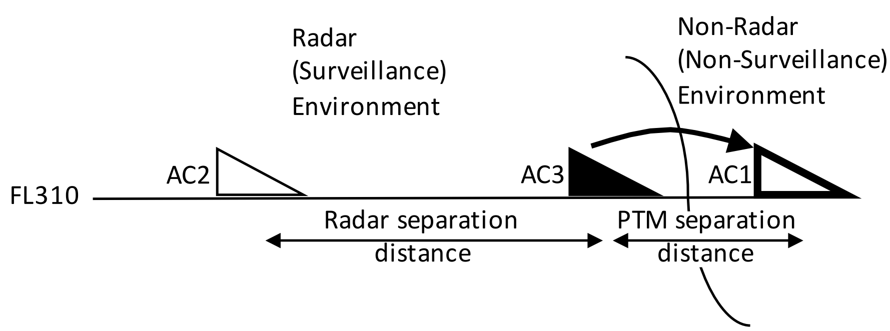


Figure A-1.17. Case 3. PTM aircraft in a PTM Pair is cleared to maintain PTM separation from a designated aircraft.

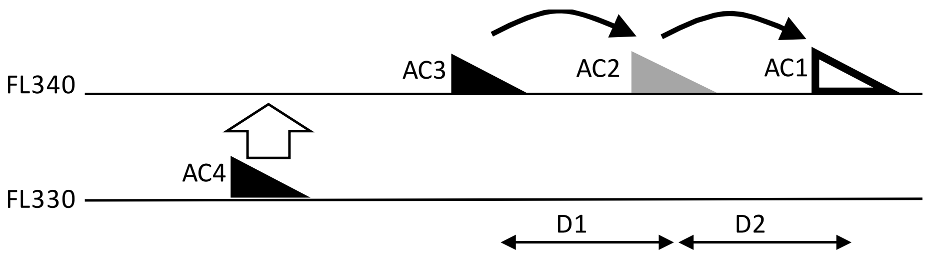
A-1.7 PROCESS FOR ADDING AN AIRCRAFT TO A PTM STRING

A PTM capable aircraft could join an existing string to form a longer string. A non-PTM capable aircraft can join an existing string to form a chain. When a PTM capable aircraft is going to join an existing string, the relative position of the joining aircraft must be determined with respect to the aircraft in the existing string.

A-1.7.1 Case 1. Climb or descend to PTM String flight level, trailing or leading the string, Figures A-1.18 and A-1.19.

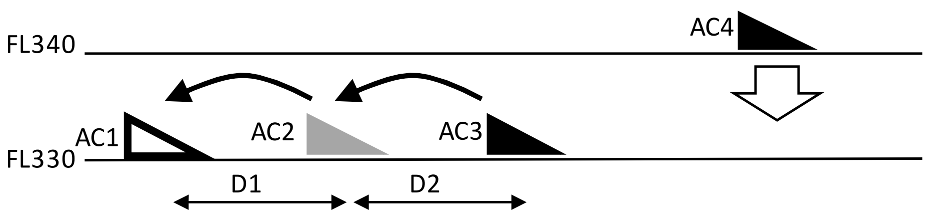
- ATC (or ground automation) must determine if the aircraft to join the PTM String is trailing, in between or leading the PTM String. If the aircraft to join the string is trailing or leading, the string Case 1 applies.
- ATC issues PTM clearance to aircraft AC4, above or below the PTM String, to maintain PTM separation from aircraft AC3.
- If oceanic non-radar Non-PTM separation does not exist between aircraft AC4 and AC2 and AC1, ATC must also issue a PTM clearance between aircraft AC4 and AC2 and AC1.

- If PTM spacing exists between aircraft AC4 and aircraft AC3, aircraft AC4 accepts the clearance and maintains separation from AC3 (and possibly AC2 and AC1).
- ATC issues a climb or descent instruction to aircraft AC4.
- If PTM spacing does not exist between aircraft AC4 and aircraft AC3, aircraft AC4 informs ATC “unable PTM.”



D1 & D2 ≥ PTM separation standard distance

Figure A-1.18. Case 1. Joining a PTM String by climbing or descending to the PTM String flight level, trailing.



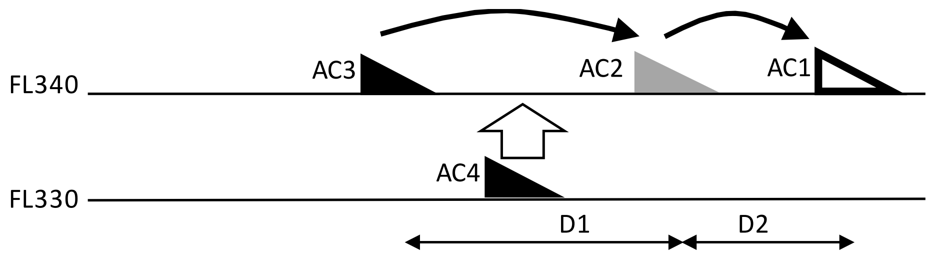
D1 & D2 ≥ PTM separation standard distance

Figure A-1.19. Case 1. Joining a PTM String by climbing or descending to the PTM String flight level, leading.

A-1.7.2 Case 2. Climb or descend to PTM String flight level, between the aircraft in the PTM String, Figure A-1.20.

- ATC (or ground automation) must determine if the aircraft to join the PTM String is trailing, in between or leading the PTM String. If the aircraft to join the string is between the aircraft in the string, Case 2 applies.
- ATC gives clearance to aircraft AC4 to maintain separation from aircraft AC2.
- If oceanic non-radar Non-PTM separation does not exist between aircraft AC4 and AC1, ATC must also issue a PTM clearance between aircraft AC4 and AC1.
- If PTM spacing exists between aircraft AC4 and aircraft AC2, aircraft AC4 accepts the clearance.
- ATC gives clearance to aircraft AC3 to maintain separation from aircraft AC4.

- If PTM spacing exists between aircraft AC3 and aircraft AC4, aircraft AC3 accepts the clearance.
- ATC issues a climb or descent instruction to aircraft AC4.
- If PTM spacing does not exist between aircraft AC4 and AC2 and/or between aircraft AC3 and AC4, the flight crew of AC4 and/or the flight crew of AC3 inform ATC “unable PTM.”



D1 & D2 ≥ PTM separation standard distance

Figure A-1.20. Case 2. Joining a PTM String by climbing or descending to the PTM String flight level, between the aircraft.

Cases 3 and 4 for an aircraft joining a string are similar to cases 3 and 4 for an aircraft joining a pair to form a string.

A-1.8 PROCESS FOR ADDING AN AIRCRAFT TO A PTM CHAIN

A PTM capable aircraft could join a chain to form a more numerous chain. When an aircraft is going to join an existing chain, the relative position of the joining aircraft must be determined with respect to the aircraft in the existing chain.

A-1.8.1 Climb or descend to a PTM Chain, Figure A-1.21.

- ATC (or ground automation) must determine the relative position of the aircraft to join the PTM Chain with respect to the aircraft in the chain.
- ATC gives clearance to aircraft AC5 to maintain separation from aircraft AC2 and AC3.
- If oceanic non-radar Non-PTM separation does not exist between aircraft AC5 and AC1 and/or AC4, ATC must also issue a PTM clearance between aircraft AC5 and AC1 and/or AC4.
- If PTM spacing exists between aircraft AC5 and aircraft AC2 and AC3, aircraft AC5 accepts the clearance.
- ATC issues a clearance to aircraft AC2 to maintain separation from AC5.
- ATC issues a clearance to aircraft AC3 to maintain separation from AC5.
- If aircraft AC5, AC2 and AC3 have accepted the clearances, ATC climbs/descends aircraft AC5 to the flight level of the chain.
- If PTM spacing does not exist between aircraft AC5 and aircraft AC2 or AC3, the flight crew of AC5 informs ATC “unable PTM.”

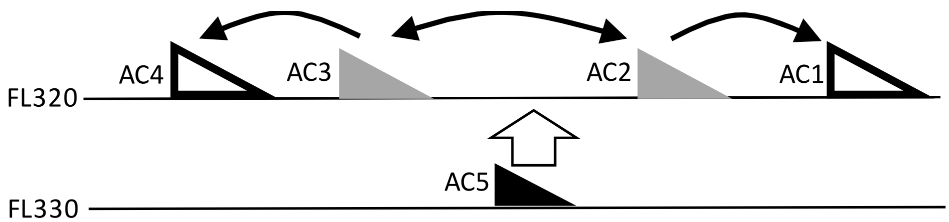


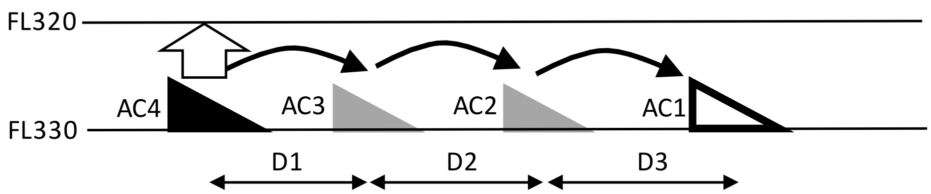
Figure A-1.21. Joining a PTM Chain by climbing or descending to the PTM Chain flight level.

A-1.9 PROCESS FOR AN AIRCRAFT DEPARTING A PTM STRING

An aircraft can depart a string vertically or horizontally. When an aircraft departs a string, a shorter string or pair will remain.

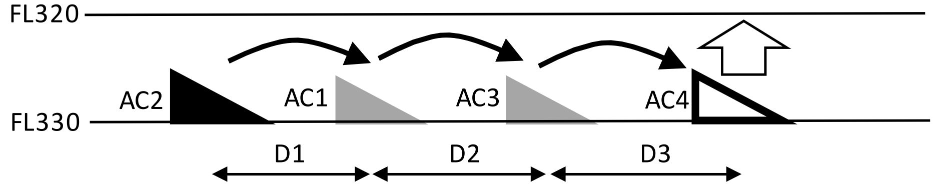
A-1.9.1 Case 1. Departing a PTM String from the leading or trailing position by climbing or descending, Figures A-1.22 and A-1.23.

- ATC clears aircraft AC4, in the PTM String, to climb or descend.
- Trailing PTM aircraft (Figure A-1.22): After aircraft AC4 reports reaching the new flight level, ATC cancels PTM clearance for aircraft AC4 to maintain separation from aircraft AC3 (and possibly AC2 and AC1).
- Leading non-PTM aircraft (Figure A-1.23): After aircraft AC4 reports reaching the new flight level, ATC cancels PTM clearance for aircraft AC3 to maintain separation from aircraft AC4 (and possibly aircraft AC1 and AC2 to maintain separation from AC4).



D1, D2, & D3 ≥ PTM separation standard distance

Figure A-1.22. Case 1. Departing a PTM String by climbing or descending, trailing.



D1, D2, & D3 ≥ PTM separation standard distance

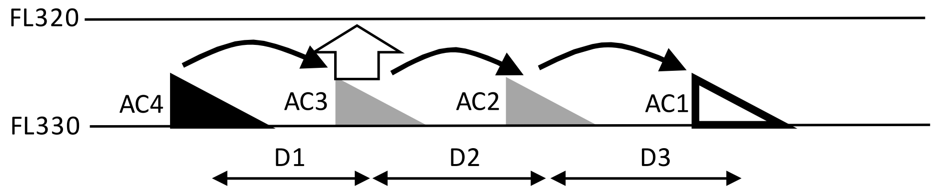
Figure A-1.23. Case 1. Departing a PTM String by climbing or descending, leading.

Note that in the example of Figure A-1.23, the aircraft departing the string might or might not be PTM capable. In this example, aircraft AC3 is PTM capable but it becomes a non-PTM aircraft not performing a PTM clearance after aircraft AC4 departs.

A-1.9.2 Case 2. Departing a PTM String from inside the PTM String by climbing or descending, Figure A-1.24.

- ATC clears aircraft AC3, in the PTM String, to climb or descend.
- After aircraft AC3 reports reaching the new flight level, ATC cancels PTM clearance for aircraft AC3 to maintain separation from AC2 (and possibly cancels between AC3 and AC1).
- ATC cancel PTM clearance for aircraft AC4 to maintain separation from AC3.

Note: if non-PTM non-radar separation existed between aircraft AC4 and AC2, the string becomes a PTM Pair AC1-AC2 and aircraft AC4 not performing PTM operations. If Non-PTM non-radar separation did not exist between aircraft AC4 and AC2, then AC4 must have been keeping PTM separation from AC2 and the string becomes AC1, AC2, and AC4.

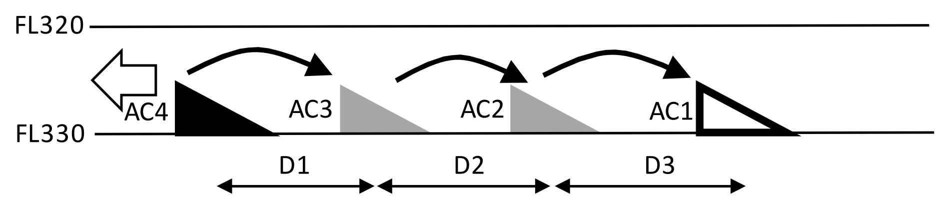


D1, D2, & D3 ≥ PTM separation standard distance

Figure A-1.24. Case 2. Departing a PTM String by climbing or descending from inside the PTM String.

A-1.9.3 Case 3. Departing a PTM String horizontally, Figure A-1.25.

- ATC establishes non-PTM separation between aircraft AC3 and aircraft AC4.
- ATC cancels PTM clearance for aircraft AC4 to maintain separation from aircraft AC3 (and possibly cancels between AC4 and AC2 and AC1).



D1, D2, & D3 ≥ PTM separation standard distance

Figure A-1.25. Case 3. Departing a PTM String horizontally.

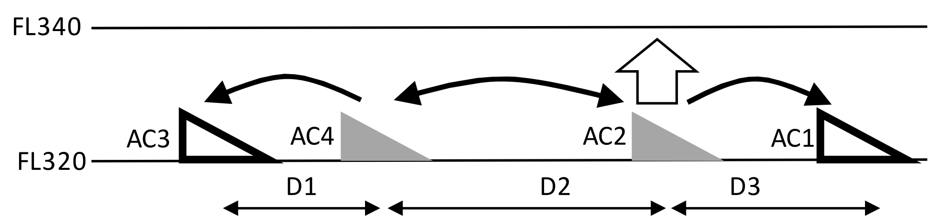
A-1.10 PROCESS FOR AN AIRCRAFT DEPARTING A PTM CHAIN

An aircraft can depart a chain vertically or horizontally. When an aircraft departs a chain, a less numerous chain, a string, a pair or non-PTM operations could result.

A-1.10.1 Case 1. Departing a PTM Chain vertically with possibly a PTM Chain remaining, Figure A-1.26.

- ATC gives clearance to aircraft AC2 to climb or descend.
- After aircraft AC2 reports reaching the new flight level, ATC cancels PTM clearance for aircraft AC2 to maintain separation from AC1 and AC4 (and possibly AC3).
- ATC cancels PTM clearance for aircraft AC4 to maintain separation from aircraft AC2.

Note: If Non-PTM non-radar separation existed between aircraft AC4 and AC1, then the chain becomes a PTM Pair AC4-AC3 and aircraft AC1 not part of a PTM operation. If Non-PTM non-radar separation did not exist between aircraft AC4 and AC1, then AC4 must have been keeping PTM separation from AC1 and the chain remains and becomes AC1, AC4, and AC3.



D1, D2, & D3 ≥ PTM separation standard distance

Figure A-1.26. Case 1. Aircraft leaving a PTM Chain vertically with a PTM Chain remaining.

A-1.10.2 Case 2. Departing a PTM Chain horizontally with a PTM String remaining, Figure A-1.27.

- ATC establishes non-PTM separation between aircraft AC1 and AC2.
- ATC cancels PTM clearance for aircraft AC2 to maintain separation from AC1.
- ATC cancels PTM clearance for aircraft AC4 to maintain separation from AC2.

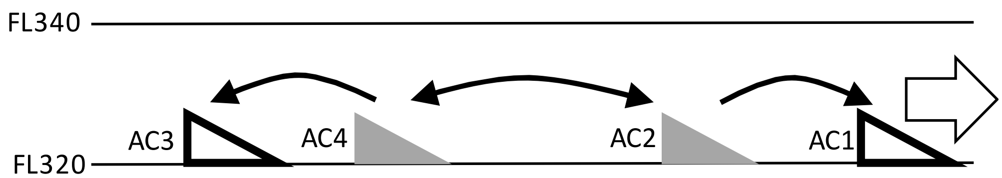


Figure A-1.27. Case 2. Aircraft leaving a PTM Chain horizontally with a PTM String remaining.

Appendix B: Future Considerations for the Pairwise Trajectory Management (PTM) Concept

Potential Future Updates for the PTM OSED

Version 3.0
February 2017

INTRODUCTION

This paper is intended to serve as a collection of topics that should be considered for future versions of the Pairwise Trajectory Management (PTM) Operational Services and Environment Description (OSED) document. Each section of this paper contains some discussion of a different aspect of the PTM concept. These sections may be used to clarify details of the PTM concept, cover a new idea that should be included in the OSED, or explain some changes that occurred after the last public release of the OSED. The concept modifications in this paper have not been developed in sufficient detail for inclusion in a new revision of the OSED. However, it was desired to capture these ideas and clarifications prior to the conclusion of the NASA PTM project.

SEPARATION BY ORDER

When there are multiple aircraft performing PTM in a sequence within a non-PTM separation standard distance, as discussed in section A.4.2 of the PTM OSED version 3.0, special rules apply. In this case, PTM must be conducted on all aircraft that are within the non-PTM separation standard distance in the direction of the designated aircraft. This ensures there is an appropriate separation standard being applied between all pairs of aircraft.

In the illustration in figure 1 below, PTM aircraft AC2 is conducting PTM on designated aircraft AC1. PTM aircraft AC3 is conducting PTM operations on AC2 (in the direction of the designated aircraft AC1). However, because AC3 and AC1 are within the minimum non-PTM separation standard distance, AC3 must also conduct PTM on the designated aircraft AC1. Without this addition, there is no separation standard being applied between AC3 and AC1.

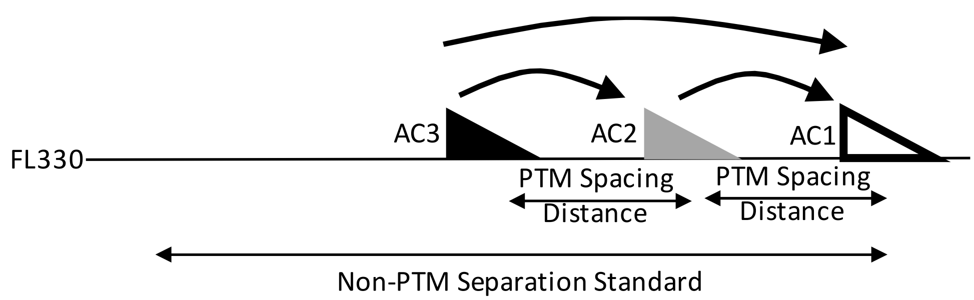


Figure 1: Multiple PTM operations within a non-PTM separation distance.

It has been recommended that the concept for the PTM separation standard should be revised to include the concept of “separation by order”. Currently, the proposed PTM separation standard does not account for the fact that aircraft AC2 is between AC3 and AC1. Rather than require AC3 to conduct PTM on AC1, the revised PTM separation standard would only require AC3 to conduct PTM on AC2. AC3 would be separated from AC1 by virtue of the fact that AC2 is between the two aircraft and that AC3 would get too close to AC2 before it would get too close to AC1; essentially taking advantage of the order of the aircraft.

If this revision to the proposed PTM separation standard was adopted, PTM aircraft would only need to conduct PTM operations on aircraft that are closest to them (as depicted in figure 2). This would simplify PTM operations, the flight crew’s Human Machine Interface (HMI) and the PTM message queues.

Prior to adopting this simplification, a thorough, updated safety analysis must be performed. One advantage of the current approach is that if AC2 has a problem and must suddenly exit out of the string (e.g., if AC2 has an engine failure), there is already a PTM operation in place between AC3 and AC1. With the revised concept, if AC2 leaves a string, a PTM operation would have to be initiated between AC3 and AC1. Due to the relatively small speed differences (low closure rates) between aircraft operating in oceanic airspace regions, there should be sufficient time to apply PTM to these aircraft before they get closer to each other than the minimum PTM spacing distance.

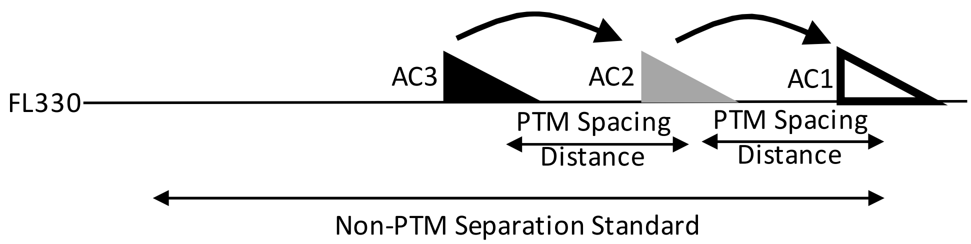


Figure 2: Multiple PTM operations within a non-PTM separation distance including the separation by order revision to the PTM separation standard.

In PTM OSED, version 3.0, it was postulated that the practical, maximum number of PTM targets required for PTM would be eight (section A.5.6). Figure 3 below is a duplication of figure A.30 from the OSED and illustrates the number and complexity of the PTM operations required. During a climb from FL330 to FL340, AC5 would be required to conduct PTM operations on AC1, AC2, AC3, AC4, AC6, AC7, AC8 and AC9. Once AC5 reaches FL340, AC5 would need to continue PTM operations on AC6, AC7, AC8 and AC9.

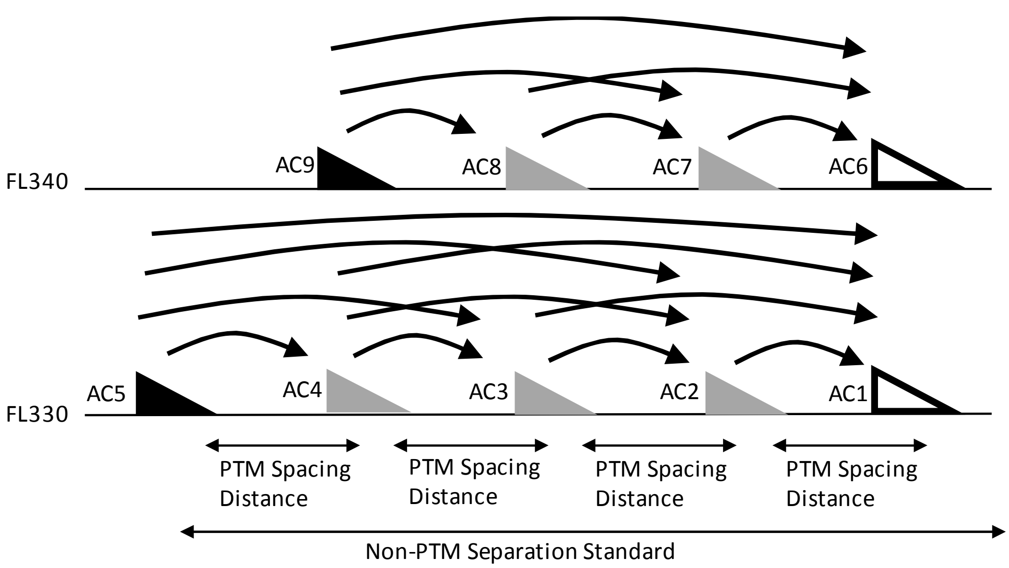


Figure 3: PTM eight aircraft scenario; current PTM separation standard.

Figure 4 below illustrates how the revised PTM separation standard would simplify operations. For this scenario, using separation by order, as AC5 climbs from FL330 to FL340, AC5 would be required to conduct PTM operations only on aircraft AC4 and

AC9. Once AC5 reaches FL340, AC5 would only need to conduct PTM on aircraft AC9.

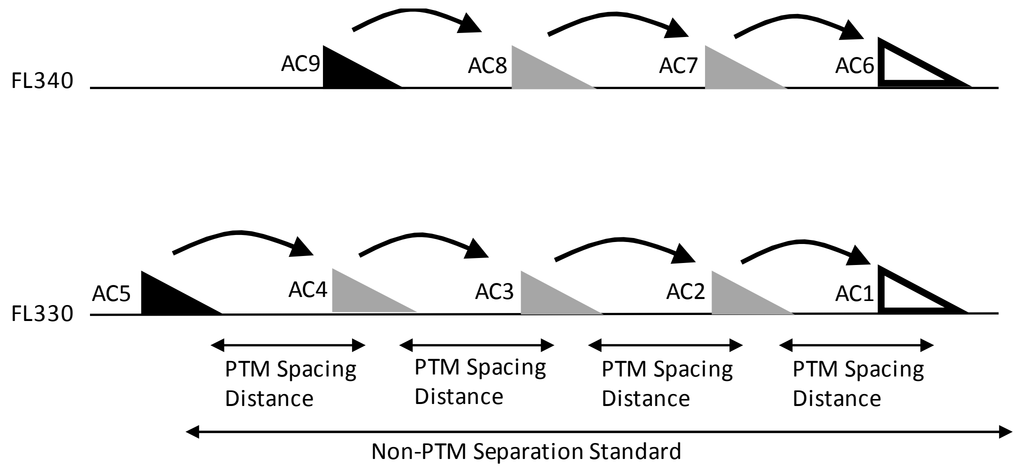


Figure 4: PTM eight aircraft scenario; revised PTM separation standard.

This example demonstrates the value of pursuing this area of research for PTM.

AVIONICS INTEGRATION

There was a potential issue identified during an HMI pilot-in-the-loop focus group study. During the study, a number of pilots (from a small sample size) sent an accept message to ATC when the equipment displayed an unable notification (indicating the PTM clearance should not be accepted). When this occurs, neither the aircraft nor ATC are ensuring spacing. The FIM equipment should be designed to prevent these situations from occurring.

One possible solution to this issue would be to integrate the FIM equipment with the data communications system on board the aircraft. In the scenario described above, if the FIM equipment determined that a PTM operation was not possible, it would not allow the flight crew to accept the clearance (flight crews would only be allowed to send a reject clearance to ATC). This level of avionics integration was not assumed during the NASA HMI study but given additional time, this level of integration could be incorporated into the NASA HMI.

CONTROLLER MONITORING OF PROCEDURE COMPLIANCE

During the development of the PTM concept, a one-way data link between the ground automation and the FIM equipment was assumed. In other words, the ground automation has the ability to communicate with the FIM equipment, but the FIM equipment has no means of sending data link messages to the ground automation. If it were possible and practical to remove that constraining assumption, so that the avionics could have a two-way data link with the ground system, then there are some possible benefits that could be realized.

Due to communications and surveillance limitations, ATC currently uses procedural separation in oceanic airspace. However, in airspace in which aircraft spacing is guaranteed with procedural separation, it is not uncommon for controllers to monitor the aircraft compliance with the procedure (not the spacing between aircraft but compliance with the procedure). A very common example of this is ground system alerting to deviations from an assigned altitude and route. Whether or not there is an associated loss of aircraft separation, the controller monitors and reacts to deviations from the assigned procedural clearance. This same concept could be valuable in PTM procedural operations.

When a PTM clearance is issued and accepted, the ground system could receive reports on the avionics health, the status (engaged vs. not engaged), target status (loss of signal), and certain crew alerts that the crew has not responded to within an appropriate interval. This monitoring would improve the PTM overall safety performance by reducing the impact of any flight crew training and performance issues, and provide ground monitoring of avionics system health.

Actual and projected aircraft spacing information should never be data linked to the controller. The controller is neither trained nor capable of applying tactical separation with aircraft involved in PTM. It would be incorrect to attempt to use any monitoring function to pass this role to the controller.

This channel could include the following standard message from the avionics:

PTM state [Pending, Pending/Engaged, Engaged, no activity]
Target Status
Call sign of all PTM engaged aircraft
Any (and all) level three or higher alerts displayed to flight crew

A new complete message would be sent if there is a change in any of the fields.

MAINTAINING A PTM CLEARANCE THROUGH SURVEILLANCE AIRSPACE

There are certain oceanic routes which could transition surveillance airspace. If this transition is for a short duration, it would be easier for both pilot and controller to continue the PTM clearance while in surveillance airspace. This should not be a difficult activity, but does require consideration of a number of issues (e.g., all parties need to know who is providing spacing at all times, what trajectory flexibility do all participants have, notifications of all parties of changes in status, ground software).
This appears to be a relatively straight forward expansion of the PTM concept but is something that should be studied further prior to including this in the PTM OSED.

USE OF PTM DURING WEATHER DEVIATIONS

During current oceanic operations, flight crews may encounter un-forecasted weather systems along their route of flight. Some of these weather systems may be significant enough that flight crews will need to request a route deviation around the weather.
With current separation standards, there are times when controllers are required to issue operationally inefficient altitude changes to the deviating aircraft due to the proximity of other aircraft in order to approve a route deviation. With PTM, controllers may be able to minimize these inefficient altitude changes.

In the example shown below in figure 5, AC2 encounters some significant weather along its route of flight. The flight crew requests a deviation 10 NM to the right for weather. If AC1 is an ADS-B Out aircraft and AC2 is an appropriately equipped PTM aircraft, the controller can issue a PTM clearance to AC2 instructing AC2 to conduct PTM behind AC1. As with other PTM clearances, the flight crew of AC2 reviews the clearance and determines whether PTM clearance is acceptable. If the clearance is acceptable, AC2 engages PTM and accepts the clearance. Once the controller has received the acceptance of the clearance, the controller issues a second clearance authorizing the route deviation.

It should be noted that although the PTM algorithm treats this operation as an in-trail operation, AC2 is not required to follow the same identical route as AC1.

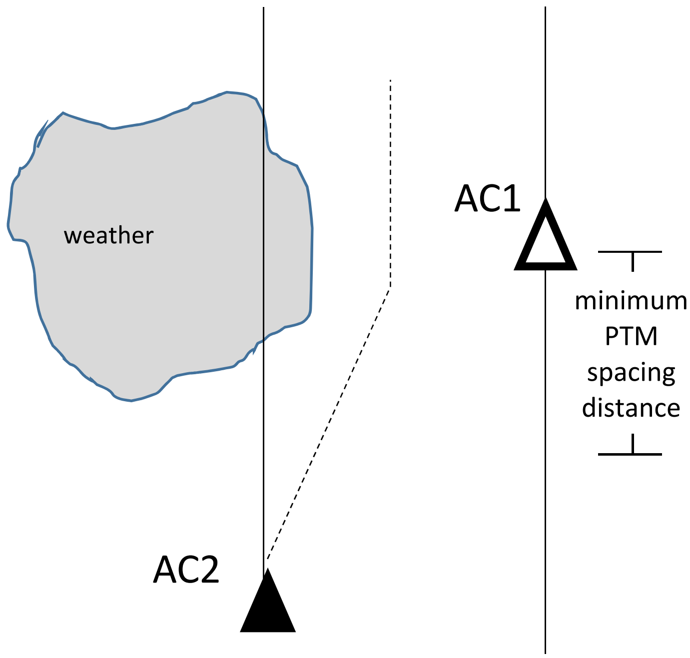


Figure 5: Use of PTM to support weather deviations.

FLIGHT CREW ENTRY OF DESIRED MACH LIMITS

The PTM algorithm determines the Mach number or range of Mach numbers required to support PTM operations. To provide a realistic solution, a lower and upper limit for allowable Mach numbers must be entered into the algorithm. These entries bound the algorithm generated solution set to Mach numbers that can be flown by that aircraft. Unless otherwise modified, the lower limit is set at the minimum cruise speed for the aircraft and the upper limit is set at the Mach limit for that aircraft.

During focus group discussions, pilots expressed a strong desire to be able to enter the Mach numbers for that flight. Some expressed a desire to be able to enter these upper and lower limits multiple times during the flight.

The PTM algorithm can accommodate these changes, even during a PTM operation, as long as the Limit Mach remains within the flight crew desired Mach limits. Designers of a flight crew Human Machine Interface (HMI) should take this into account when designing a PTM HMI.

INITIAL MOPS REVISIONS TO SUPPORT INCLUSION OF PTM

Members of RTCA SC-186, Working Group 4 (WG4) reviewed an earlier version of the PTM OSED looking for potential key revisions that would be required to the Advanced-Interval Management MOPS document. The results of this analysis is listed below.

- ASSAP Section 2.2.4.4.2 Waypoint Sequence
    - Needs section for PTM special case
        - Bootstrapping trajectory change points mid-operation
        - Exclusion of PTP

- New Sub-Section for ASSAP 2.2.4.4 IM Initiation – PTM calculations
    - Unique operational parameters
        - Point of Closest Approach
        - Horizontal range to designated aircraft
    - Calculation of Merge Point/Point of Intersection
    - Can operate ahead of or behind a designated aircraft
        - Checks for relative location

- New Sub-Section for ASSAP 2.2.4.5 IM Speeds – PTM calculations
    - IM Speed guidance as a range of acceptable speeds defined as upper and lower bounds
        - IM Speed guidance based on multiple target constraints, Upper/Lower Limit Mach
        - Possible based on new PTM Calculations (e.g., range)

- Unique PTM Display Mode and Features
    - Designated Traffic behind, among other things

- CDTI Section 2.3.6.1.2 Traffic Identification
    - Must include designation of multiple aircraft (PTM)

- Background (non-CPDLC) Information Exchange

- New PTM Sample Algorithm

Appendix C: Safety Assessment for Pairwise Trajectory Management (PTM)

Version 1.1.0

Victor Carreño
31 August 2015

Version History

Version	Description	Document date
1.0.0	First draft	31 Oct. 2014
1.0.1	Changes to names and updates to concept	25 March 2015
1.1.0	Added System Hazard Analysis, Appendix A	31 August 2015

Executive Summary

1 Introduction

This document contains a safety assessment of the Pairwise Trajectory Management (PTM) application. Pairwise Trajectory Management is an Interval Management (IM) concept that utilizes airborne and ground-based capabilities to enable the implementation of airborne pairwise spacing capabilities in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage an “at or greater than” inter-aircraft spacing. On-board PTM tools will aid the flight crew in implementing the PTM procedure. The PTM on-board tools will give guidance to the flight crew to maintain a spacing, which is greater that the separation standard minimum.

A controller can assign multiple PTM clearances to aircraft in a sequence.
A controller can also assign more than one PTM clearance to the same aircraft. For example, Figure ES-1 shows a PTM operation where aircraft 1 has been given a clearance to maintain separation from aircraft 2 and 3. Although intuitively aircraft 1 will be separated from aircraft 3 if it is separated from 2, the concept of operation has been defined such that a PTM clearance is needed between 1 and 3 if no other means of separation is present. This provides robustness and safety to the operation.

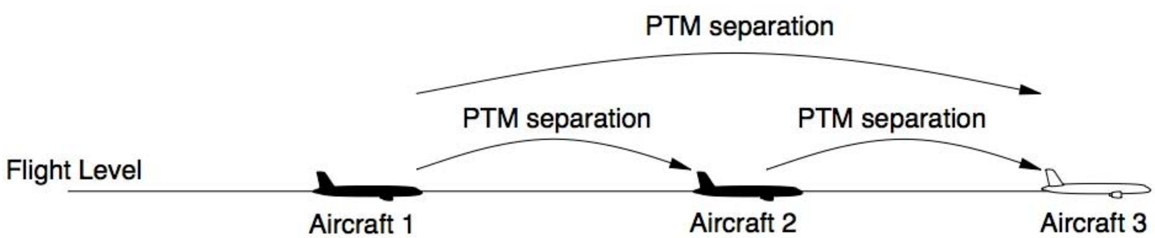


Figure ES-1. Example PTM operations.

In the example of Figure ES-1, aircraft depicted in black are aircraft that have been given PTM clearances and the aircraft in white is a designated aircraft.

2 Summary of Findings

Four hazards have been identified for PTM operations between pairs of aircraft. Hazard PTM-4 has been subdivided into 4 sub-hazards depending on the cause of the hazard. Using the worst credible severity and the likelihood of this severity, the initial risk is assessed as shown in Table ES-1.

Table ES-1. Initial and Predicted Residual Risk.

Hazard No.	Hazard Title	Initial Risk	Predicted Residual Risk
PTM-1	Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver	3C, Medium	TBD
PTM-2	Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level	4D, Low	TBD
PTM-3	Flight crew accepts a clearance with an aircraft for which no PTM spacing exists	2E, Medium	TBD
PTM-4a	Flight Crew unable to maintain PTM spacing from designated aircraft (Designated aircraft changes speed)	2E, Medium	TBD
PTM-4b	Flight Crew unable to maintain PTM spacing from designated aircraft (Mechanical failure)	4D, Low	TBD
PTM-4c	Flight Crew unable to maintain PTM spacing from designated aircraft (System failures)	1E, Medium	TBD
PTM-4d	Flight Crew unable to maintain PTM spacing from designated aircraft (Incorrect implementation)	2E, Medium	TBD

3 Conclusion

Four hazards have been identified for PTM operations between two aircraft. Hazard PTM-4 has been subdivided into 4 sub-hazards. Hazards PTM-1 and PTM-2, dealing with the safety risk of wake turbulence encounters, have a initial safety risk assessment of Medium and Low, respectively. Hazards PTM-3 and PTM-4 have an initial safety assessment of Medium. Hazard PTM-4, sub-hazard PTM-4c, has a safety assessment of 1-E, which implies a severity of Catastrophic with a likelihood of Extremely Improbable. This means that it must be shown that this sub-hazard does not have a single point of failure or a single event that can lead to the effect. It can be seen in the event tree for PTM-4c in APPENDIX C that several mitigations must fail to arrive at the worst credible effect. Further analysis and scenarios will be developed for this sub-hazard to show that this hazard does not have a single point of failure.

Abstract

This document contains a safety assessment of the Pairwise Trajectory Management (PTM) application. This first version of the safety assessment only includes PTM operations between two aircraft; a PTM aircraft and a designated aircraft. PTM operations also include operations with multiple PTM aircraft. These types of operations may be included in a subsequent version of the safety assessment.

1. Current System (Base Line)

Oceanic and remote airspaces without surveillance use non-radar separation to maintain safe separation between aircraft. Several separation standards are currently used in different operational areas. For example, the North Atlantic Organized Track System uses predefined tracks with 1 degree of latitude laterally and typically Mach technique that separate aircraft 10 minutes in-trail. When Mach technique cannot be used, 15 minutes in-trail is the nominal separation standard.

In the Pacific region, one of the separation standards in use is 50 NM laterally and 50 NM longitudinally. The methods of implementing these separation standards also vary. The position of the aircraft could be obtained by air traffic control (ATC) from way point position reports transmitted over voice communication, from way point position reports transmitted over data link, from latitude and longitude reports (automatic dependent surveillance - contract, or ADS-C) over data link, etc.

The separation standard that is applied between aircraft is dependent on the airspace and also on the level of equipment of the aircraft. For example, aircraft must be equipped with Future Air Navigation System (FANS) 1/A systems to be eligible for 30 NM lateral and 30 NM horizontal separation.

2. Proposed Changes to the NAS

Pairwise Trajectory Management is an Interval Management (IM) concept that utilizes airborne and ground-based capabilities to enable the implementation of airborne pairwise spacing capabilities in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage an “at or greater than” inter-aircraft spacing. The PTM operation is an ATC initiated operation. When a controller determines that a PTM operation is desirable and beneficial for the efficient and safe management of the airspace, he or she issues a PTM clearance to the aircraft that will be implementing the PTM operation.

The flight crew receiving the instruction (clearance) accepts or refuses (unable) the clearance. Acceptance or refusal of the clearance depends on a set of criteria

and the ability of the aircraft and flight crew to perform the operation. The PTM operation is for non-surveillance environments such as Oceanic and remote airspaces.
The PTM application defines a new separation standard in non-surveillance airspace. The new separation standard has a separation standard minimum distance, which should not be infringed upon. In order to implement the PTM separation standard and maintain the separation standard minimum, a spacing is defined which consists of the minimum distance plus a buffer.

When an aircraft accepts a PTM clearance, it follows the procedures defined for PTM operations. The flight crew responsibilities include: complying with speed guidance given by the PTM equipment, monitoring the operational status of the PTM equipment, being familiar with and prepared to execute appropriate procedures should the PTM equipment fails, being familiar with and able to execute responses to PTM alerts.

The vertical dimension is not part of the PTM operation and the PTM aircraft shall maintain its assigned altitude or flight level. That is, the PTM aircraft is not cleared to maneuver vertically to maintain PTM spacing.

PTM capable aircraft will have on board equipment to aid the flight crew in maintaining PTM spacing. This equipment will include a traffic display and decision support tools.

3. Assumptions

Assumption 1.	PTM operations will be conducted in non-surveillance airspace
Assumption 2.	ATC ground automation will be updated and be part of the PTM separation standard implementation
Assumption 3.	Aircraft that are PTM capable will have PTM equipment on-board to aid the flight crew in implementing the PTM procedure
Assumption 4.	The PTM equipment will have a traffic display that will show, as a minimum the designated aircraft

4. System Description

Pairwise Trajectory Management is a concept that utilizes airborne and ground-based capabilities to enable the implementation of airborne pairwise spacing capabilities in oceanic regions. Airborne surveillance and tools are used to manage an “at or greater than” inter-aircraft spacing.

A PTM operation is conducted between a PTM aircraft and one or more designated aircraft. ATC determines if a PTM operation is applicable and desirable to maintain safe and efficient traffic flow. Ground automation aids the controller in evaluating the traffic conditions and determining if a PTM clearance is applicable. If the controller determines that he or she wants to apply a PTM separation standard to a set of aircraft, he/she initiates the operation.

ATC sends a PTM clearance to a PTM capable aircraft. The flight crew receiving the PTM clearance uses airborne decision support tools to evaluate the clearance. The flight crew accepts or rejects the clearance based on PTM criteria and their sole discretion. If the flight crew accepts the clearance, they use the on-board PTM equipment to maintain spacing. The PTM equipment provides speed guidance to the flight crew to maintain spacing. The spacing that the PTM aircraft maintain is the sum of the PTM separation standard minimum and a distance buffer. By maintaining the PTM spacing, the PTM operation insures that the PTM separation standard minimum is not infringed upon.

The vertical dimension is not part of the PTM operation and the PTM aircraft shall maintain its assigned altitude or flight level. That is, the PTM aircraft is not cleared to maneuver vertically to maintain PTM spacing.

4.1. Types of operations

The PTM operation can be classified into two types of operations:

- Along-track operation in which the aircraft are following the same routes, Figure 4-1. The aircraft turn at the same waypoints and follow the same route segments. In this type of operation, the on-board PTM equipment monitors the one-dimensional along-track distance and produces speed guidance such that the along-track distance is equal to or greater than the PTM spacing.

- Crossing operation in which the routes of the aircraft will intersect, Figure 4-2. The aircraft may turn at different waypoints, cross and diverge or cross and merge. In this type of operation, the on-board PTM equipment uses the designated aircraft “intent information” and the own ship’s expected route to calculate the speed guidance. The intent information consists of the designated aircraft’s next and next-plus-one waypoints and the estimated time of arrival at the next waypoint. Based on the designated aircraft and own ship’s trajectories, the PTM equipment calculates the closest point of approach, and the 2-dimensional distance (horizontal range) at the closest point of approach. The PTM equipment generates speed guidance such that the distance at the closest point of approach is equal to or greater than the PTM spacing.

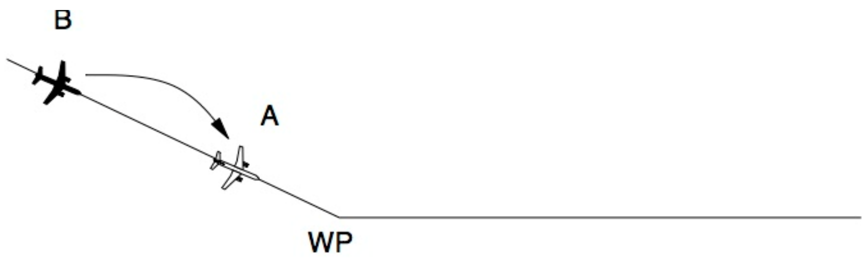


Figure 4-1. One-dimension PTM operation.

In the PTM operation of Figure 4-1, the white aircraft (A) is the designated aircraft and the black aircraft (B) is the PTM aircraft. Aircraft A and B are on identical same tracks and have the same routes and waypoints. Aircraft B must maintain one-dimensional longitudinal PTM spacing from aircraft A.

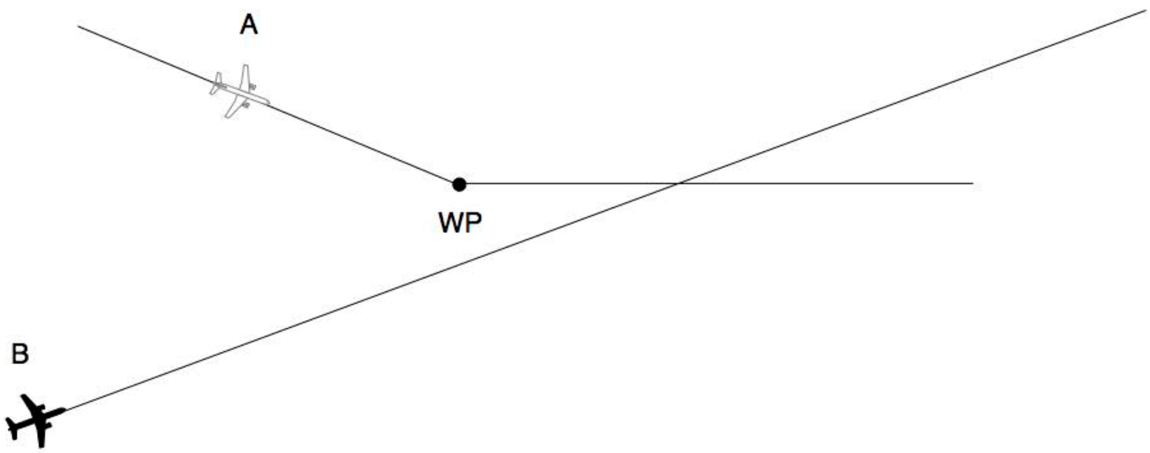


Figure 4-2. Two-dimensional PTM operation.

In the PTM operation of Figure 4-2, the white aircraft (A) is the designated aircraft and the black aircraft (B) is the PTM aircraft. Aircraft A and B could be turning at different waypoints, crossing and diverging or crossing and merging. Aircraft B has been cleared and has accepted a PTM clearance. Aircraft B must maintain two-dimensional longitudinal and lateral PTM spacing from aircraft A.

4.2. Clearance and Establishment of PTM Separation

For the along-track PTM operation, a clearance can be given from 3 different initial conditions:

1. The PTM aircraft could climb or descend to the flight level of the designated aircraft or the designated aircraft could climb or descend to the flight level of the PTM aircraft.

2. The aircraft are already on the same flight level with legacy separation (see definitions section) and the PTM clearance is given. The expectation being that legacy separation will no longer be needed.

3. The aircraft are transitioning from a surveillance to a non-surveillance environment.

In the example of Figure 4-3, ATC clears aircraft B to maintain PTM spacing from aircraft A. If aircraft B accepts the clearance, ATC can climb the aircraft to the flight level of aircraft A.

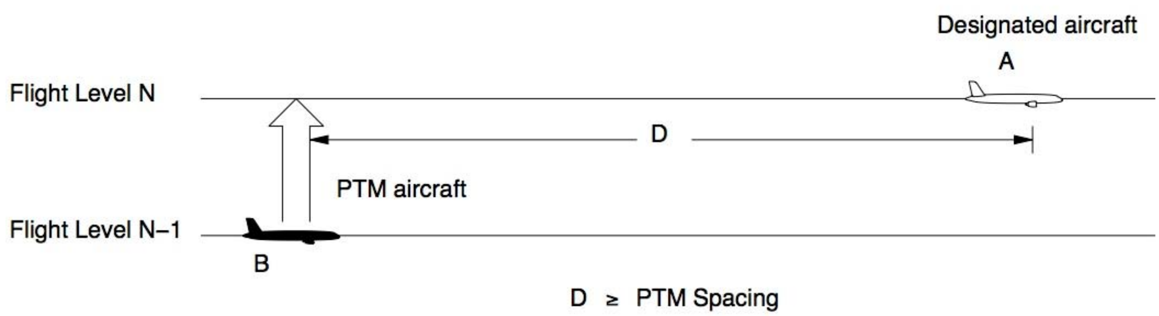


Figure 4-3. Creating a PTM Pair by climb.

In the example of Figure 4-4, ATC clears aircraft B to maintain PTM spacing from aircraft A. At the time of the clearance, there is legacy separation between aircraft A and B. If aircraft B accepts the clearance, ATC no longer has to maintain legacy separation between aircraft A and B.

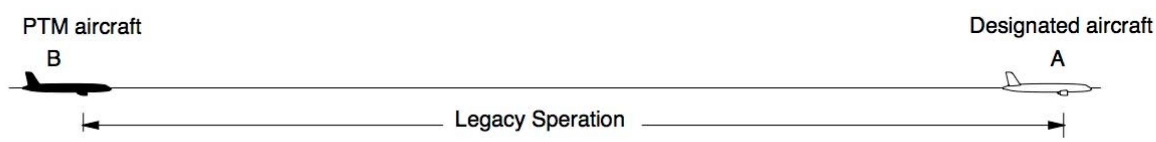


Figure 4-4. Creating a PTM Pair from legacy separation.

In the example of Figure 4-5, the aircraft are transitioning from surveillance to non-surveillance environments. When the aircraft transition to non-surveillance, ATC could establish legacy non-radar separation, or ATC could clear the aircraft for PTM separation.

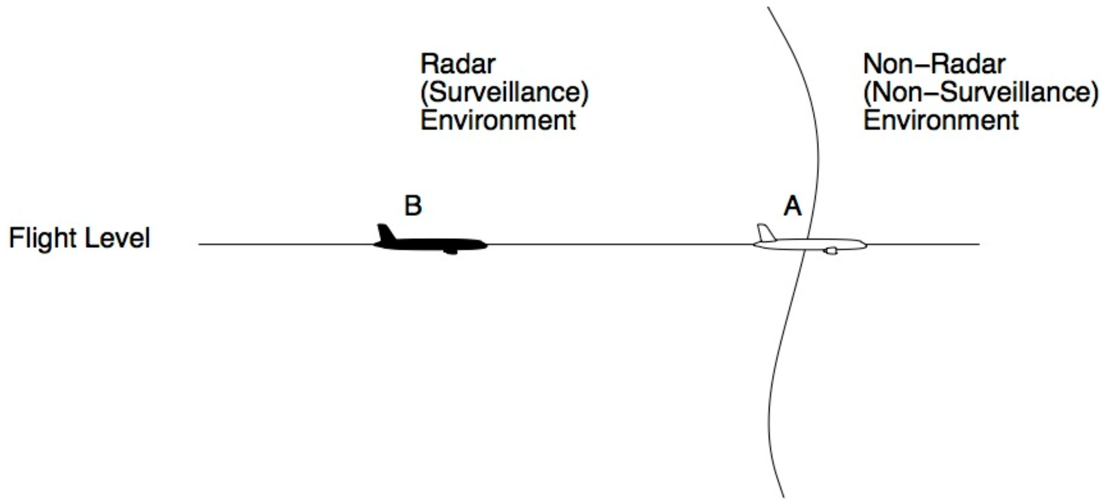


Figure 4-5. Establishing PTM separation before entering non-surveillance environment.

5. Identified Hazards

The safety and operations teams have identified 4 operational hazards. These hazards apply to PTM operations between pairs of aircraft. Hazards that apply to PTM operations that include multiple aircraft performing PTM operations will be covered in a second version of the safety assessment.

PTM-1. Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver

PTM-2. Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level

PTM-3. Flight crew accepts a clearance with an aircraft for which no PTM spacing exists

PTM-4. Flight crew unable to maintain PTM spacing from designated aircraft

6. Risk Analysis and Risk Assessment

Each of the identified hazards is analyzed to determine the probabilities of the hazard occurring, the possible effects of the hazards, the severity of the effects and the overall likelihood from cause to effect.

6.1. Hazard Analysis

The hazard analysis consists of two general parts: 1. Determining the possible causes that can lead to a hazard, the probability of the causes and the interrelationships between the causes that can lead to the hazards. 2. Determining the possible effects that a hazard can have, the paths to the effects, and the existing mitigations that can reduce the probability that the hazard leads to a given effect. The severity of each effect is determined using the Federal Aviation Administration, Air Traffic Organization, Safety Management System severity classification.

6.1.1. Bow-Tie Analysis

This safety assessment includes the development of a "Bow-Tie Model" to evaluate the causes and potential effects of hazards identified by the SRMP. The Bow-Tie Model is a safety assessment tool that combines fault tree and event tree analysis to determine overall hazard risk. An example of the Bow-Tie Model is shown in Figure 6-1.

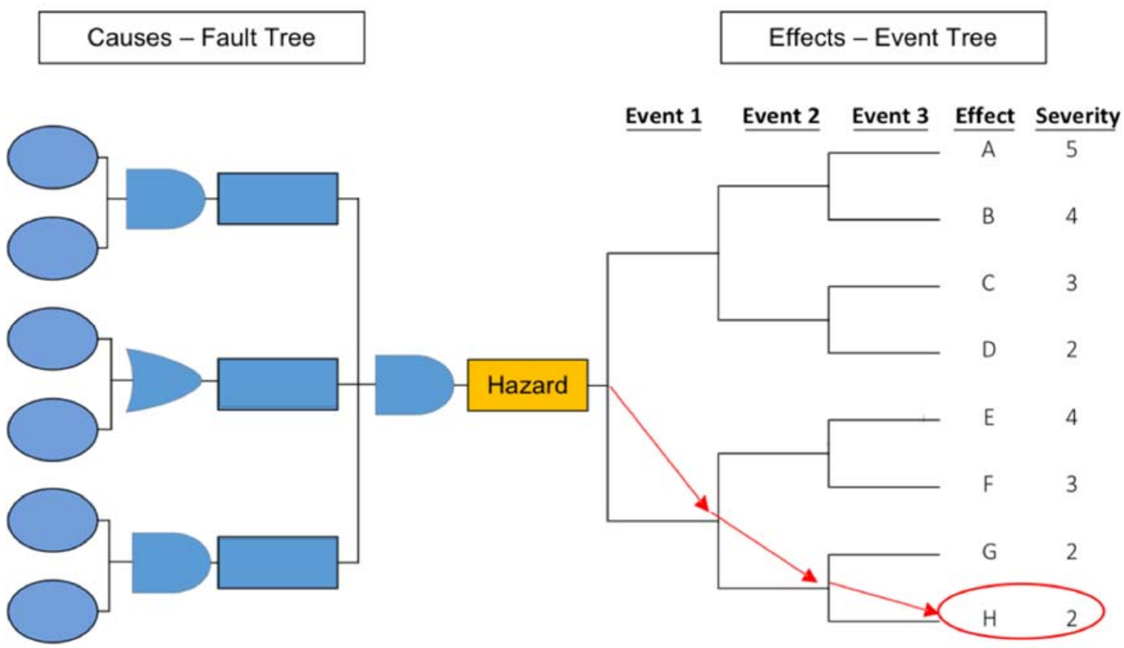


Figure 6-1. Bow-Tie Model, example.

The fault trees show the logical relationship between hazard causes and determine the probability that the hazard occurs or be present. The event trees show the paths from the hazard to the possible effects.

6.1.2. Severity Definition

Severity is the consequence or impact of a hazard’s effect or outcome in terms of degree of loss or harm. Severity is defined by the Safety Management System Manual according to effects on air traffic services, effects on people on the ground, effects on the flying public, effect on aircraft or equipment, and effect on the flight crew. Table 6-2 shows the hazard severity classification.

Table 6-2. Hazard Severity Definitions.

Effect On: ↓	**Hazard Severity Classification** *NOTE: Severities related to ground-based effects apply to movement areas only.*				
	Minimal **5**	**Minor** **4**	**Major** **3**	**Hazardous** **2**	**Catastrophic** **1**
	CONDITIONS RESULTING IN ANY ONE OF THE FOLLOWING:				
ATC Services	A minimal reduction in ATC services CAT D RI[1], PE, OD, or MOC greater than or equal to 66 percent[2]	A slight reduction in ATC services Low RAE[3] CAT C RI	A partial loss of ATC services Medium RAE CAT B RI	Unplanned ATC Zero[4] High RAE CAT A RI	Ground Collision[5] MAC[6] CFIT[7]
Unmanned Aircraft Systems (UAS)	Discomfort to those on the ground Loss of separation leading to an MOC greater than or equal to 66 percent	Loss of separation resulting in a Low RAE Non-serious injury to three or fewer people on the ground	Loss of separation resulting in a Medium RAE Non-serious injury to more than three people on the ground A reduced ability of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins Manned aircraft making an evasive maneuver, but proximity from Unmanned Aircraft remains greater than 500 feet	Loss of separation resulting in a High RAE Incapacitation to UAS crew Proximity of less than 500 feet to a manned aircraft Serious injury to persons other than the UAS crew	A collision with a manned aircraft Fatality or fatal injury to persons other than the UAS crew
Flying Public	Minimal injury or discomfort to POB[8]	Physical discomfort to passenger(s) (e.g., extreme braking action; clear air turbulence causing unexpected movement of aircraft resulting in injuries to one or two passengers out of their seats) Minor injury to less than or equal to 10 percent of POB[9]	Physical distress to passengers (e.g., abrupt evasive action; severe turbulence causing unexpected aircraft movements) Minor injury to greater than 10 percent of POB	Serious injury to POB[10]	Fatal injuries to POB[11]

Effect On: ↓	Hazard Severity Classification *NOTE: Severities related to ground-based effects apply to movement areas only.* **Minimal** **5**	 **Minor** **4**	 **Major** **3**	 **Hazardous** **2**	 **Catastrophic** **1**
	CONDITIONS RESULTING IN ANY ONE OF THE FOLLOWING:				
NAS Equipment (with table 3.3)	Flight crew inconvenience Slight increase in ATC workload	Flight crew increased workload Significant increase in ATC workload Slight reduction in safety margin	Large increase in ATC workload Significant reduction in safety margin	Large reduction in safety margin	Collision between aircraft and obstacles or terrain
Flight Crew	Pilot is aware of traffic (identified by TCAS traffic alert, issued by ATC, or observed by flight crew) in close enough proximity to require focused attention, but no action is required. PD[12] where loss of airborne separation falls within the same parameters of a PE or MOC greater than or equal to 66 percent Circumstances requiring a flight crew to initiate a go-around	Aircraft is in close enough proximity to another aircraft (identified by TCAS resolution advisory, issued by ATC, or observed by flight crew) to require specific pilot action to alter or maintain current course/ altitude, but intentions of other aircraft are known and a potential collision risk does not exist. PD where loss of airborne separation falls within the same parameters of a Low RAE Reduction of functional capability of aircraft but overall safety not affected (e.g., normal procedures as per AFMs[13]) Circumstances requiring a flight crew to abort takeoff (rejected takeoff); however, the act of aborting takeoff does not degrade the aircraft performance capability	Aircraft is in close enough proximity to another aircraft (identified by TCAS resolution advisory, issued as a safety alert by ATC, or observed by flight crew) on a course that requires corrective action to avoid potential collision; intentions of other aircraft are not known PD where loss of airborne separation falls within the same parameters of a Medium RAE Reduction in safety margin or functional capability of the aircraft, requiring crew to follow abnormal procedures as per AFMs Circumstances requiring a flight crew to reject landing (i.e., balked landing) at or near the runway threshold Circumstances requiring a flight crew to abort takeoff (i.e., rejected takeoff); the act of aborting takeoff degrades the aircraft performance capability	Near mid-air collision results due to a proximity of less than 500 feet from another aircraft, or a report is filed by pilot or flight crew member that a collision hazard existed between two or more aircraft PD where loss of airborne separation falls within the same parameters of a High RAE Reduction in safety margin and functional capability of the aircraft requiring crew to follow emergency procedures as per AFMs	Ground Collision MAC CFIT Failure conditions that would prevent continued safe flight and landing

1. Definitions of Runway Incursions (RIs), per Order 7050.1A, Runway Safety Program:
   a. Accident. An incursion that results in a collision. For the purpose of tracking incursion performance, an accident will be treated as a Category A runway incursion.
   b. Category A. A serious incident in which a collision was narrowly avoided.
   c. Category B. An incident in which separation decreases and there is a significant potential for collision, which may result in a time critical corrective/evasive response to avoid collision.
   d. Category C. An incident characterized by ample time and/or distance to avoid a collision
   e. Category D. An incident that meets the definition of a runway incursion (such as incorrect presence of a single vehicle/person/aircraft on the protected area of a surface designated for the landing and take-off of aircraft), but with no immediate safety consequences.

f. Category E. An incident in which insufficient or conflicting evidence of the event precludes assigning another category.

2. PEs (Proximity Events) and ODs (Operational Deviations) are no longer used to measure losses of separation, but they are applicable when validating old data. The minimal loss of standard separation in now represented as a Measure of Compliance (MOC) of greater than or equal to 66 percent.
3. RAEs (Risk Analysis Events) reflect losses of separation. RAEs are events where less than 66 percent of standard separation is maintained, though other air traffic incidents may be characterized as RAEs in the future. Ratings are as follow:
   a. High RAE: An event that would rate 5/5, 5/4, 5/3, 5/2, 5/1, 4/5, 4/4, 4/3, 3/5, or ¾ on the RAP (Risk Analysis Process) tool.
   b. Medium RAE: An event that would rate 4/2, 4/1, 3/3, 2/5, or 2/4 on the RAP tool.
   c. Low RAE: An event that would rate 3/2, 3/1, 2/3, 2/2, 2/1, 1/5, 1/4, 1/3, 1/2, or 1/1 on the RAP tool.
4. Unplanned ATC Zero. A total loss of ATC capability and the complete loss of control services.
5. Ground Collision. An airplane on the ground collides with an object or person.
6. Mid-Air Collision (MAC)
7. Controlled Flight Into Terrain or Obstacles (CFIT)
8. Persons on Board (POB)
9. Minor Injury. Any injury that is neither fatal nor serious.
10. Serious injury. Any injury that:
    a. Requires hospitalization for more than 48 hours, commencing within seven days from the date the injury was received;
    b. Results in a fracture of any bone (except simple fractures of fingers, toes, or nose);
    c. Causes severe hemorrhages, nerve, muscles, or tendon damage;
    d. Involves any internal organ; or
    e. Involves second or third-degree burns, or any burns affecting more than five percent of the body surface.
11. Fatal injury. Any injury that results in death within 30 days of the accident.
12. Refer to ATO Order JO 8020.16, *Air traffic Organization Aircraft Accident and Incident Notification, Investigation, and Reporting.*
13. Airplane Flight Manual (AFM)

6.1.3. Likelihood Definition

Likelihood is defined as the estimated probability or frequency, in quantitative or qualitative terms, of a hazard's effect or outcome. Likelihood is defined in the Safety Management System Manual and is shown in Table 6-3 and Table 6-4.

Table 6-3. Likelihood of the Effect Standards – ATO Operations and NAS Equipment.

	Operations: Expected Occurrence Rate (per operation/flight hour/operational hour[3])
	Quantitative (ATC / Flight Procedures / Systems Engineering)
Frequent A	(Probability) ≥ 1 per 1000
Probable B	1 per 1000 > (Probability) ≥ 1 per 100,000
Remote C	1 per 100,000 > (Probability) ≥ 1 per 10,000,000
Extremely Remote D	1 per 10,000,000 > (Probability) ≥ 1 per 1,000,000,000
Extremely Improbable E	1 per 1,000,000,000 > (Probability) ≥ 1 per 10^{14}

Table 6-4. Likelihood of the Effect Definitions – Operations/Domain-wide.

	Operations: Expected Occurrence Rate (Calendar-based)
	Qualitative (Domain-wide: NAS-wide, Terminal, or En Route)
Frequent A	Equal to or more than once per week
Probable B	Less than once per week and equal to or more than once per three months
Remote C	Less than once per three months and equal to or more than once per three years
Extremely Remote D	Less than once per three years and equal to or more than once per 30 years
Extremely Improbable E	Less than once per 30 years

6.1.4. Safety Risk Assessment

Safety risk is a combination of severity and likelihood. Each hazard is analyzed and its effects are determined. Each effect is given a severity rating using the definition in Section 6.1.2. For each effect, likelihood is estimated or calculated. The safety risk of a hazard is the worst credible effect of the hazard. The risk matrix shown in Figure 6-2 is then used to assess the safety risk of the hazard on 3 categories:

1. High safety risk. This is unacceptable risk, and the change cannot be implemented unless the hazard's associated risk is mitigated to medium or low. Existing high-risk hazards must also be mitigated to medium or low risk.

Hazards with catastrophic effects that are caused by a single point event or failures, common cause events or failures, or undetectable latent events in combination with single point or common cause events are considered high risk, even if the possibility of occurrence is extremely improbable.

2. Medium safety risk. This is acceptable risk and is the minimum acceptable safety objective. A NAS change with a medium-risk hazard may be implemented with additional mitigations. Although initial medium risk is acceptable, it is recommended and desirable that safety requirements be developed to reduce severity and/or likelihood. The risk must be monitored and tracked in relation to the safety performance targets until the predicted residual risk is verified.

3. Low safety risk. This is acceptable risk without restriction or limitation. It is not mandatory to develop safety requirements for low-risk hazards; however, develop a monitoring plan with at least one safety performance target.

6.2. Hazard Assessment

As described in Section 5, four hazards have been identified for PTM operations between pairs of aircraft. Hazard PTM-4 has been subdivided into 4 sub-hazards depending on the cause of the hazard. The worst credible severity of the hazards and the likelihood are determined using fault trees shown in APPENDIX B of this paper and event trees shown APPENDIX C of this paper. Using the worst credible severity and the likelihood of this severity, the initial risk is assessed as shown in Table 6-5 and in the Risk Matrix of Figure 6-2.

Table 6-5. Initial and Predicted Residual Risk.

Hazard No.	Hazard Title	Initial Risk	Predicted Residual Risk
PTM-1	Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver	3C, Medium	TBD
PTM-2	Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level	4D, Low	TBD
PTM-3	Flight crew accepts a clearance with an aircraft for which no PTM spacing exists	2E, Medium	TBD
PTM-4a	Flight Crew unable to maintain PTM spacing from designated aircraft (Designated aircraft changes speed)	2E, Medium	TBD

Hazard No.	Hazard Title	Initial Risk	Predicted Residual Risk
PTM-4b	Flight Crew unable to maintain PTM spacing from designated aircraft (Mechanical failure)	4D, Low	TBD
PTM-4c	Flight Crew unable to maintain PTM spacing from designated aircraft (System failures)	1E, Medium	TBD
PTM-4d	Flight Crew unable to maintain PTM spacing from designated aircraft (Incorrect implementation)	2E, Medium	TBD

Predicted Residual Risk is the risk that is estimated to exist after additional safety requirements have been identified and implemented. Additional safety requirements could include training developed for personnel involved in PTM operations, maintenance requirements, equipment changes, changes or additions to the PTM procedure, and others. Once additional safety requirements are identified, the Predicted Residual Risk is estimated using the same risk assessment methods shown in this section.

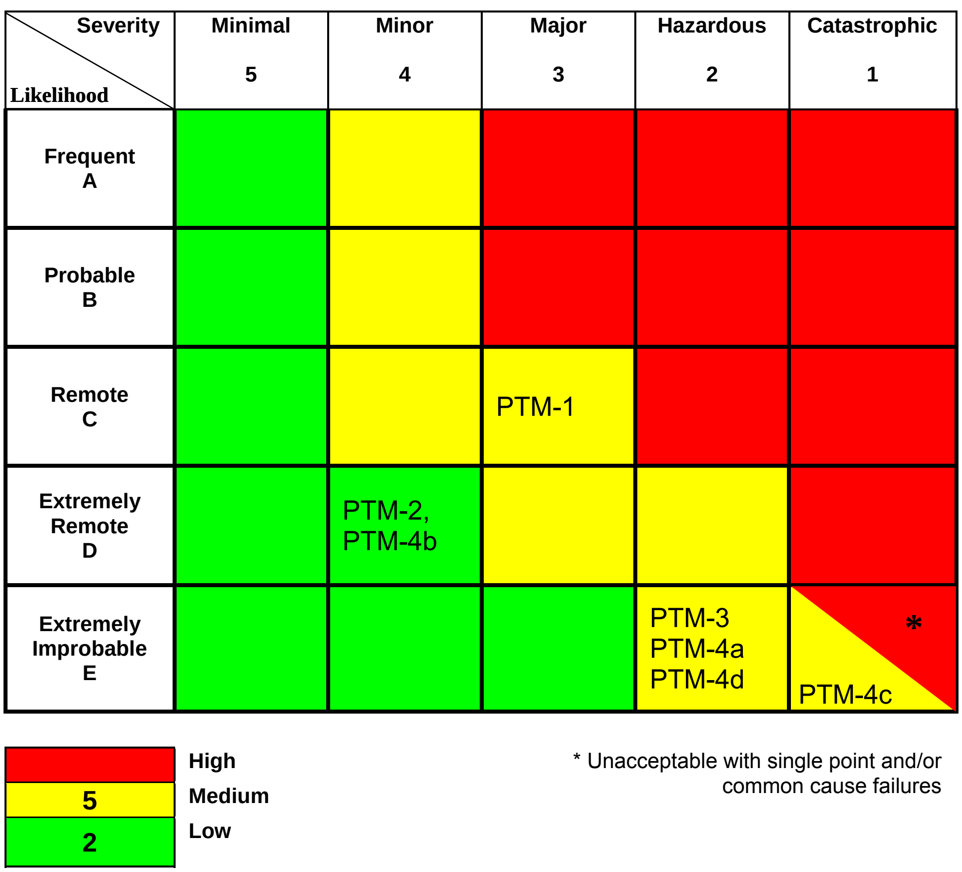


Figure 6-2. Risk matrix, initial risk.

7. Summary and Conclusion

Four hazards have been identified for PTM operations between two aircraft. Hazard PTM-4 has been subdivided into 4 sub-hazards. Hazards PTM-1 and PTM-2 deal with the safety risk of wake turbulence encounters. Hazard PTM-1 has an initial safety risk of 3-C, Medium. Hazard PTM-2 has an initial safety risk of 4-D, Low. Hazards PTM-3 and PTM-4 have an initial safety assessment of Medium. Hazard PTM-4, sub-hazard PTM-4c, has a safety assessment of 1-E, which implies a severity of Catastrophic with a likelihood of Extremely Improbable. This means that it must be shown that this sub-hazard does not have a single point of failure or a single event that can lead to the effect. It can be seen in the event tree for PTM-4c in APPENDIX C that several mitigations must fail in order to arrive at the worst credible effect. Further analysis and scenarios will be developed for this sub-hazard to show that this hazard does not have a single point of failure.

For the hazards that have been rated to have a safety risk of Medium, additional mitigations could be developed and a monitoring program must be developed and put in place prior to implementation of the change.

8. Definitions

Same track – Tracks whose protected airspaces are coincident, overlap, or intersect and whose angular difference is less than 45 degrees.

Identical same track – Tracks whose protected airspaces are coincident, overlap, or intersect and whose angular difference is zero.

Legacy separation – A Separation standard as defined in FAA Order JO 7110.65 or in ICAO PANS-ATM Doc. 4444 that is not PTM separation.

PTM separation – PTM separation is an ATC assigned separation where a PTM aircraft performs PTM operations with a designated aircraft and maintains spacing from the designated aircraft.

Separation Standard Minima – The minimum distance that must exist between two aircraft when implementing the given separation standard.

Spacing – An operational implementation distance that is the sum of the separation standard minima plus a buffer.

Designated aircraft – An aircraft with which the PTM aircraft performs PTM operations and from which the PTM aircraft maintains spacing.

APPENDIX A. SYSTEM HAZARD ANALYSIS

No	Hazard Title	Causes	System State	Possible Effects	Severity / Rationale	Existing Controls & Requirements	Likelihood / Rationale	Current Risk	Recommended Safety Requirements	Predicted Residual Risk
PTM-1	Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver	Wake horizontally in the path of an aircraft climbing in-trail (C-2) Wake rising and horizontally in the path of an aircraft descending in-trail (C-4) Trailing aircraft horizontally in the rising wake of a leading climbing aircraft (C-6) Trailing aircraft horizontally in the wake of leading descending aircraft (C-8)	Aircraft on identical same track	Physical distress to passengers (e.g., abrupt evasive action; severe turbulence causing unexpected aircraft movements) Minor injury to greater than 10 percent of POB	Major, 3 Defined in SMS 4.0	The PTM separation standard minimum will be equal or greater than the wake turbulence application minimums as defined in FAA JO 7110.65, Section 5-5-4 paragraph f.	Remote, C Severe wake turbulence encounters resulting in injury to more than 10 percent of persons on-board occur less than once every 3 months in the NAS, where the separation standard is typically 5 miles en-route and 3 miles in terminal area.	3C, Medium		
PTM-2	Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level	Wake of the leading aircraft stays at the altitude where generated without disruption to the wake (C-22) Wake horizontally in the path of the trailing aircraft (C-23)	Aircraft on identical same track	Physical discomfort to passengers (e.g., clear air turbulence causing unexpected movement of aircraft resulting in injuries to one or two passengers out of their seats) Minor injury to less than or equal to 10 percent of POB	Minor, 4 Defined in SMS 4.0	The PTM separation standard minimum will be equal or greater than the wake turbulence application minimums as defined in FAA JO 7110.65, Section 5-5-4 paragraph f.	Extremely Remote, D Wake produced by aircraft sink in the majority of cases. Under certain atmospheric conditions, the wake might stay at the generated level or rise. These same atmospheric conditions that prevent the wake from sinking also contribute to a more rapid decay of the wake strength. Hence, it is significantly less likely to encounter severe wake turbulence at the same flight level than when climbing or descending through.	4D, Low		

PTM-3	Flight crew accepts a clearance with an aircraft for which no PTM spacing exists	Flight crew overrides the airborne PTM system (C-13) The PTM airborne automation incorrectly calculates the along-track distance between the aircraft (C-14)	PTM and designated aircraft one flight level apart. Identical same track.	Aircraft is in close enough proximity to another aircraft on a course that requires corrective action to avoid potential collision;	Hazardous, 2	When along-track distance is less than the minimum spacing required, the PTM equipment will advise the flight crew to reject the PTM clearance. The preformatted reply message to accept the PTM clearance will not be available. A traffic display is part of the PTM equipment in the cockpit, which allows the flight crew to see the location of the designated aircraft. Flight crew training in the use and operation of the PTM equipment.	Extremely Improbable, E The worst credible effect is a combination of the PTM equipment failing or the crew overriding the PTM equipment and the crew climbing or descending close to the designated aircraft, event though the crew is aware of the location of the designated aircraft. This combination of probabilities makes the worst credible event extremely improbable.	2E, Medium		
PTM-4a	Flight crew unable to maintain PTM spacing from designated aircraft (Designated aircraft changes speed)	Designated aircraft slows down (C-22a) Designated aircraft speeds up (C-22b) PTM aircraft performance does not allow to follow the speed guidance (to slow down)(C-23a) PTM aircraft performance does not allow to follow the speed guidance (to speed up)(C-23b)	Identical same track	Aircraft is in close enough proximity to another aircraft on a course that requires corrective action to avoid potential collision;	Hazardous, 2	PTM aircraft communicates with ATC to obtain an alternate clearance. PTM aircraft communicates with designated aircraft via VHF voice. PTM aircraft implements Strategic Lateral Offset Procedure. PTM aircraft implements regional contingency procedures. Flight crew of PTM aircraft is aware of the location of the designated aircraft and avoids a potential collision.	Extremely Improbable, E Due to the slow closure rate of aircraft in trail, there is abundant time to implement the existing mitigations. With a closure of 0.02 Mach and initial distance of 7 NM, it will take approx. 36 minutes to close the distance. For the worst credible effect to occur (near mid air collision) several mitigations will have to fail.	2E, Medium		

PTM-4b	Flight crew unable to maintain PTM spacing from designated aircraft (Mechanical failure)	Engine failure (C-24) Cabin depressurization (C-25) Other mechanical failure (C-26)	Identical same track	Aircraft is in close enough proximity to another aircraft to require specific pilot action to alter or maintain current course/ altitude, but intentions of other aircraft are known and a potential collision risk does not exists with the designated aircraft	Minor, 4 This severity refers to the severity of losing separation when conducting a PTM operation due to mechanical failure. It does not refer to the severity of the mechanical failure.	Aircraft follows regional contingency procedures Flight crew notifies ATC of emergency and requests guidance	Extremely Remote, D The PTM separation will not be an issue when an aircraft departs from its track and descends from its assigned flight level. The likelihood is based on the frequency of engine failures and other causes in the oceanic environment and the probability of following contingency procedures and being able to contact ATC	4D, Low		
PTM-4c	Flight crew unable to maintain PTM spacing from designated aircraft (System failures)	Failure of PTM equipment on-board PTM aircraft (C-17) Failure of ADS-B transponder/ equipment on-board designated aircraft (C-18) PTM equipment produces erroneous guidance (C-20)	Identical same track	Mid-air collision	Catastrophic, 1	PTM aircraft communicates with ATC to obtain alternate clearance Flight crew of PTM aircraft maintains last speed guidance from PTM equipment with little or no closure rate PTM aircraft contacts designated aircraft via VHF radio (situational awareness, turn all available lights, coordinate vertical offset, coordinate horizontal offset, etc) PTM aircraft implements Strategic Lateral Offset Procedure PTM aircraft implements regional contingency procedures Flight crew of either aircraft detects threatening situation and avoids potential collision	Extremely Improbable, E Due to the slow closure rate or no closure rate of aircraft in trail, there is abundant time to implement the existing mitigations. Flight crew is aware of the existence and location of the designated aircraft before the PTM system failure.	1E, Medium		

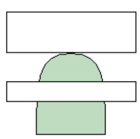
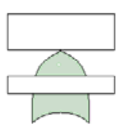
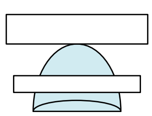
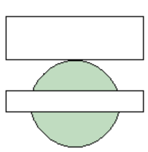
PTM-4d	Flight crew unable to maintain PTM spacing from designated aircraft (Incorrect implementation)	Flight crew erroneously implements guidance	Identical same track	Aircraft is in close enough proximity to another aircraft on a course that requires corrective action to avoid potential collision;	Hazardous, 2	The PTM equipment continuously produces a speed guidance which could rectify a previously erroneous implementation A warning is issued by the PTM equipment that the distance is less than spacing and new guidance produced to achieve spacing An alert is issued by the PTM equipment that the distance is less that separation standard minimum and new guidance is produced to achieve separation and spacing Visual and aural alerts are issued for a severe loss of separation Flight crew has traffic display with location of the designated aircraft on the display Flight crew of either aircraft detects threatening situation and avoids potential collision	Extremely Improbable, E Due to the slow closure rate of aircraft in trail, there is abundant time to for the mitigations to be successful.	2E, Medium		

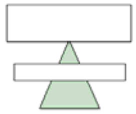
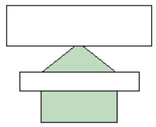
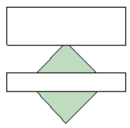
APPENDIX B. FAULT TREES

The fault trees shown below represent the left-hand side of the bow-tie model used to evaluate the identified Operational Hazards. Fault trees are used to identify the relationships between identified hazard causes, taking into account existing controls and mitigations internal to the system. While the System Hazard Analysis (SHA), APPENDIX A, lists all identified causes of hazards, the fault trees graphically show the dependencies between causes and events. In many cases, multiple events or causes must occur in order to produce an operational hazard. The fault tree analysis is used to assess the likelihood that operational hazards occur in the identified environment. The likelihoods calculated for each fault tree are used as inputs to the event tree analyses, Appendix C.

Causes identified in the SHA can be cross-referenced with the fault trees using the Cause (C) numbering in the SHA and fault tree cause titles. Tables of identified causes and likelihood rationales are included with each fault tree to show the sources of values used in the analysis. Table B-6 shows the symbols used in the fault trees and the Description or meaning for each symbol.

Table B-6 Fault Tree Legend.

Event type	Symbol	Description
AND		Output event occurs if all input events occur simultaneously
OR		Output event occurs if any one of the input events occurs
EXCLUSIVE OR		Output event occurs if one but not both of the input events occurs
BASIC EVENT		Indicates an event for which probability of occurrence is known or estimated

TRANSFER		Output event occurs if the input event does occur. Input is developed in a different part of the diagram or on a different page
HOUSE EVENT		Indicates whether an event is definitely operating or definitely not operating (dormant)
UNDEVELOPED EVENT		Indicates a system event that is yet to be developed
<u>Definitions:</u> Q – Probability of occurrence W – Occurrence frequency		

PTM-1. Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver.

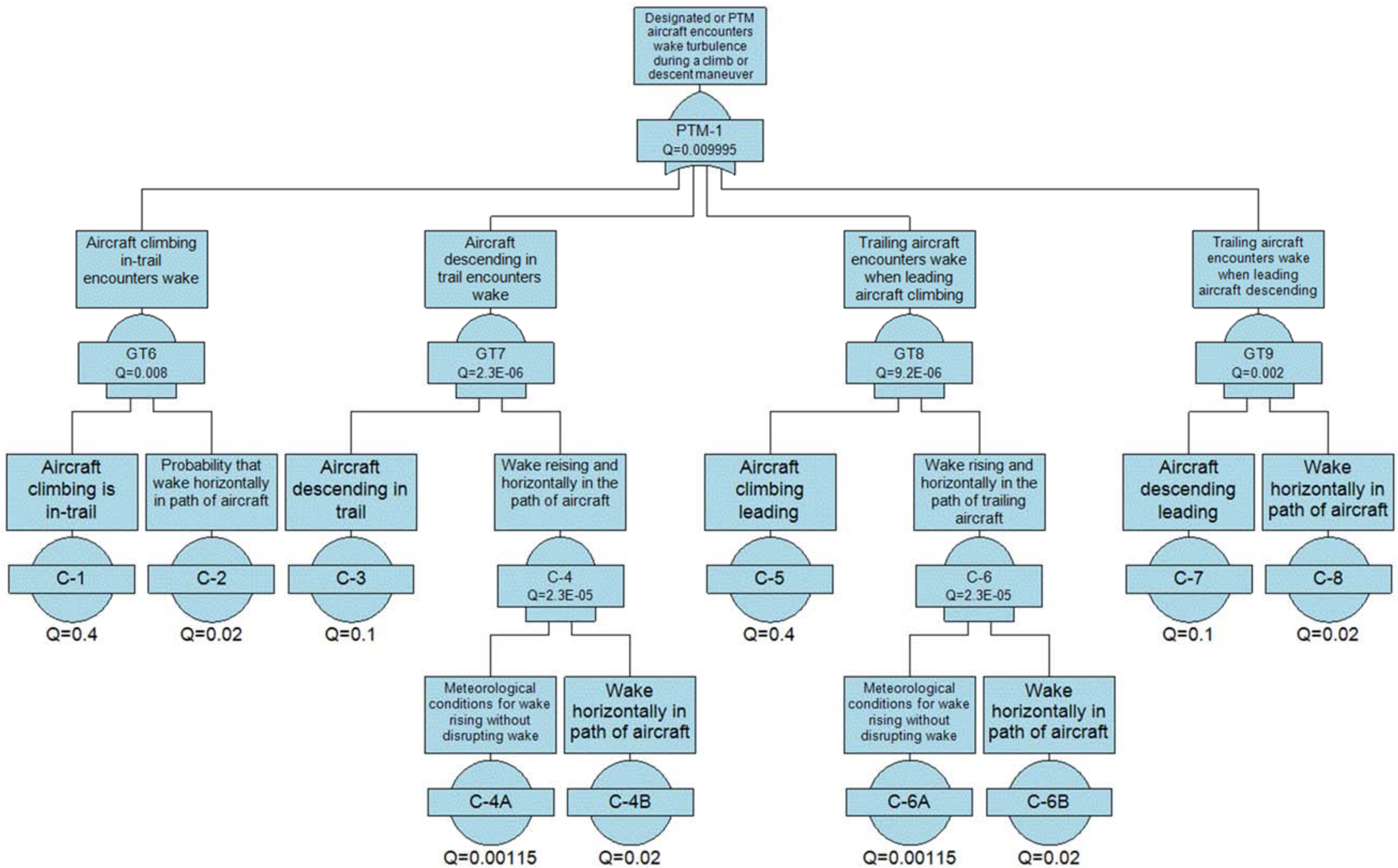


Table B-7. PTM-1. Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver.

Number	Description	Comment	Probability
C-1	Aircraft climbing in-trail	Type of maneuver. For every 100 climbs or descent maneuvers, 94 will be climbing, and 6 will be descending. Probability based on subject matter expert estimations. As the aircraft burns fuel, the optimal altitude increases. In oceanic airspace, must flight level change request are climb requests. Of the 94 percent of climb requests, half will be in front of an aircraft and half will be in-trail resulting in a probability of 47 percent of climbs in-trail.	0.47 (SME TJG)
C-2	Aircraft climbing in trail in the wake of the leading aircraft	Probability of lateral drift of 0.98 is estimated from cross wind directions and magnitude based on observations using NOAA's Rapid Update Cycle (RUC). Probability of encountering the wake is 1 – 0.98 = 2.0E-2.	2.0E-02
C-3	Aircraft descending in trail	Type of maneuver. For every 100 climbs or descents, 6 will be descending (see C-1). Of the 6 percent of descents, half will be in front of an aircraft and half will be in-trail resulting in a 3 percent descent in-trail.	0.03 (SME TJG)
C-4	Aircraft descending in trail in the wake of the leading aircraft	The estimated probability of a wake rising in the optimal meteorological condition for rising is 1/29 = 3.4E-02. The probability of the rising meteorological conditions are 1/30. The probability of lateral drift is 0.98. (NASA CR 4767)	2.24E-05 3.4E-02 x 3.3E-02 x 2.0E-02
C-5	Aircraft climbing leading	Type of maneuver. For every 100 climbs or descent maneuvers, 94 will be climbing, and 47 will be climbing leading (see C-1).	0.47

C-6	Trailing aircraft in the wake of the climbing leading aircraft		2.24E-05
C-7	Aircraft descending leading	Type of maneuver. For every 100 climbs or descents, 6 will be descending and 3 descending leading (see C-1 and C-3).	0.03 (SME TJG)
C-8	Trailing aircraft in the wake of the descending leading aircraft		2.0E-02

PTM-2. Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same level.

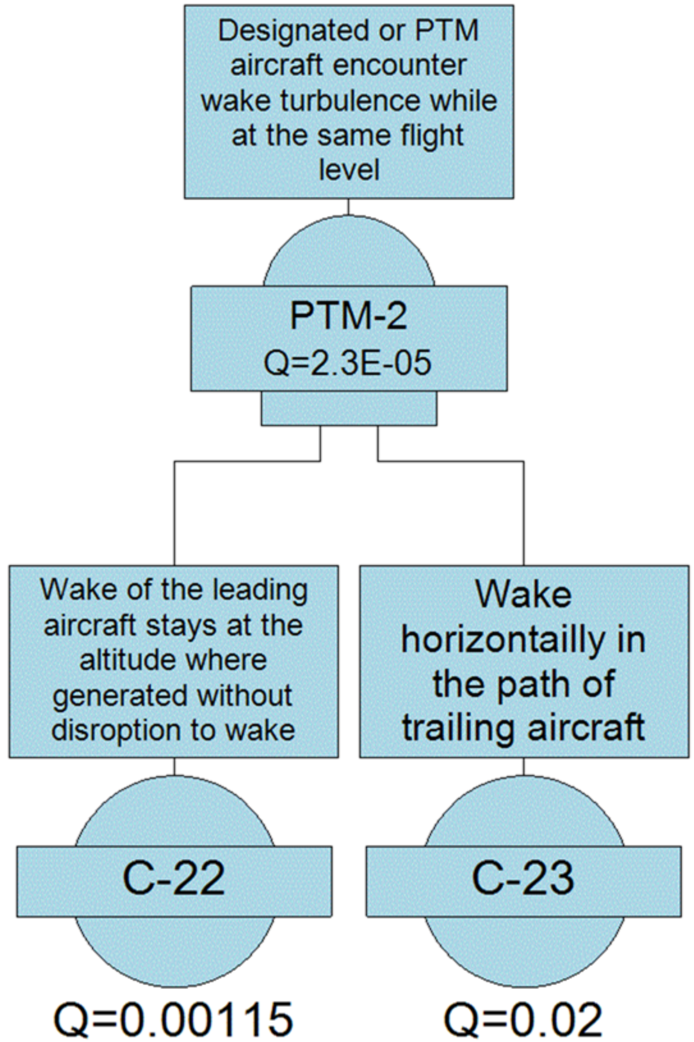
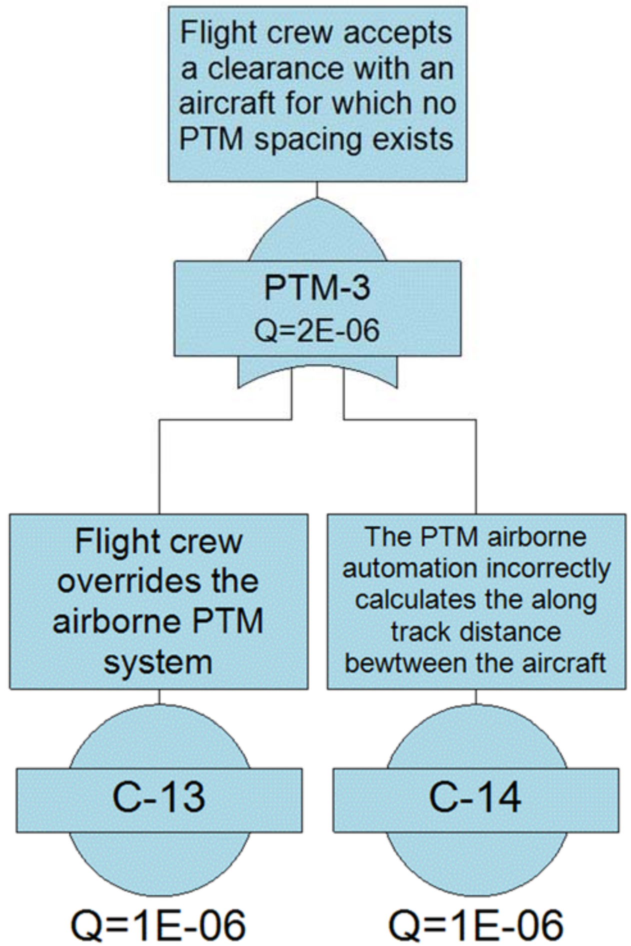


Table B-8 PTM-2. Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same level.

Number	Description	Comment	Probability
C-22	Wake of the leading aircraft stays at the altitude where generated without disruption to the wake	In general, the wake of an aircraft drifts down from the level at which it is generated. Some meteorological conditions can make the wake rise or stay at the same level that it is generated. These meteorological conditions can also disrupt and make the vortex of the wake decay faster than normally. This cause is the probability that the wake stays at the same level as generated without being broken down by the meteorological conditions. (See Appendix E of the Technical Paper).	0.00115
C-23	Wake horizontally in the path of the trailing aircraft	Probability of lateral drift of 0.98 is estimated from cross wind directions and magnitude based on observations using NOAA's Rapid Update Cycle (RUC). Probability of encountering the wake is 1 – 0.98 = 2.0E-2.	0.02

PTM-3. Flight crew accepts a clearance with an aircraft for which no PTM spacing exists.



TableB-9 PTM-3. Flight crew accepts a clearance with an aircraft for which no PTM spacing exists.

Number	Description	Comment	Probability
C-13	Flight crew overrides the airborne PTM system	The probability of this cause will be dependent on how the PTM airborne system is implemented.	1E-06
C-14	The PTM airborne automation incorrectly calculates the range between the aircraft	This probability is based on the expected design assurance level of the PTM equipment.	1E-06

PTM-4a. Flight Crew unable to maintain PTM spacing from designated aircraft (Designated aircraft changes speed).

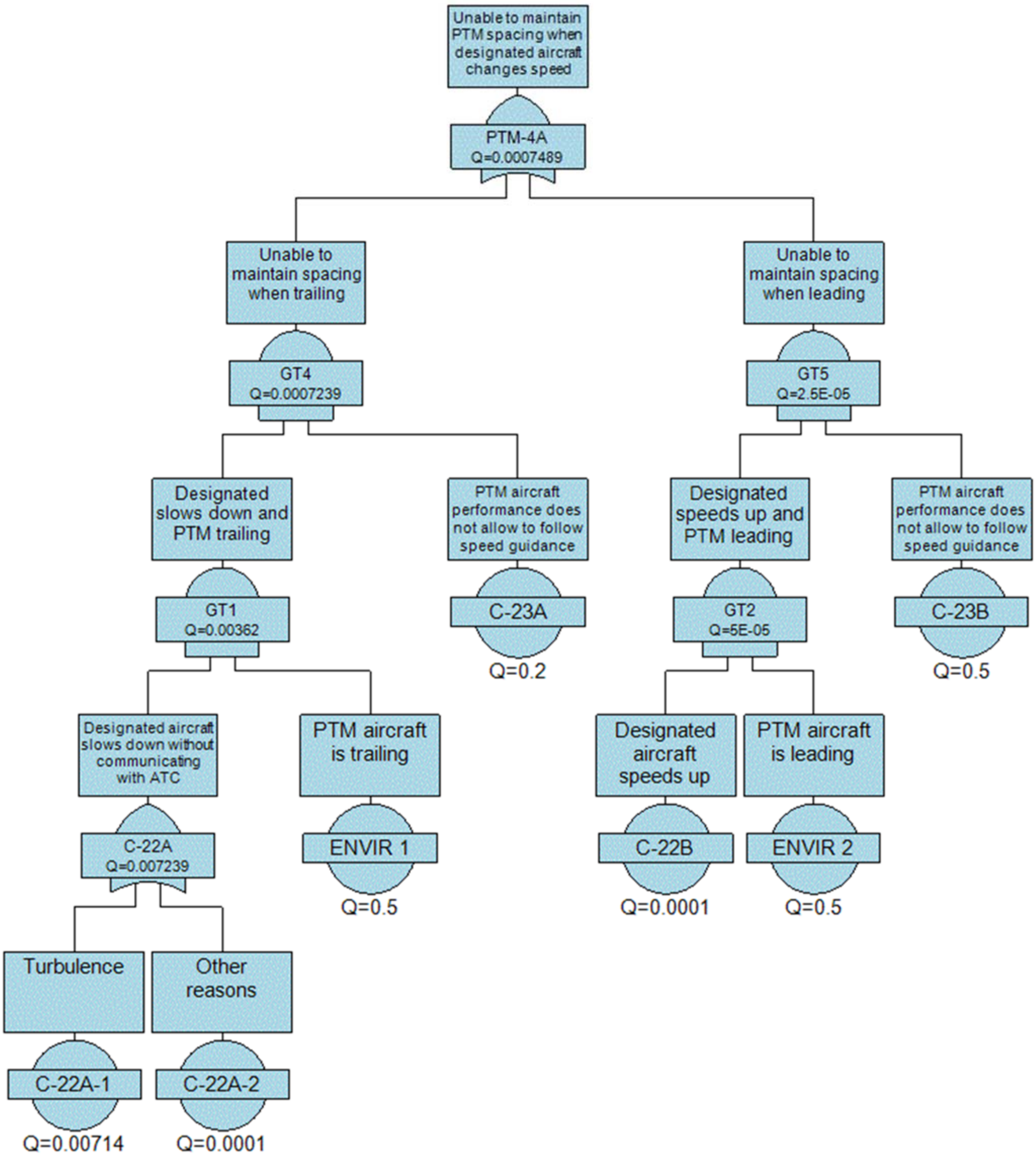


Table B-10 PTM-4a. Flight Crew unable to maintain PTM spacing from designated aircraft (Designated aircraft changes speed).

Number	Description	Comment	Probability
C-22a-1	Designated aircraft slows down due to turbulence	The flight crew of the designated aircraft, without contacting ATC, slows down due to turbulence. (SME TJG) Probability of slowing down due to turbulence I'd guess about once per 4 crossings. Probability of not telling ATC within 4 minutes, 0.1. Probability of both happening during a PTM, ??? Probability of them happening if they have been informed that they are leading in a PTM operation, 0.05? Probability of slowing down without telling ATC is: 3.5 hours crossing x 4 = 1 slow down per 14 hours. Not informing ATC 0.1. 1/14 x 0.1 = 7.14E-03	7.14E-03
C-22a-2	Designated aircraft slows down for undefined reasons	The flight crew of the designated aircraft, without contacting ATC, slows down for reasons other than turbulence, engine failure or depressurization. (SME TJG) This is much less urgent than the external causes above. Therefore this is more like a simple violation of an ATC clearance, and much less likely. A value of 1.0E-04 is picked arbitrarily as much lower than 7.14E-03. This value is the combination of slowing down of undefined reasons AND not informing ATC.	1.0E-04
ENVIR-1	PTM aircraft is trailing	PTM aircraft is performing a PTM operation trailing the designated aircraft.	0.5
ENVIR-2	PTM aircraft is leading	PTM aircraft is performing a PTM operation with leading the designated aircraft.	0.5
C-23a	PTM aircraft performance does not allow to follow the speed guidance	When the PTM aircraft is trailing and the designated aircraft slows down, the PTM aircraft might receive a speed guidance that is too slow and below its flight envelope.	
C-22b	Designated aircraft speeds up	The flight crew of the designated aircraft, without contacting ATC, speeds up above the assigned Mach speed.	1.0E-04 Same value as C-22a-2
C-23b	PTM aircraft performance does not allow to follow speed guidance	When the PTM aircraft is leading and the designated aircraft speeds up, the PTM aircraft might receive a speed guidance that is too fast and above its flight envelope.	

PTM-4b. Flight Crew unable to maintain PTM spacing from designated aircraft (Mechanical failure).

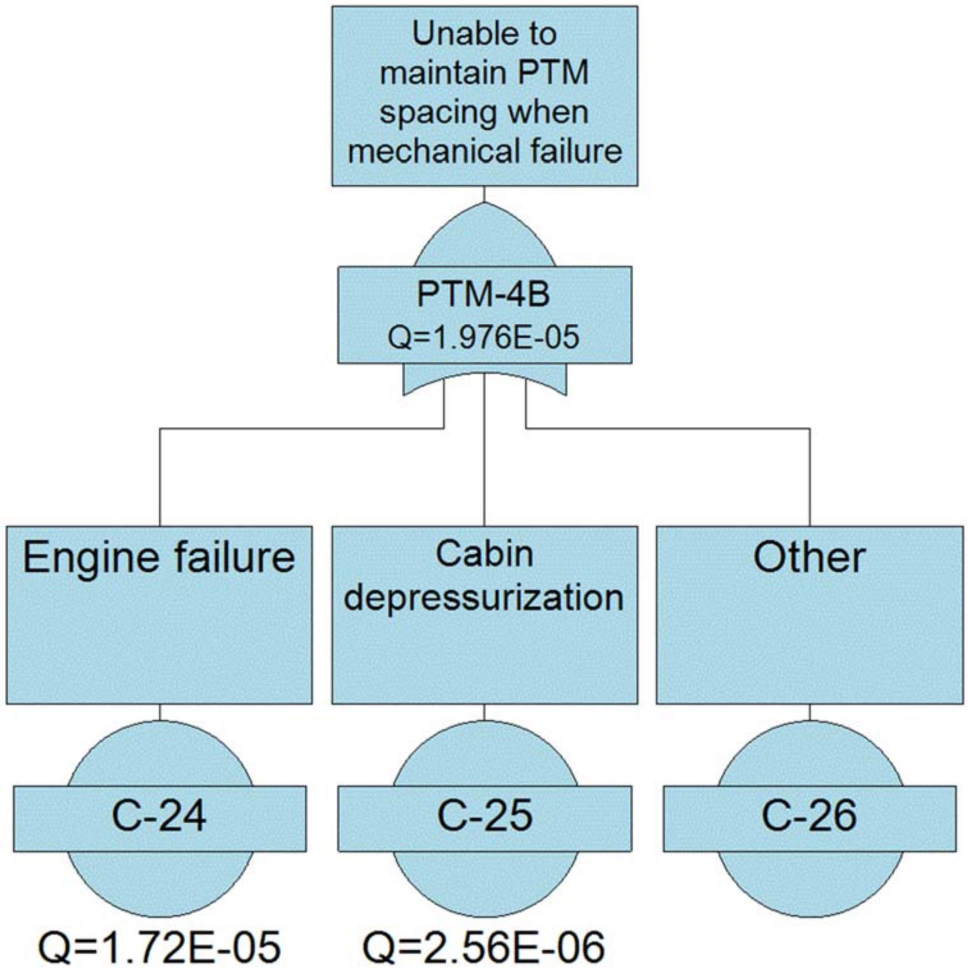


Table B-11 PTM-4b. Flight Crew unable to maintain PTM spacing from designated aircraft (Mechanical failure).

Number	Description	Comment	Probability
C-24	Engine failure	An engine failure that prevents the designated or PTM aircraft from maintaining the assigned Mach speed or the guidance speed. In 2008, AA had the largest rate of in-flight engine shutdowns. There were 24 reported shutdowns. In 2008. AA had 1,392,792 flight hours in 2008. This results in one shutdown every 58,033 flight-hours. (DOT)	1.72E-05 AA rate of in-flight engine shutdowns in 2008. Engine failure rate might be lower for oceanic extended twin-engine operations.
C-25	Cabin depressurization	Cabin depressurization will force the designated or PTM aircraft to immediately descend to a lower altitude while following contingency procedure.	2.56E-06 US Domestic incidents per flight hour for 2013. (DOT)
C-26	Other mechanical failures or incidents	Any mechanical failure or incident on-board the aircraft that causes a change in speed or departure from the intended flight path.	

PTM-4c. Flight Crew unable to maintain PTM spacing from designated aircraft (System failures).

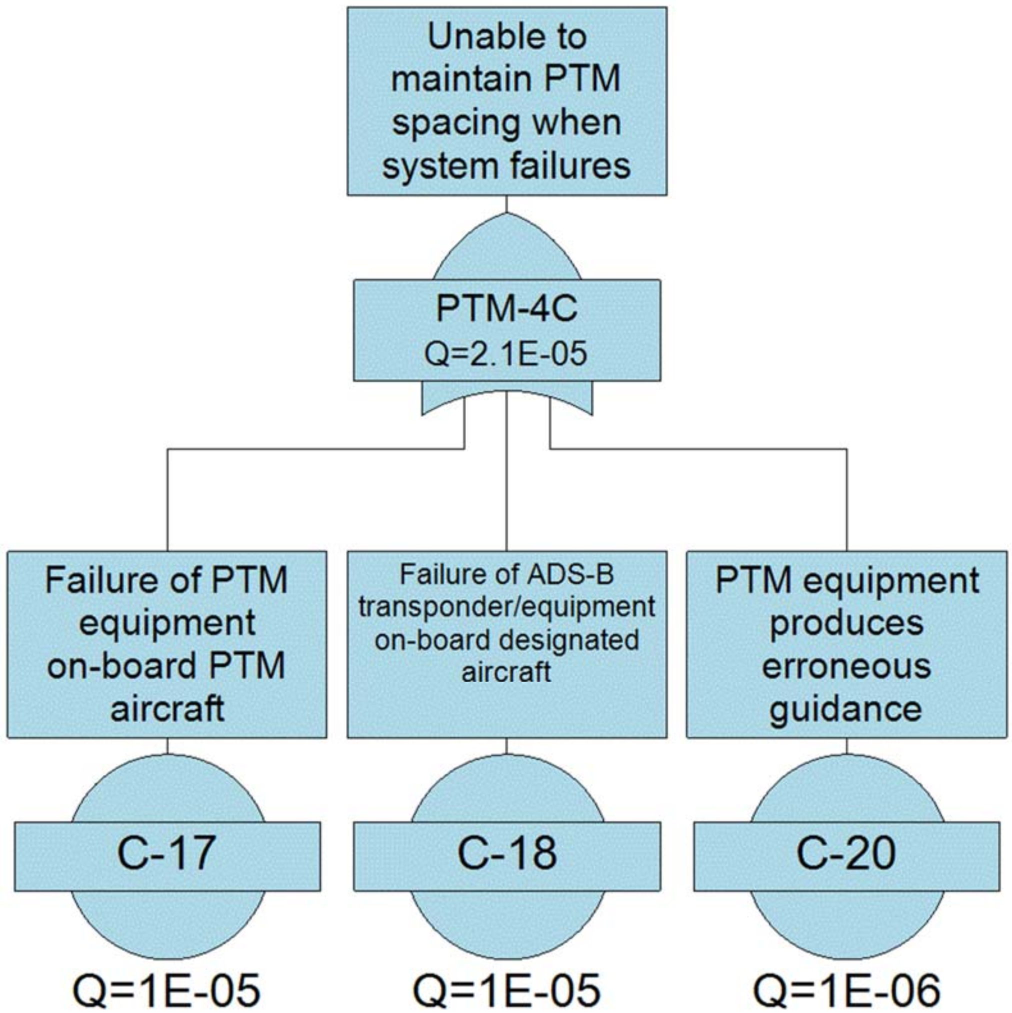


Table B-12 PTM-4c. Flight Crew unable to maintain PTM spacing from designated aircraft (System failures).

Number	Description	Comment	Probability
C-17	Failure of PTM equipment on-board PTM aircraft	The PTM equipment on-board the PTM aircraft gives speed guidance in the case of 1-D operations and speed and heading guidance in the case of 2-D operations. Failure of the PTM equipment will make PTM operations sub-nominal and will require that the flight crew inform ATC to suspend PTM operations or follow contingency procedures.	1E-05 This value is a place holder for the failure rate of the PTM equipment
C-18	Failure of ADS-B transponder/equipment on-board designated aircraft	Failure of the ADS-B transponder or ADS-B equipment on the designated aircraft will prevent the PTM equipment from generating speed and heading guidance for PTM operations.	1E-05 This value is a place holder for the failure rate of the ADS-B transponder and equipment
C-20	PTM equipment produces erroneous guidance	The PTM equipment calculates a speed or heading guidance to maintain spacing but the guidance is incorrect and does not achieve the desired spacing.	

PTM 4d. Flight Crew unable to maintain PTM spacing from designated aircraft (Incorrect guidance or implementation).

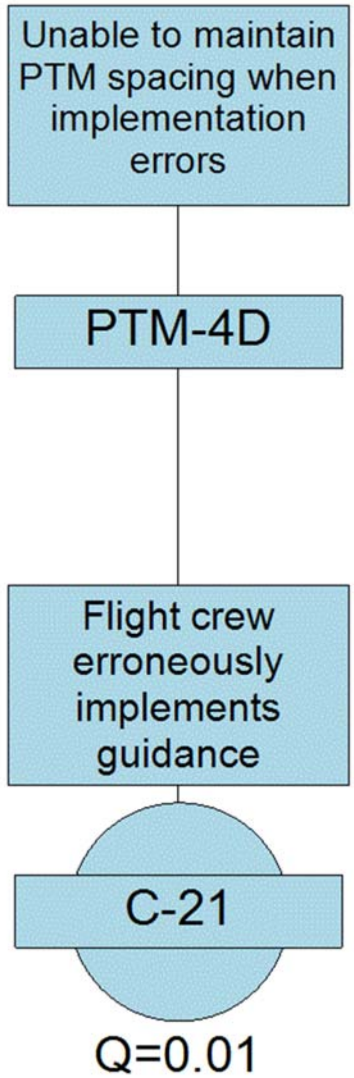
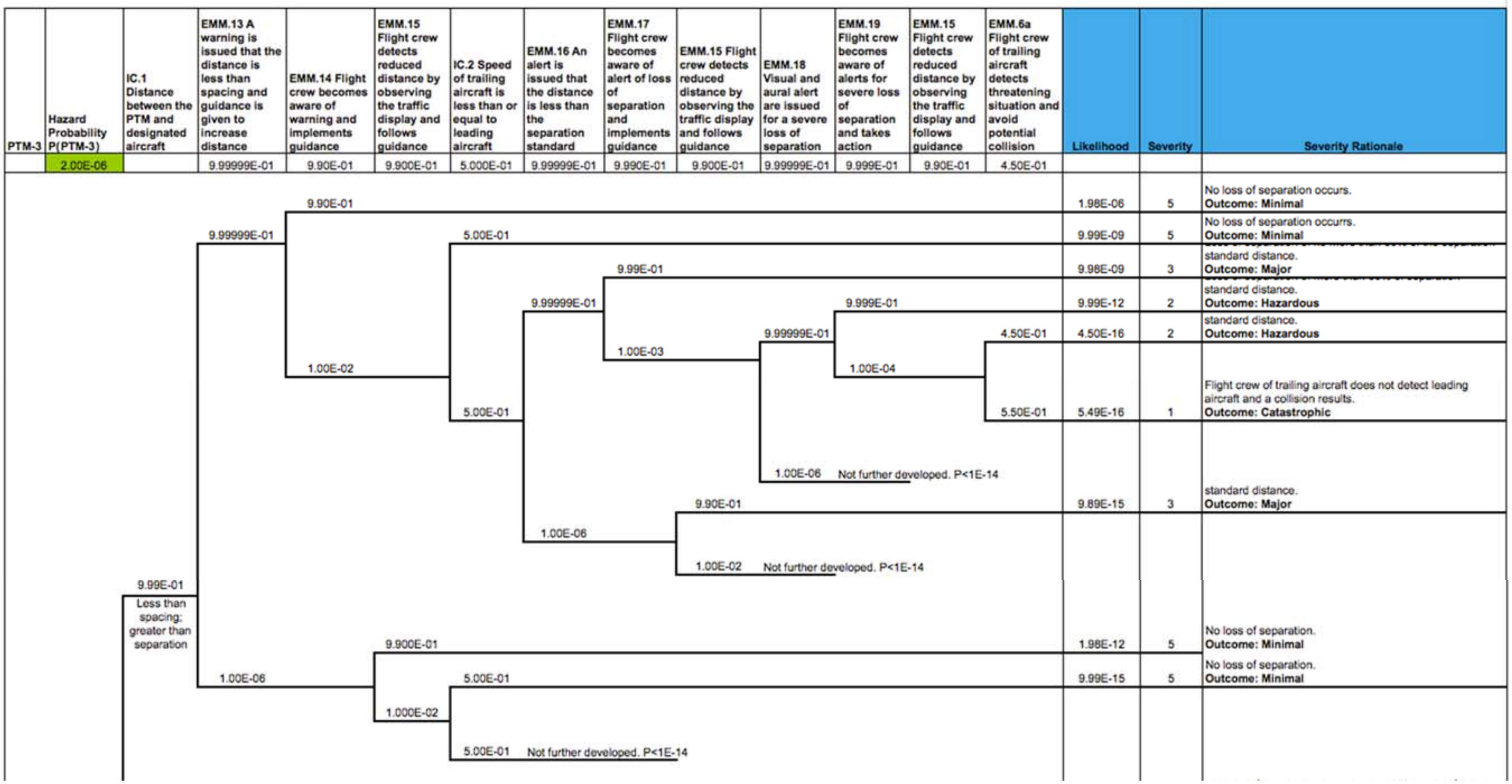


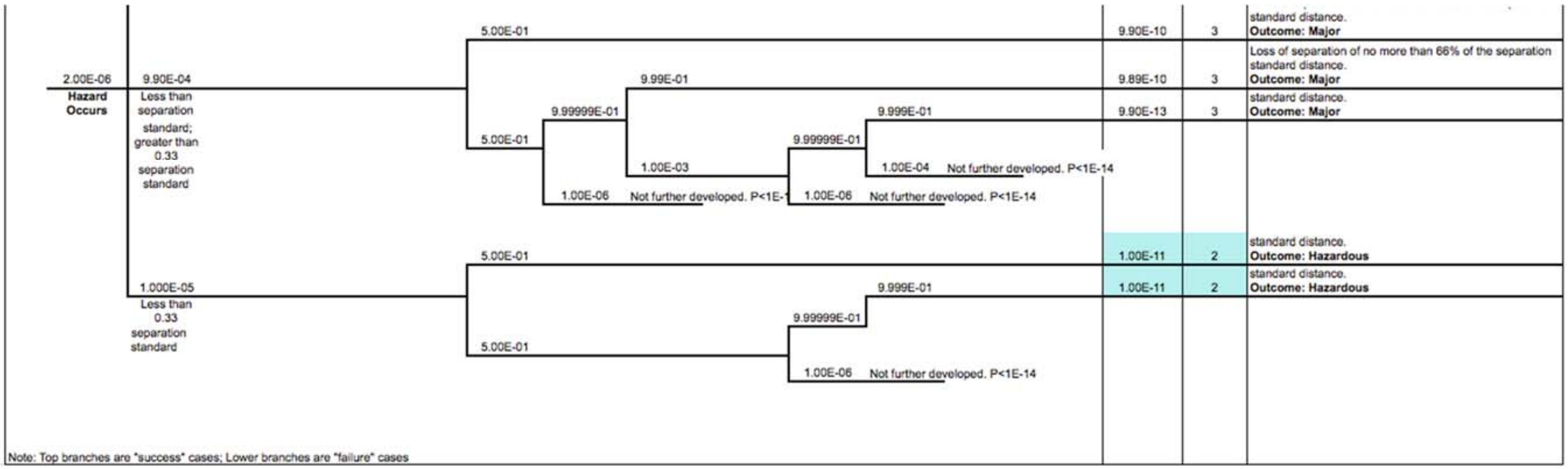
Table B-13 PTM-4d. Flight Crew unable to maintain PTM spacing from designated aircraft (Incorrect implementation).

Number	Description	Comment	Probability
C-21	Flight crew erroneously implements guidance	The PTM equipment calculates a speed guidance or heading that will achieve the desired spacing but the flight crew incorrectly implements the guidance.	0.01 (SME TJG)

APPENDIX C. EVENT TREES

PTM-3. Flight crew accepts a clearance with an aircraft for which no PTM spacing exists




standard distance.
Outcome: Major
Loss of separation of no more than 66% of the separation standard distance.
Outcome: Major
standard distance.
Outcome: Major
standard distance.
Outcome: Hazardous
standard distance.
Outcome: Hazardous
2.00E-06
Hazard Occurs
9.90E-04
Less than separation standard; greater than 0.33 separation standard
1.000E-05
Less than 0.33 separation standard
5.00E-01
5.00E-01
9.99E-01
9.99999E-01
1.00E-03
1.00E-06
Not further developed. P<1E-14
9.999E-01
9.99999E-01
1.00E-04
Not further developed. P<1E-14
1.00E-06
Not further developed. P<1E-14
9.90E-10
3
9.89E-10
3
9.90E-13
3
5.00E-01
5.00E-01
9.999E-01
9.99999E-01
1.00E-06
Not further developed. P<1E-14
1.00E-11
2
1.00E-11
2
Note: Top branches are "success" cases; Lower branches are "failure" cases

PTM-4a. Flight crew unable to maintain PTM spacing from designated aircraft when designated aircraft changes speed

PTM-4a	Hazard Probability P(PTM-4a)	EMM.1 PTM aircraft communicates with ATC	EMM.3 Flight level above or below the PTM/ desiganted aircraft is available	EMM.2 PTM aircraft communicates with designated aircraft and resolves speed issue	EMM.4 PTM aircraft implements the Strategic Lateral Offset Procedure	EMM.5 PTM aircraft implements regional contingency procedures	EMM.10 Flight crew of the PTM aircraft is aware of the designated aircraft location and avoids a potential collision.	Likelihood	Severity	Severity Rationale
	7.49E-04	9.90E-01	9.99E-01	9.90E-01	9.99E-01	9.99E-01	9.90E-01			
			9.99E-01					7.40E-04	5	ATC instructs PTM or designated aircraft to climb or descend to another flight level. **Outcome: Slight increase in air traffic controller's workload, Minimal.**
		9.90E-01		9.90E-01				8.52E-06	5	Desiganted aircraft returns to assigned Mach speed. **Outcome: Minimal**
					9.99E-01			8.60E-08	3	The PTM aircraft pases 2 miles from the designated aircraft using the SLOP **Outcome: Pilot deviation resulting in LOS equivalent to category B, Mayor.**
	7.49E-04 **Hazard Occurs**	1.05E-02	1.00E-03			9.99E-01		7.48E-12	3	**Outcome: Reduction in safety margin, FC follow abnormal prcedures, Mayor.**
				1.00E-02			9.90E-01	8.52E-14	2	Flight crew is aware of the location of the designated aircraft from trafic display and avoids a potential collision. **Outcome: Near mid-air colliision, Hazardous**
					1.00E-03	1.00E-03	1.00E-02	8.61E-16	1	Flight crew does not contact ATC, does not offset from the track, does not implement regional contingency procedures, and does not avoid reference aircraft. **Outcome: Mid-air collision, Catastrophic**

Note: Top branches are "success" cases; Lower branches are "failure" cases

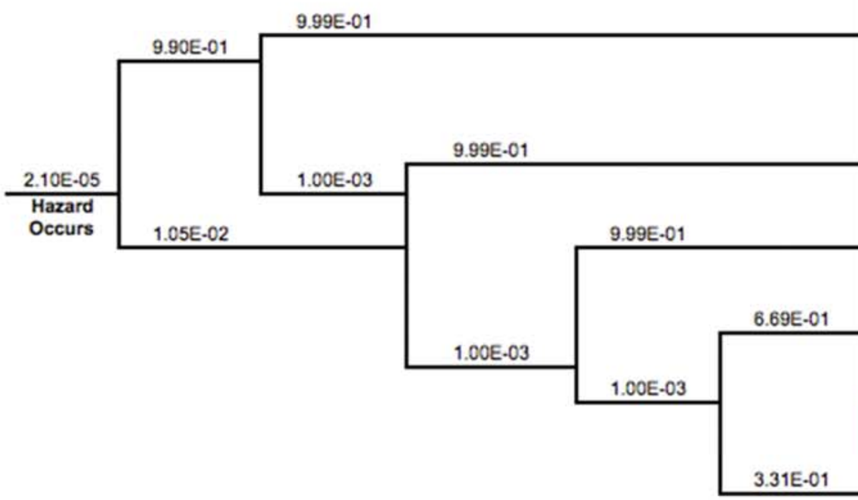
PTM-4b. Flight crew unable to maintain PTM spacing from designated aircraft when there is a mechanical failure

PTM-4b	Hazard Probability P(PTM-4b)	EMM.7 Aircraft starts descent	EMM.8 Aircraft follows regional contingency procedures and notifies ATC	Likelihood	Severity	Severity Rationale
	1.98E-05	1.00E+00	9.99E-01			
			9.99E-01	1.98E-05	5	**Outcome: Slight increase in ATC workload, Minimal.**
		1.00E+00				
			1.00E-03	1.98E-08	4	If the designated aircraft has the failure, the flight crew of the PTM aircraft attempts to maintain spacing from the designated aircraft but this aircraft is no longer at the same flight level. If the PTM aircrarft has the failure, the PTM equipment might continue to give speed guidance and conflicts alerts while the flight crew deals with the failure on-board. **Outcome: Slight increase in ATC workload, Significant increase in flight crew work load, Minor.**
	1.98E-05 **Hazard Occurs**					
		0.000E+00				

Note: Top branches are "success" cases; Lower branches are "failure" cases

PTM-4c. Flight crew unable to maintain PTM spacing from designated aircraft when there are system failures

PTM-4c	Hazard Probability P(PTM-4c)	EMM.1 PTM aircraft communicates with ATC	EMM.3 Flight level above or below the PTM/ designanted aircraft is available	EMM.4 PTM aircraft implements the Strategic Lateral Offset Procedure	EMM.5 PTM aircraft implements regional contingency procedures	EMM.6 Flight crew of either aircraft detects threatening situation and avoids potential collision	Likelihood	Severity	Severity Rationale
	2.10E-05	9.90E-01	9.99E-01	9.99E-01	9.99E-01	6.69E-01			

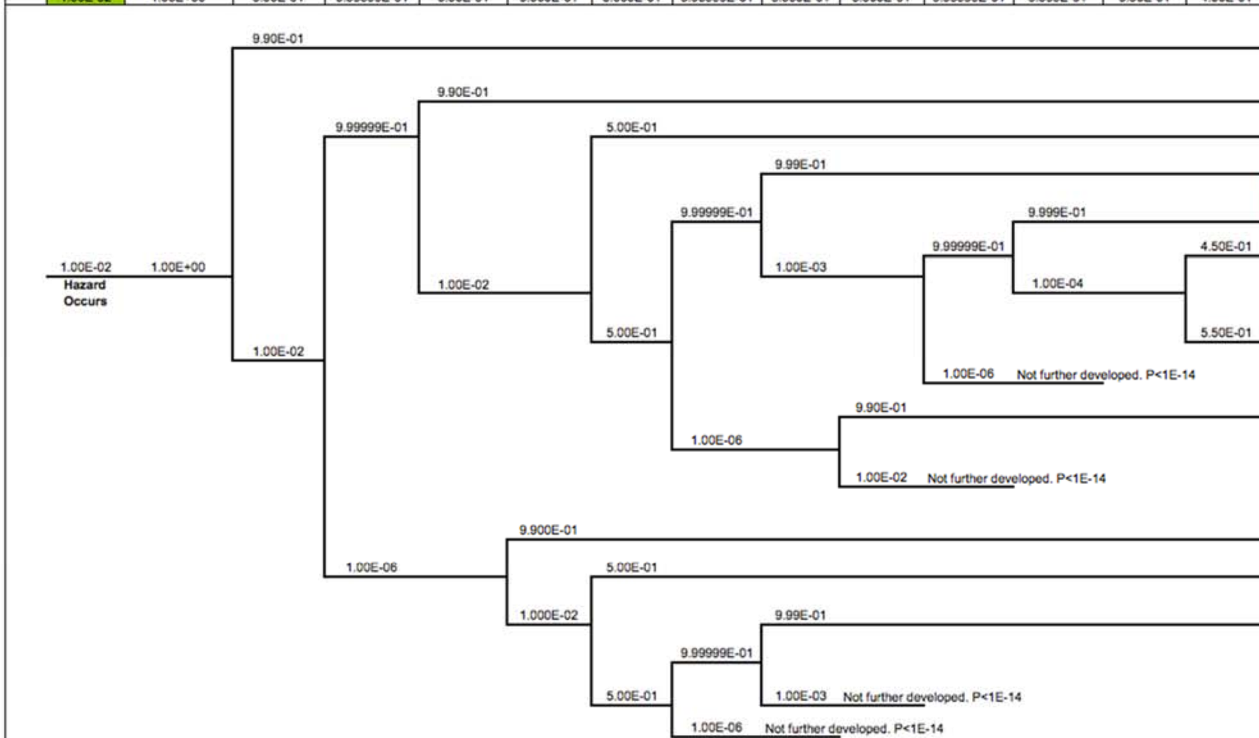


Likelihood	Severity	Severity Rationale
2.08E-05	5	ATC instructs PTM or designated aircraft to climb or descend to another flight level. **Outcome: Slight increase in air traffic controller's workload, Minimal.**
2.41E-07	3	The PTM aircraft pases 2 miles from the designated aircraft using the SLOP **Outcome: Pilot deviation resulting in LOS equivalent to category B, Mayor.**
2.10E-11	3	**Outcome: Reduction in safety margin, FC follow abnormal prcedures, Mayor.**
1.62E-13	2	Flight crew is aware of the location of the designated aircraft from trafic display and avoids a potential collision. **Outcome: Near mid-air colliision, Hazardous**
7.98E-14	1	Flight crew does not contact ATC, does not offset from the track, does not implement regional contingency procedures, and neither aircraft avoid the other aircraft. **Outcome: Mid-air collision, Catastrophic**

Note: Top branches are "success" cases; Lower branches are "failure" cases

PTM-4d. Flight crew unable to maintain PTM spacing from designated aircraft when there are implementation errors

PTM-4d	Hazard Probability P(PTM-4d)	EMM.20 The PTM equipment continously produces a speed and/or heading guidance. If the aircraft is not compliant, the PTM equipment will make the guidance a commanded speed or	EMM.21 Flight Crew correctly implements PTM guidance	EMM.13 A warning is issued that the distance is less than spacing and guidance is given to increase distance	EMM.14 Flight crew becomes aware of warning and implements guidance	EMM.15 Flight crew detects reduced distance by observing the traffic display and follows guidance	IC.2 Speed of trailing aircraft is less than or equal to leading aircraft	EMM.16 An alert is issued that the distance is less than the separation standard	EMM.17 Flight crew becomes aware of alert of loss of separation and implements guidance	EMM.15 Flight crew detects reduced distance by observing the traffic display and follows guidance	EMM.18 Visual and aural alert are issued for a severe loss of separation	EMM.19 Flight crew becomes aware of alerts for severe loss of separation and takes action	EMM.15 Flight crew detects reduced distance by observing the traffic display and follows guidance	EMM.6a Flight crew of trailing aircraft detects threatening situation and avoid potential collision	Likelihood	Severity	Severity Rationale
	1.00E-02	1.00E+00	9.90E-01	9.99999E-01	9.90E-01	9.900E-01	5.000E-01	9.99999E-01	9.990E-01	9.900E-01	9.99999E-01	9.999E-01	9.90E-01	4.50E-01			



Likelihood	Severity	Severity Rationale
9.90E-03	5	No loss of separation occurs. **Outcome: Minimal**
9.90E-05	5	No loss of separation occurs. **Outcome: Minimal**
5.00E-07	5	No loss of separation occurrs. **Outcome: Minimal**
4.99E-07	3	separation standard distance. **Outcome: Major**
5.00E-10	2	Loss of separation of more than 66% of separation standard distance. **Outcome: Hazardous**
2.25E-14	2	standard distance. **Outcome: Hazardous**
2.75E-14	1	Flight crew of trailing aircraft does not detect leading aircraft and a collision results. **Outcome: Catastrophic**
4.95E-13	3	separation standard distance. **Outcome: Major**
9.90E-11	5	No loss of separation. **Outcome: Minimal**
5.00E-13	5	No loss of separation. **Outcome: Minimal**
4.99E-13	3	Loss of separation of no more than 66% of the separation standard distance. **Outcome: Major**

Note: Top branches are "success" cases; Lower branches are "failure" cases

Appendix D: Safety and Performance Evaluation of the Pairwise Trajectory Management (PTM) Crossing and Merging Operations

Victor Carreño

Version 2
30 October 2016

1 Introduction

Pairwise Trajectory Management (PTM) is a cockpit-based operation where the controller clears an aircraft to maintain spacing from one or more designated aircraft. On-board PTM tools will aid the flight crew in implementing the PTM spacing. The tools are expected to consist of a traffic display, decision support tools to accept or reject a PTM clearance, speed guidance to maintain spacing, conflict detection, alerting and resolution logic, automatic dependent surveillance – broadcast (ADS-B) IN capabilities, and controller-pilot data link communications (CPDLC) communications.

There are two types of PTM operations:

1. One-dimensional in-trail where the PTM aircraft is following the same route as the designated aircraft
2. Two-dimensional operations where the PTM aircraft is crossing or merging with the designated aircraft

Two types of algorithms are used to provide speed guidance to the flight crew of the PTM aircraft. When the PTM operation is one-dimensional (same route) or when the operation is two-dimensional and there are no waypoints before the crossing or merging point, then a state based algorithm is used.

When the PTM operation is two-dimensional (crossing or merging) and there are waypoints before the crossing or merging point, then an intent based algorithm is used. The intent based algorithm takes into consideration turns at waypoint to calculate the speed guidance. The nature of two-dimensional operations could create inaccuracies that erode the spacing between the aircraft. The factors that affect the accuracy of the speed guidance include different wind fields for the aircraft and changes in ground speed when aircraft turn at waypoints.

This paper presents an analysis and evaluation of the PTM operations when the intent algorithm is used for guidance. Performance metrics and safety risk are considered for two-dimensional PTM operations and mitigations to the safety risk are proposed.

2 Two-dimensional PTM operations

2.1 Crossing or merging without waypoints

The PTM equipment on-board the aircraft gives speed guidance to the flight crew in order for the PTM aircraft to pass in front or behind the designated aircraft at a distance no less than a desirable distance defined as spacing. The PTM algorithm calculates the speed guidance based on projected times of arrival at crossing or merging points. Figure 2-1 shows an example of a crossing case where the designated aircraft (white) is 160 NM from the crossing point and the PTM aircraft (black) is 170 NM from the crossing point at time 12:00:00. The designated aircraft has a speed of 0.82 Mach.

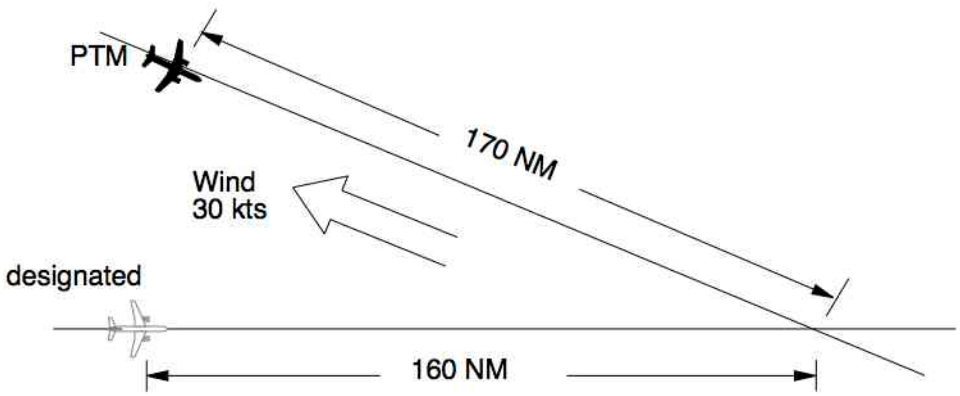


Figure 2-1. Example of a crossing PTM operation.

Because there are no waypoints before the crossing point for this scenario, a state based algorithm is used. The algorithm determines that the PTM aircraft can pass behind the designated aircraft. The algorithm calculates the designated aircraft crossing point arrival time at 12:21:29. The calculated arrival time is based on the designated aircraft position and velocity vector from the ADS-B report.

The algorithm calculates a speed guidance such that the PTM aircraft passes at an along-track distance of 8.5 NM (spacing) or greater behind the designated aircraft. For the example of Figure 2-1, the PTM aircraft should fly no faster than 0.83 Mach to pass at an along-track distance of 8.5 NM or more behind the designated aircraft. In this example, the lower guidance will be the aircraft minimum speed and the upper guidance will be the maximum speed to pass behind or 0.75 to 0.83 Mach.

During this operation, the PTM equipment on-board the PTM aircraft recalculates the designated aircraft arrival time at the crossing point and the speed guidance continuously (for example every one second). If the wind changes or the designated aircraft changes speed, the guidance will change to keep the PTM aircraft for getting any closer than the spacing distance.

2.2 Crossing or merging with waypoints

A PTM operation could include a scenario where the aircraft's routes have waypoints and turns before the crossing or merging point. The intent based algorithm is used in these scenarios to provide speed guidance. Figure 2-2 shows an example where there are waypoints and turns before the crossing point.

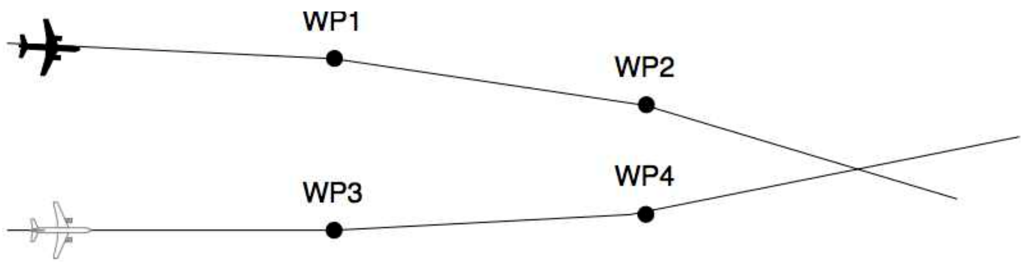


Figure 2-2. Example of crossing case PTM operation with waypoints before crossing.

The intent algorithm uses the estimated times of arrival (ETA) at waypoints provided by the ground automation to the PTM aircraft. The ground automation has the reported ETAs of aircraft at the next waypoints and calculates the ETAs at the next plus one, next plus two, etc. Aircraft broadcast their ETAs to the ground automation via automatic dependent surveillance – contract (ADS-C) or high frequency (HF) voice reports.

The ability of the PTM intent algorithm to provide speed guidance to the PTM aircraft depends on the accuracy of the ETAs. Inaccurate ETAs could result in loss of spacing or loss of separation. The following example illustrates the worst case scenario in which an inaccurate ETA could result in a near mid-air collision. Figure 2-3 shows a scenario where the crossing point is immediately after a designated aircraft waypoint.

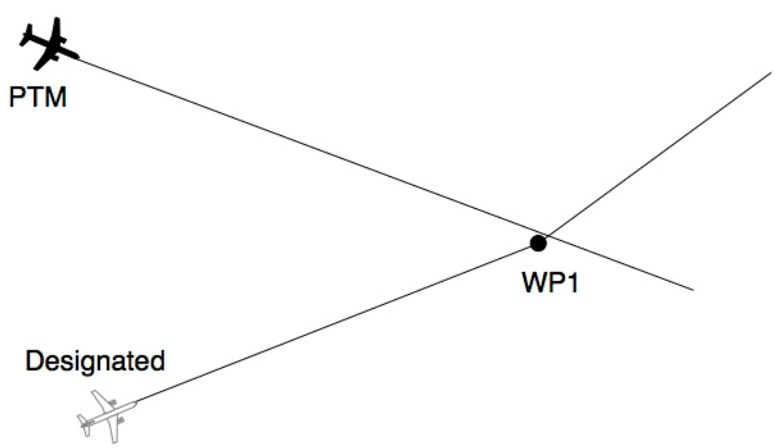


Figure 2-3. Example worst case scenario.

The designated aircraft ETA at waypoint WP1 is 15:00:00. The PTM algorithm calculates a speed guidance to pass behind, given the designated aircraft ETA at WP1. The calculated guidance will have the PTM aircraft passing the crossing point at approximately 15:01:04 or 1 minute 4 seconds after the designated aircraft has passed the crossing point. If the designated aircraft ETA is inaccurate and it arrives 1 minute and 4 seconds late to the waypoint, a collision or near mid-air collision could occur.

2.3 ETA accuracy and safety risk

Preliminary work performed by the MITRE Corporation and by Johns Hopkins University Applied Physics Laboratory analyzed the accuracy of ETA at waypoints in the oceanic environment. This work used ADS-C surveillance reports to compare the ETA of the aircraft before a waypoint and the actual time at waypoint crossing. Aircraft in oceanic airspace equipped with ADS-C capabilities broadcast periodic reports, typically every 10 minutes. These periodic reports contain ETA at next waypoint and other information. ADS-C reports are also broadcast at waypoint crossings.

The preliminary data shows that the ETA error diminishes as the aircraft reports closer to the waypoint. However, some examples presented with these data show errors as large as 33 seconds only 2 minutes and 15 seconds before waypoint crossing.

A preliminary ETA error distribution is used to estimate the safety risk of the ETA errors in PTM operations and is shown in Figure 2-4.

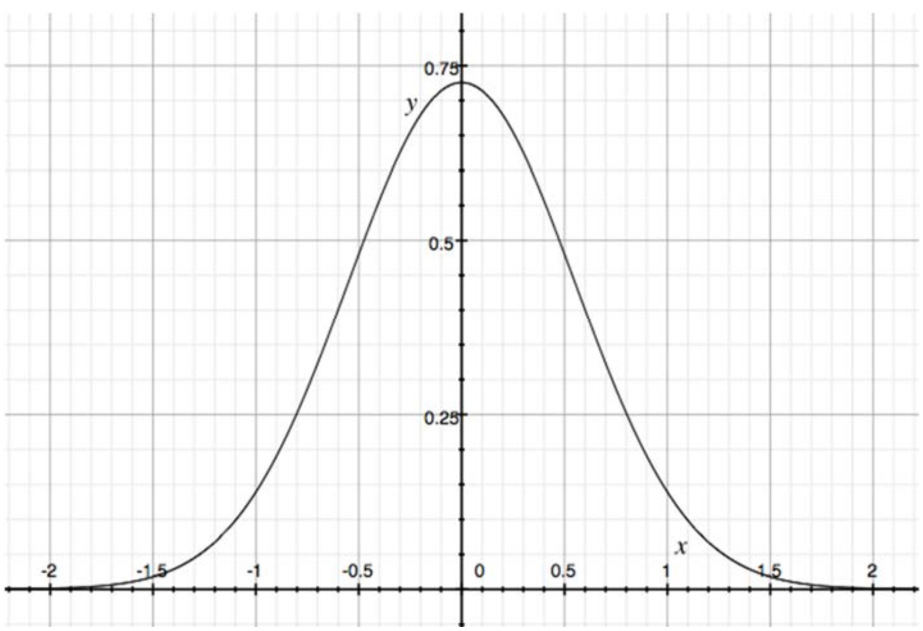


Figure 2-4. Probability density function of ETA error (The x axis is the time error in minutes and the y axis the continuous relative frequency).

This distribution is Normal (Gaussian) and has zero mean and 0.55 minutes standard deviation. This distribution is used for simplicity. A more accurate distribution will have a larger cumulative area on the left side of the mean, which represents aircraft arriving late at the waypoint. That is, there are more instances of aircraft arriving late at a waypoint than arriving early. This preliminary distribution is considered to show the ETA error approximately 5 minutes before a waypoint crossing.

Assuming a spacing of 8.5 nautical miles (NM) and a separation standard minimum of 5 NM for PTM crossing operations, it can be estimated using the ETA error distribution how often an aircraft will be in a loss of separation trajectory. For a loss of separation trajectory, the time error must be greater than or equal to 0.4375 minutes and less than or equal to 1.6875 minutes. The probability is calculated by integrating the distribution in this range,

$$P(LOS)=\int_{0.4375}^{1.6875}\frac{1}{\alpha\sqrt{2\pi}}e^{\frac{-x^2}{2\alpha^2}}=0.2121 \qquad 2.1$$

where,

α is the standard deviation of 0.55 minutes.

In a similar manner, the probability of being in a collision course and a near mid-air collision course can be calculated with different integration limits. Table 2-1 shows the probabilities of different courses.

Table 2-1. Probabilities of loss of separation courses due to ETA error.

Course	Integration limits		Probability
Loss of Separation	0.4375	1.6875	0.2121
Less than 50% separation minima	0.75	1.375	8.01E-02
Near mid-air collision	1.0522	1.0727	2.31E-02
Collision	1.0584	1.0666	9.20E-03

The calculations show that there is a relatively high probability of being in a loss of separation, loss of more than 50% separation minima, near mid-air collision trajectory, and collision trajectory. Although being on a collision course, near mid-air collision course, etc. does not necessarily lead to those outcomes, it is clear, from an operational and safety point of view, that it is unacceptable for an operation to put two aircraft in this situation in approximately 1 in every 100 crossings.

Therefore, PTM operations cannot rely solely on the ETA of the designated aircraft to maintain spacing. The PTM equipment on-board must calculate an alternate distance and velocity to determine when the designated aircraft will cross the trajectory of the PTM aircraft. The next section details a method to achieve this calculation.

3 Mitigation for inaccurate ETA

In the previous section, it was shown how an inaccurate ETA could lead to a loss of separation, near mid-air collision, and collision trajectories. A possible method to mitigate this safety risk is to have an alternate way of calculating the ETA. The PTM aircraft receives ADS-B reports from the designated aircraft. The PTM aircraft could calculate the designated aircraft's arrival time at the waypoint using the designated aircraft's reported position and velocity vector.

Once the PTM aircraft makes an on-board calculation of the times of arrival at the next and next-plus-one waypoints, it can compare the calculated ETAs with the ETAs obtained from the ground automation. If the difference between the ETAs exceeds a threshold, the PTM equipment on board could: 1. Issue an alert to the flight crew. 2. Use the more conservative estimate (the estimate that will give a guidance that will put the aircraft the farthest at crossing).

3.1 Method to use the ETA conservative estimate

The method to use the on-board calculated ETA is presented through an example. The same example from Section 2, Figure 2-3 is used. In this operation, the PTM aircraft will pass behind the designated aircraft. The figure is reproduced in this section as Figure 3-1.

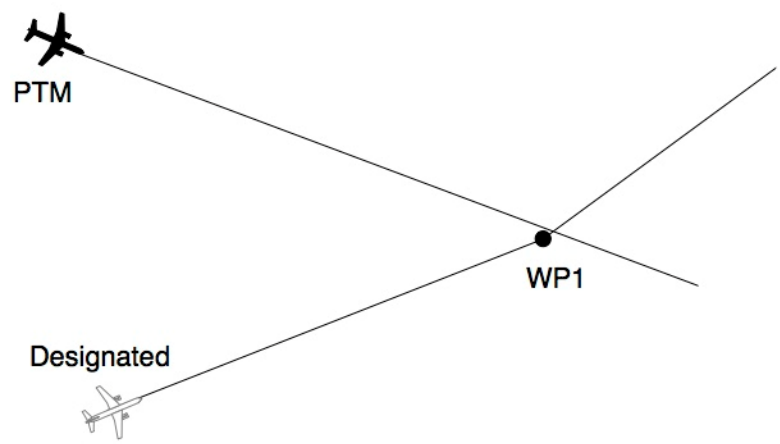


Figure 3-1. Example scenario with PTM aircraft crossing behind designated aircraft.

The reported ETA of the designated aircraft is 15:00:00. The PTM equipment on-board generates speed guidance such that the PTM aircraft will cross behind the designated aircraft no closer than 8.5 NM or at approximately at 15:01:15 or later. The PTM equipment on-board also estimates the time at which the designated aircraft will pass the waypoint and the crossing point. The estimation is based on the velocity vector of the designated aircraft and the distance to the waypoint and crossing points. If the PTM equipment estimated arrival time is later than the ETA reported by the designated aircraft, the later time is used to generate speed guidance. Table 3-1 shows examples of how the reported ETA from the designated aircraft and the PTM estimated times would be used.

Table 3-1. Using the more conservative estimate of time.

Case	Reported ETA from designated aircraft	PTM equipment estimated time using velocity vector and distance	PTM equipment generates speed guidance to cross at
1	15:00:00	14:59:30	15:01:15
2	15:00:00	15:00:00	15:01:15
3	15:00:00	15:00:30	15:01:45

In case 1, the reported ETA is later than the PTM estimate time. The more conservative time of 15:00:00 is used to calculate speed guidance. If the reported ETA is correct and the designated aircraft crosses at 15:00:00, the PTM aircraft will cross with an 8.5 NM spacing. If the PTM estimated time is correct, the PTM aircraft will cross approximately 12.5 NM behind

In case 2, the reported ETA and PTM estimated time are in agreement.

In case 3, the PTM estimate is later than the reported ETA. The more conservative time of 15:00:30 is used to calculate speed guidance. If the PTM estimated time is correct and the designated aircraft crosses at 15:00:30, the PTM aircraft will cross with an 8.5 NM spacing. If the reported ETA is correct, the PTM aircraft will cross approximately 12.5 NM behind.

It is important to note that the reported ETAs are updated no sooner than every 10 minutes. The PTM equipment on-board can calculate the estimated time every 1-second and readjust the crossing time of the PTM aircraft if error or inaccuracies were present in previous calculations. To give an idea of how the accuracy of the estimated time improves as the aircraft get closer to the crossing point, Table 3-2 shows the speed errors needed to produce a given time error.

Table 3-2. Errors in time estimations.

Assumptions: 0.83 Mach (~480 kts. TAS at -54 deg. C)		
Distance to crossing point	Error in estimated time	Error in ground speed to produce time error
600 NM	1 minute	6.5 kts.
300 NM	1 minute	13.2 kts.
100 NM	1 minute	41.7 kts.
60 NM	1 minute	73.8 kts.

A PTM equipment time estimation for an aircraft that is 60 NM to a waypoint must have a speed error of 73.8 kts to have a 1-minute inaccuracy. The system estimates that the aircraft will arrive at the waypoint in 7.5 minutes but it arrives in 6.5 minutes. The system estimates the aircraft ground speed at 480 kts. but the aircraft ground speed is 553.8 kts. This large speed error will be extremely unlikely at such short range.

4 Conclusion

The use of the designated aircraft reported ETA at waypoints to generate speed guidance and maintain spacing poses an unacceptable safety risk. The procedure could also be deemed unacceptable from operational considerations.

A mitigation method of calculating estimated times by the PTM on-board equipment could be used. Further analysis and simulation is needed to determine the effectiveness of the mitigation method proposed.

Appendix E: Assessment of Wake Turbulence during Pairwise Trajectory Management (PTM) Operations

Victor Carreño
Version 1
30 October 2016

1 Introduction

Pairwise Trajectory Management (PTM) is a cockpit-based operation where the controller clears an aircraft to maintain spacing from one or more designated aircraft. As part of the development of the concept, a safety assessment has been performed which identifies hazards. Four operational hazards have been identified. This paper covers two of the four operational hazards. These two hazards are:

PTM-1. Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver

PTM-2. Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level

2 PTM operations

PTM operations are described in Reference [1]. There are three phases of the PTM operation:

1. Giving a PTM clearance and starting or adding a PTM operation;
2. A steady state PTM operation;
3. Giving a clearance to cancel a PTM operation.

Starting a PTM operation or canceling a PTM operation generally involves a climb or descent to the Flight Level of the designated aircraft. Steady state PTM operations generally involve operations at the same flight level of the designated aircraft.

An aircraft that is given a PTM clearance and accepts the clearance will maintain spacing from the designated aircraft. The PTM aircraft maintains spacing with the aid of speed guidance from PTM equipment on-board. The controller can climb or descend the PTM or designated aircraft such that both aircraft are at the same flight level. A PTM operation could also be formed before entering oceanic airspace where they are already at the same flight level.

A PTM operation could be terminated by establishing an alternate means of separation and then canceling the PTM clearance. An alternate means of separation could be climbing or descending the PTM or the designated aircraft.

3 Wake turbulence characteristics and behavior

3.1 Cross sectional area

Research by Rossow and Tinling [2] has shown that a cross sectional area can be defined that contains the hazardous wake vortex region. The cross sectional area is a function of the aircraft generating the wake vortex and the aircraft encountering the wake. Figure 3-1 shows an illustration of this area in 3 dimensions and Figure 3-2 shows the cross sectional area in 2 dimensions.

Figure 3-1. Wake vortex containment region.

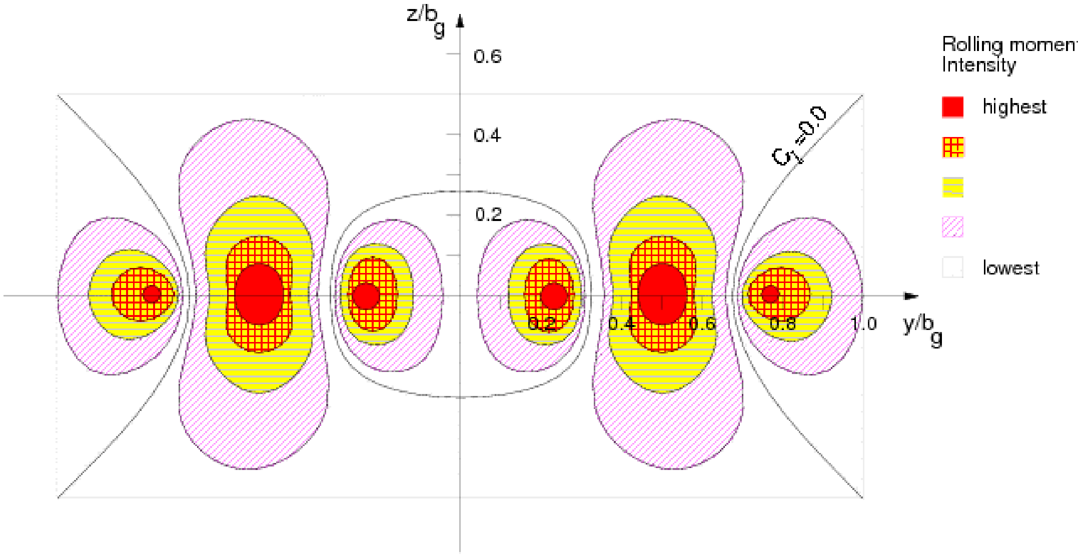


Figure 3-2. Two Dimensional Cross Section Area of Wake Vortex with Constant Rolling Moment Coefficient Contours.

The wake vortex center-to-center distance is estimated in references [3] [4] to be,

$$b' = \frac{\pi}{4} b_g \qquad 3.1$$

where b_g is the wing span of the generating aircraft.

3.2 Wake vortex vertical movement

Wake vortices generated by aircraft have a tendency to sink when not affected by atmospheric conditions. Conditions that might make a wake vortex rise or remain at the generated level instead of sinking include atmospheric stratification, wind shear, non-linear cross wind, thermal convection, and ground interaction when at low altitude [5][6].

When undisturbed by atmospheric conditions and generated by an aircraft at level flight, a wake vortex will sink at an approximate rate given by,

$$w = -\frac{W}{2\pi \rho V_\infty b'^2} \qquad 3.2$$

where,
W is the weight of the wake generating aircraft,
ρ is air density,
V_∞ is air speed of the wake generating aircraft, and
b' is wake vortices center-to-center distance.

3.3 Wake vortex horizontal movement

The motion of the wake vortex on the horizontal plane is determined by the crosswind and the ground effect. At cruising altitude, there will be no ground effect and only the cross wind will have an effect. The distribution of the cross wind is obtained from data in Reference [7] which was recorded in the North Atlantic in May, June and July 2007, at latitude 50 degrees north and longitude 60 degrees west. Only winds between 20,000 and 42,000 feet are considered. For the crosswind calculations and generation of distributions, 4,372 data points are used.

In many oceanic operations, routes are set to follow the prevailing winds. Therefore, the aircraft routes will follow the general wind direction and the routes will have the same heading at all flight levels. In order to determine what the prevailing winds are, the wind direction at a reference altitude is taken as the reference direction.

Example: The reference altitude is selected to be 30,000 feet. The wind direction at 30,000 feet is 86 degrees. The aircraft is assumed to be flying with an 86 degree heading at all altitudes. At 31,000 feet, the wind direction and magnitude are 97 degrees and 53 knots, respectively. The cross wind at 31,000 feet is 10.11 knots. The geometry of this example is shown in Figure 3-3.

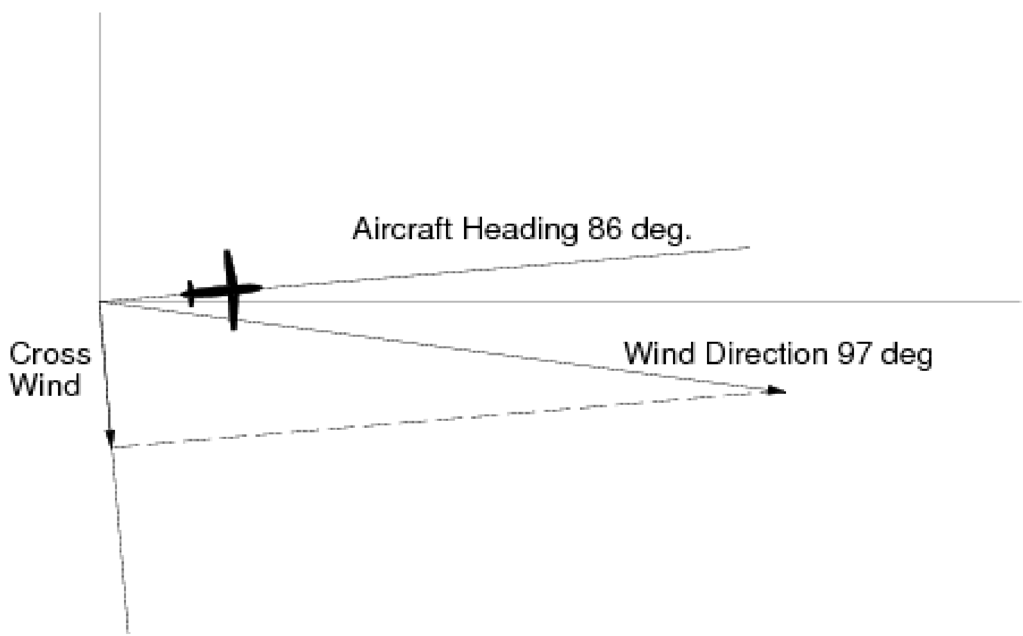


Figure 3-3. Example of calculation of crosswind.

Figure 3-4 shows the distribution of cross wind when the reference wind direction is taken at 35,000 feet. The largest cross wind magnitude, for 35,000 feet as reference, is 38.63 knots.

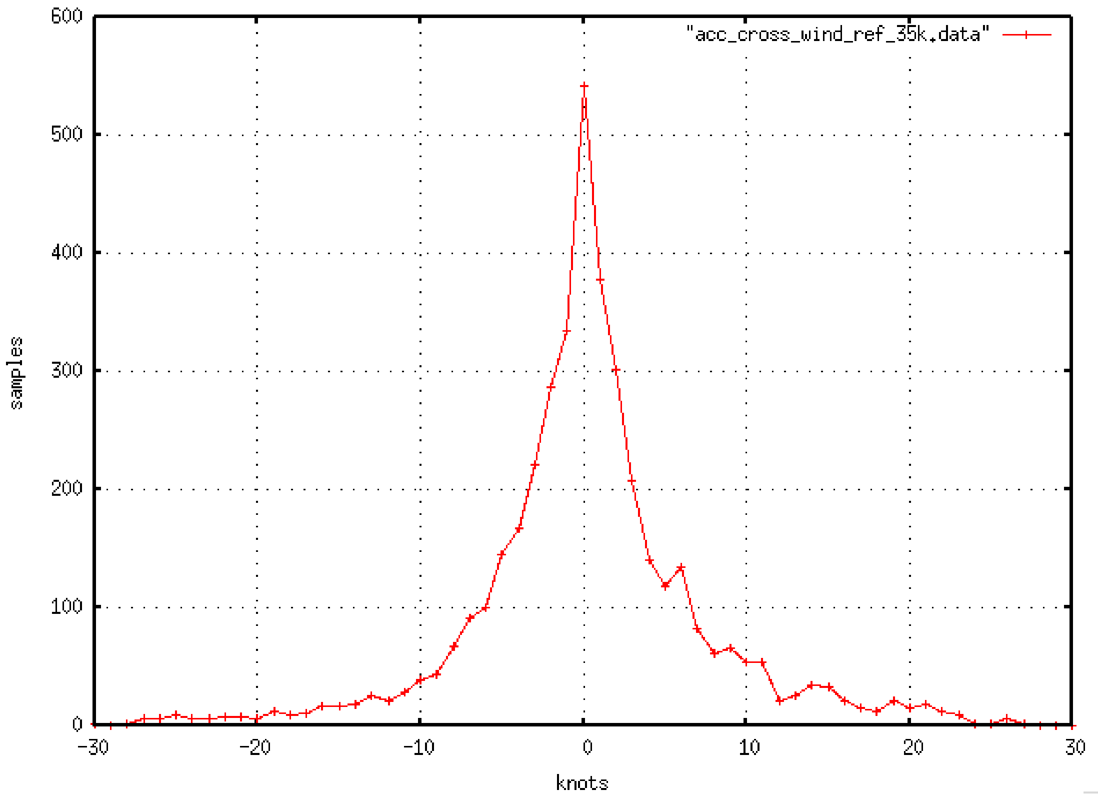


Figure 3-4. Cross wind distribution, 35,000 feet reference altitude for aircraft heading.

4 Probability of encounter

The probability that the trailing aircraft encounters the wake of the leading aircraft is a function of the path of the leading aircraft, the path of the trailing aircraft, and the crosswind. It is assumed that the PTM and designated aircraft are following the same identical track as defined in Reference [8]. The difference between the track and the aircraft flight paths is determined by the position error and the flight technical error. Figure 4-1 is an illustration of the flight paths of the aircraft and the distributions of position and crosswinds.

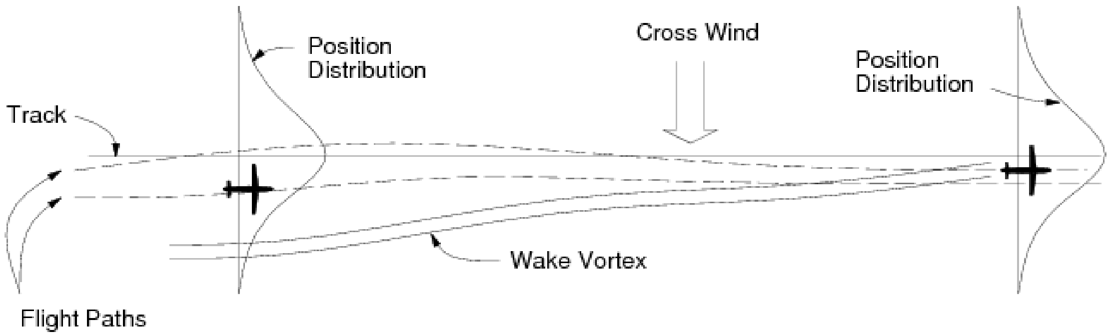


Figure 4-1. Example position distributions, flight paths, crosswind and wake vortex horizontal drift for two in-trail aircraft.

The probability of a horizontal wake vortex encounter is calculated using the navigation distributions of the aircraft and the crosswind distribution. The position error distribution and flight technical error distribution are assumed to be Gaussian (Normal) with equation,

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-x^2}{2\sigma^2}} \qquad 4.1$$

with zero mean and standard deviation σ.

The navigation error distributions are the sum of the position error and the flight technical error distribution. The value for flight technical error is taken assuming oceanic operations and using autopilot. The standard deviations for the position error and flight technical error for the leading and trailing aircraft are obtained from References [19] and [20] respectively and are:

$$\sigma_{p1} = \sigma_{p2} = 0.2551 \text{ NM} \qquad 4.2$$

$$\sigma_{fte1} = \sigma_{fte2} = 0.1276 \text{ NM} \qquad 4.3$$

The distribution for the cross wind is based on the wind data as described in Section 3.3, using as direction reference the wind at 35,000 feet. This distribution, Figure 3-4, is used because it will give the most conservative results (worst case). The distribution for the cross wind is assumed to be Gaussian with zero mean and standard deviation,

$$\sigma_w = 4.5 \text{ knots} \qquad 4.4$$

The crosswind distribution is normalized to distance by assuming an aircraft speed of 0.82 Mach and a distance of 6.5 nautical miles. The crosswind distribution in terms of distance has then a standard deviation of,

$$\sigma_{wd}=0.06187 \quad \text{NM} \tag{4.5}$$

The standard deviation of the sum of the distributions is,

$$\sigma_{wv}=\sqrt{\sigma_{p1}^2+\sigma_{p2}^2+\sigma_{fte1}^2+\sigma_{fte2}^2+\sigma_{wd}^2} \tag{4.6}$$

Using the values shown in equations 4.2, 4.3, and 4.5 into equation 4.6 we obtain

$$\sigma_{wv}=0.4081 \quad \text{NM} \tag{4.7}$$

The probability of the trailing aircraft encountering the leading aircraft wake during an ITP operation is given by,

$$P(wv) \; = \; \int_{-b_g}^{b_g} \frac{1}{\sigma_{wv}\sqrt{2\pi}} e^{\frac{-x^2}{2\sigma_{wv}^2}} \tag{4.8}$$

Using a wing span b_g of 200 feet and the standard deviation from Equation 4.7 we obtain,

$$P(wv)=6.43\times10^{-2} \tag{4.9}$$

The probability calculation indicates that for an aircraft climbing through the flight level of a leading aircraft, on identical same tracks, approximately at a distance of 6.5 nautical miles, and with tracks following the prevailing winds, it will encounter the wake vortex 6.4 out of 100 climbs.

5 Wake turbulence encounter data

Several organizations monitor wake turbulence encounters. NASA’s Aviation Safety Reporting System collects voluntary reports from flight crews, cabin crews, airline dispatchers, air traffic controllers, and maintenance personnel. These reports include wake turbulence encounters. The North Atlantic Central Monitoring Agency collects reports from flight crews and air traffic service providers related to incidents in oceanic operations.

In this section, two sets of data are examined regarding wake turbulence encounter at cruise level. Wake turbulence encounters in terminal areas and during arrival and departures are not considered because the Pair-wise Trajectory Management procedure is defined for cruise operations in oceanic airspace.

Data reported to NASA’s Aviation Safety Reporting System for domestic airspace during the year 2013 shows seven wake turbulence encounters at cruising flight levels. Table 5-1 shows a summary of the data.

Table 5-1. Reported Wake Turbulence Encounters in Domestic Airspace for year 2013.

Generating aircraft	FL	Encount. aircraft	FL	Distance NM	angle	Intensity	injuries	ac damage
A380	370	B757	360	2	45 deg	moderate	no	no
unknown	unknown	B737-8	380	unknown	ukn	unrep.	unrep.	unrep.
A380	400	B737-7	390	20	~90 deg	moderate	no	no
A380	400	B737-7	390	15	~45 deg	moderate	no	no
B747	320	MD-11	310	unrep.	0	unrep.	unrep.	unrep.
Airbus	340	A321	340	15	0	unrep.	unrep.	unrep
A330	390	B757	390	10	0	light	no	no

unrep. = unreported

Of the seven encounters shown in Table 5-1, two encounters occurred at the same flight level and five encounters occurred with the encountering aircraft one flight level below the generating aircraft. There were no reported injuries in any of the encounters and no reported aircraft damage. The intensity of the encounter reported by the flight crew was light to moderate or was not reported.

Data collected by the United Kingdom Civil Aviation Authority during the period 27th March 1997 to 16th December 1997 in oceanic airspace is shown in Table 5-2 [12]. This data was of particular interest because Reduced Vertical Separation Minima (RVSM) was introduced in oceanic airspace on 27th March 1997.

Table 5-2. Wake Turbulence Encounters in Oceanic Airspace.

Distance	**Date**	**Type of encounter**	**Trailing aircraft**	**Leading aircraft**	**Roll**	**Severity as reported by flight crew**
10 NM	1 APR 97	Trailing aircraft climbing	B767 climb to FL350	Unknown FL340	No	unreported
10 NM	3 SEP 97	Leading aircraft descending	B767 FL370	B777 descending through FL370	17 deg.	Lasted 1 to 2 seconds. Autopilot did not disengage. [Pilot reported roll of 30 deg. Flight data recorder shows 17 deg.]
15 NM	24 JUN 97	Leading aircraft one flight level above	B767 FL340	MD11 FL350	No	Light to occasional moderate turbulence. Fly 2 NM offset to avoid wake.
15 NM	7 SEP 97	Leading aircraft one flight level above	DC10 FL340	B767 FL350	No	Two hard “jolts” [Flight data recorder shows 0.1g jolts.]

16 NM	27 JUN 97	Leading aircraft one flight level above	B747 FL330	B747 FL340	No	Occasional severe turbulence. Requested climb to FL350.
16 NM	19 JUL 97	Leading aircraft one flight level above	B767 FL340	B747 FL350	No	Caught his wake briefly. Turned right and offset 3 NM and upwind.
17 NM	27 JUN 97	Leading aircraft one flight level above	B767 FL340	MD11 FL350	No	Flying conditions were smooth until there was a sudden onset of moderate turbulence.
20 NM	4 APR 97	Leading aircraft one flight level above	B747 FL340	B747 FL350	No	Experiencing severe turbulence due to the vortex wake of the B747 ahead, and had been for some considerable time.
20 NM	20 JUL 97	Leading aircraft one flight level above	B767 FL350	B747 FL360	No	Moderate turbulence encountered suddenly due to preceding B747.
20 NM	21 JUL 97	Leading aircraft one flight level above	B767 FL350	B747 FL360	No	Wake turbulence was experienced during cruise at FL350. 1 NM offset to left of track was flown to remain away from wake.
22 NM	9 SEP 97	Leading aircraft one flight level above	B747 FL330	B767 FL340	No	Sudden sharp chop – short duration. 1 NM right offset entered.
25 NM	27 JUN 97	Leading aircraft one flight level above	B767 FL350	B747 FL360	No	Difficulty with wake turbulence from aircraft above.
32 NM	7 JUL 97	Leading aircraft one flight level above	B767 FL330	B767 FL340	No	Light to moderate chop and requests higher FL. Unable to approve due to B767 4 min. ahead. [Woodfield's note: Very unlikely to get moderate turbulence from an aircraft 32 NM ahead, and pilot does not suggest wake turbulence.]
unknown	7 JUL 97	Leading aircraft one flight level above	B747 FL350	B747 FL360	No	Reported turbulence from traffic at 1000 ft separation. Aircraft was offered and accepted descent to FL340.

Table 5-2 contains 14 wake turbulence encounters. There were no encounters where the aircraft where at the same flight level. Two encounters occurred when the trailing aircraft was climbing or the leading aircraft was descending. Twelve encounters occurred with the encountering aircraft one flight level below the generating aircraft. There were no reported injuries for the 14 wake turbulence encounters.

6 Safety Management System severity classification

Severity is the consequence or impact of a hazard's effect or outcome in terms of degree of loss or harm. Severity is classified in the FAA ATO's Safety Management System (SMS) manual [11] in 5 levels. The severity is determined in accordance to effect on:

- ATC services
- Unmanned aircraft systems
- Flying public
- NAS (National Airspace System) equipment
- Flight crew

A wake turbulence encounter has the potential to affect the flying public and the flight crew. A sub-set of Table 3.3, Hazard Severity Classification, from the SMS manual is shown below, Table 6-1.

Table 6-1. Sub-set Hazard Severity Definitions.

	Hazard Severity Classification				
	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Flying public	Minimal injury or discomfort to persons on board	Physical discomfort to passenger(s) (e.g., extreme braking action, clear air turbulence causing unexpected movement of aircraft resulting in injuries to one or two passengers out of their seats) Minor injury to less than or equal to 10 percent of persons on board[1]	Physical distress to passengers (e.g., abrupt evasive action, severe turbulence causing unexpected aircraft movements) Minor injury to greater than 10 percent of persons on board	Serious injury to persons on board[2]	Fatal injuries to persons on board[3]
Flight Crew		Reduction of functional capability of aircraft, but overall safety not affected	Reduction in safety margin or functional capability of the aircraft,	Reduction in safety margin and functional capability of	Failure conditions that would prevent continued safe flight and

		(e.g., normal procedures as per Airplane Flight Manuals)	requiring crew to follow abnormal procedures as per Airplane Flight Manuals	the aircraft requiring crew to follow emergency procedures as per Airplane Flight Manuals	landing

- Minor Injury. Any injury that is neither fatal nor serious.
- Serious Injury. Any injury that:
    - Requires hospitalization for more than 48 hours, commencing within seven days from the date the injury was received;
    - Results in a fracture of any bone (except simple fractures of fingers, toes, or nose);
    - Causes severe hemorrhages, nerve, muscle, or tendon damage;
    - Involves any internal organ; or
    - Involves second or third-degree burns, or any burns affecting more than five percent of the body's surface.
- Fatal Injury. Any injury that results in death within 30 days of the accident.

Based on the data presented in Section 5 and the SMS classification shown in Table 6-1, the severity of a wake turbulence encounter during cruise could be assessed. The effect for flying public shows that Minimal is "Minimal injury or discomfort to persons on board." Minor severity is defined as "Physical discomfort to passenger(s)
Minor injury to less than or equal to 10 percent of persons on board."

For the flight crew, Minor severity is "Reduction of functional capability of aircraft, but overall safety not affected (e.g., normal procedures as per Airplane Flight Manuals)"

The data of wake turbulence encounters shows no injury to persons on board. This will result in a severity classification of Minimal. There could be physical discomfort to passengers or reduction in functional capability of aircraft when the flight crew has to disengage the autopilot or the autopilot disengages on its own. This will fall on the category of Minor. Because a climb or descent at a distance of 6.5 nautical miles is possible during a PTM operation, a conservative classification of Minor severity could be considered a credible effect of this hazard.

The probability of a wake turbulence encounter during an in-trail climb or leading descent was calculated in Section 4, Equation 4.9, to be 6.43E-02, which corresponds to a likelihood of Frequent (A) per the SMS manual.
A wake turbulence encounter when aircraft are flying at the same flight level is expected to be significantly less likely than when an aircraft is climbing or descending to the flight level of another aircraft. In Reference [5], Zak and Rodgers describe the atmospheric conditions needed for the wake vortex to rise

or remain at the same flight level as the generating aircraft. These conditions are described in detail in the reference, but are more likely to occur under the conditions that were present during the flight tests and at the altitude (2,500 to 7,300 feet) where the flight tests were conducted. The probability of a wake turbulence encounter at the same flight level is estimated in the range of 1E-05 to 1E-03.

The probabilities of the encounters together with the severity classifications are used to assess the safety risk of the hazards. The risk assessments of the hazards are shown in the risk matrix, Figure 6-1.

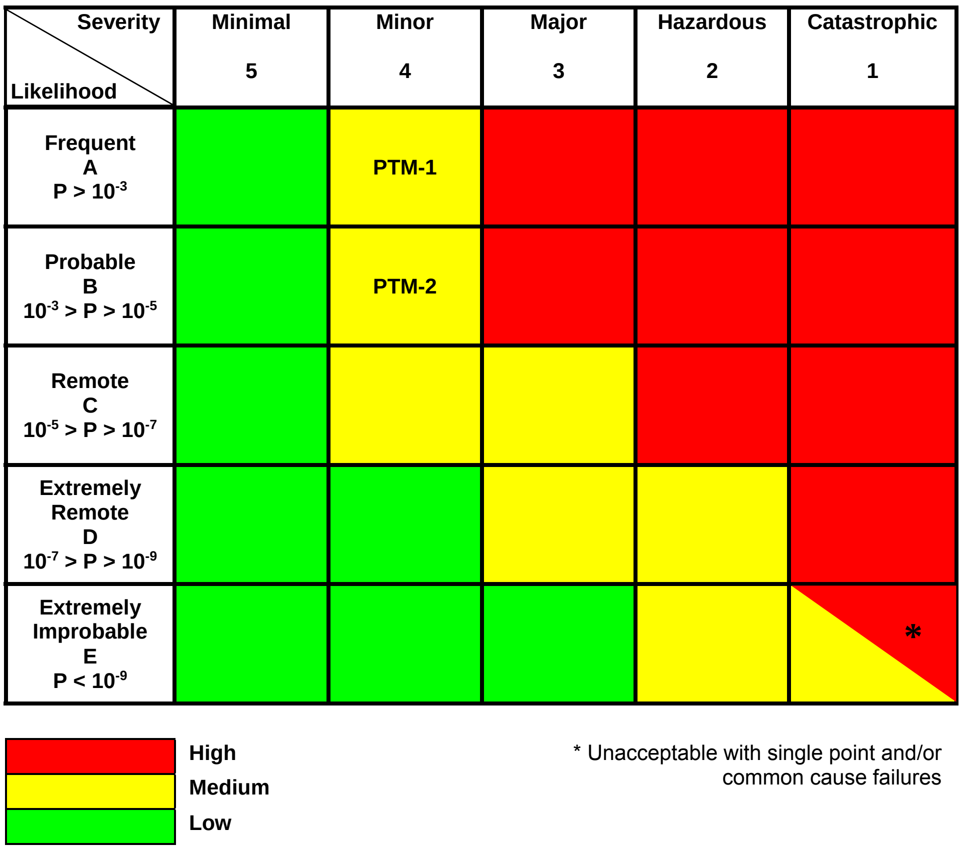


Figure 6-1. Risk matrix.

7 Mitigations

In Section 6, the hazards of wake turbulence encounters were assessed to have a safety risk of 4A, Medium and 4B, Medium for hazards PTM-1 and PTM-2, respectively. Although a Medium safety risk is an acceptable level of risk, with some implementation restrictions, it is desirable to mitigate these risks further to a possible Low safety risk. This section proposes a mitigation that can be implemented when PTM operations are in place.

A PTM equipped aircraft contains equipment that receives ADS-B signals from surrounding aircraft and specifically from the designated aircraft from which it should maintain spacing. The ADS-B information could be used to implement a lateral offset that will reduce the probability of a wake turbulence encounter. A procedure called the Strategic Lateral Offset Procedure (SLOP) [13] permits an aircraft in oceanic operations to fly an offset track of 1 or 2 nautical miles to the right of the centerline. The SLOP can be implemented at the discretion of the flight crew without the need to request a clearance from air traffic control.

Three wind conditions affecting the probability of a wake turbulence encounter could be defined while an aircraft is flying on a given track:

1. There is a crosswind component to the left of the track direction,
2. There is a zero or near zero crosswind component,
3. There is a crosswind component to the right of the rack direction.

Figure 7-1 shows graphically condition 1, where there is a crosswind component to the left of the direction of the track.

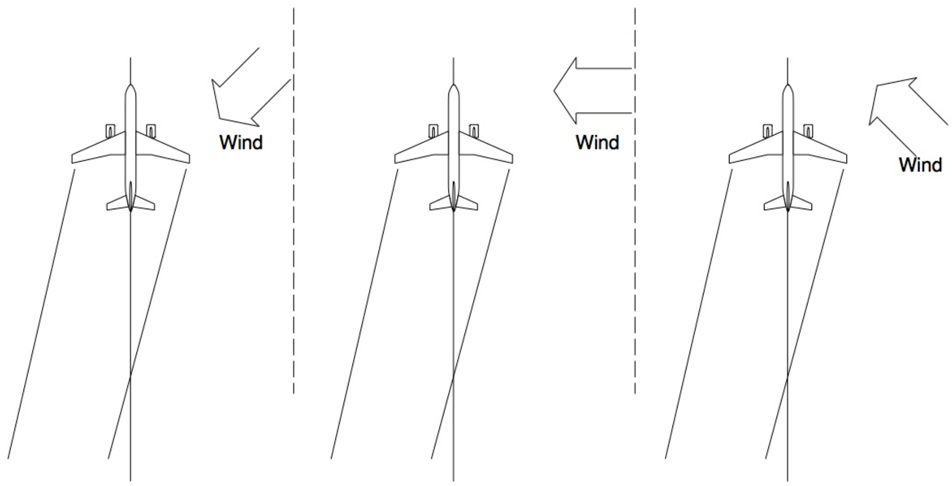


Figure 7-1. Left crosswind component.

Figure 7-2 shows condition 2, where there is a zero or near zero crosswind component.

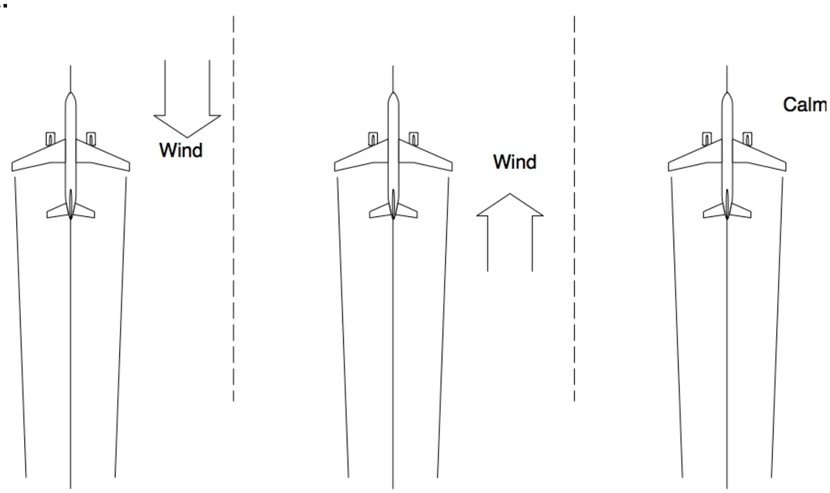


Figure 7-2. Zero or near zero crosswind component.

Figure 7-3 shows condition 3, where there is a crosswind component to the right of the direction of the track.

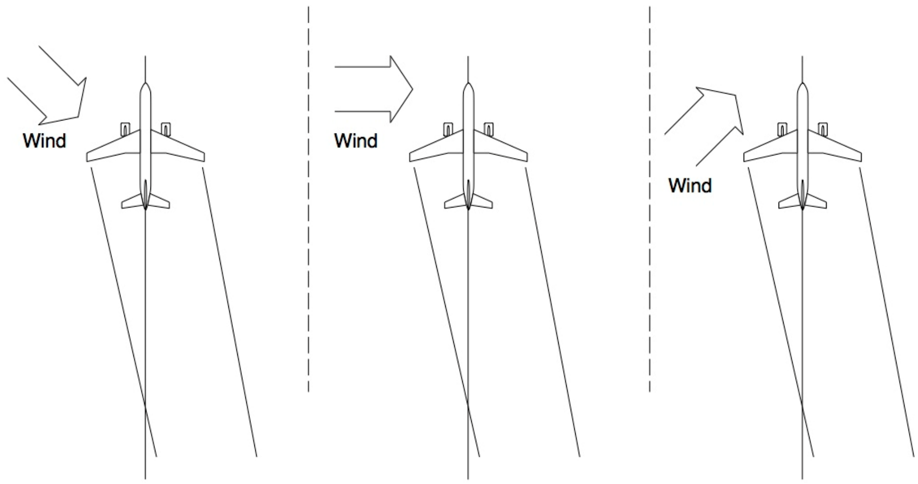


Figure 7-3. Right crosswind component.

The PTM aircraft could calculate the crosswind component for the direction of flight of the designated aircraft and the ownship. Depending on the magnitude of the crosswind component and the distance between the designated and PTM aircraft, the decision could be made to offset to the right or not offset.

As an example, let the distance between the leading and trailing aircraft be 6.5 nautical miles. A 2.4 knots cross wind will move the wake vortices of the leading aircraft by 200 feet laterally at the location of the trailing aircraft. To account for position error and to insure that the trailing aircraft misses the wake turbulence, a crosswind component threshold could be set to approximately 15 knots.

The offset rule will be:

- If left crosswind component or right crosswind component equal to or greater than 15 knots, remain centerline.
- If crosswind component less than 15 knots, offset 1 nautical mile to the right.

Figure 7-4 illustrates the offset rule to avoid the wake turbulence during PTM operations.

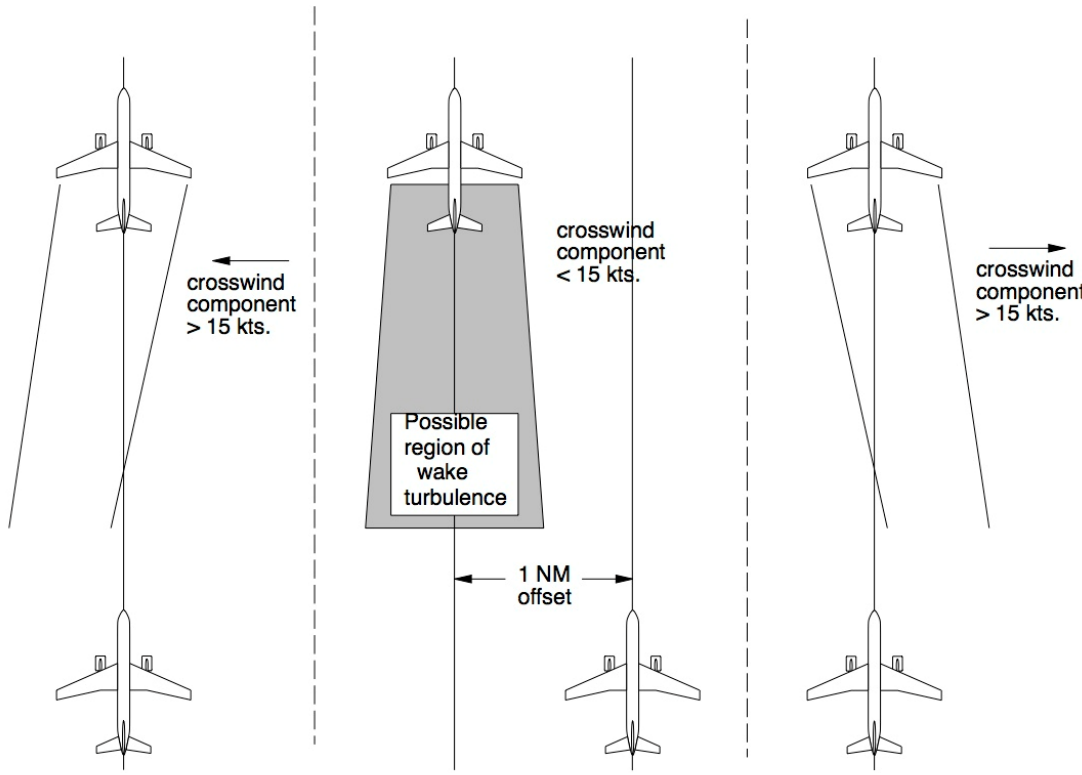


Figure 7-4. Rule illustration to avoid wake turbulence.

The rule could be implemented when a PTM aircraft receives a PTM clearance and the PTM automation on-board the aircraft advises the flight crew of the need to offset or to remain centerline.

8 Conclusion

Two hazards have been identified relating to wake turbulence encounters during PTM operations. These hazards are: PTM-1. Designated or PTM aircraft encounters wake turbulence during a climb or descent maneuver. PTM-2. Designated or PTM aircraft encounter wake turbulence while conducting PTM operations at the same flight level

The hazards have been assessed to have a Medium safety risk following the classifications and risk matrix of the FAA ATO's Safety Management System. These hazards could be further mitigated by the use of the Strategically Lateral Offset Procedure. The PTM automation could inform the flight crew of the need to remain on the track centerline or offset 1 nautical mile to the right. Implementation of this mitigation could significantly reduce the likelihood of the effects of the hazards and potentially reduce the safety risk from Medium to Low.

9 References

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Appendix F: Pairwise Trajectory Management (PTM) Initial Safety Requirements

Victor Carreño
Version 1
31 December 2016

1 Introduction

The safety requirements presented in this paper are derived from the Pairwise Trajectory Management (PTM) operational safety assessment. They typically form part of a Safety and Performance Requirements (SPR) document.

2 Safety Requirements (SR)

SR.1. The PTM airborne equipment shall provide a guidance to the flight crew that indicates whether a climb or descend should be performed with a lateral offset to mitigate the risk of a wake turbulence encounter during the climb or descent.

SR.2. The PTM separation standard minimum shall be equal to or greater than the wake turbulence application minimums as defined in Federal Aviation Administration (FAA) JO 7110.65, Section 5-5-4 paragraph f.

SR.3. When along-track distance is less than the minimum spacing required at the time of a clearance, the PTM equipment shall advise the flight crew to reject the PTM clearance.

SR.4. The PTM airborne equipment shall not allow the flight crew to accept a clearance that has been determined to be invalid. Only “Unable” should be permitted for an invalid clearance.

SR.5. A traffic display shall be part of the PTM equipment in the cockpit, which allows the flight crew to see the location of the designated aircraft.

SR.6. Flight crew shall be trained in the use and operation of the PTM equipment.

SR.7. ATC shall be trained in PTM operations.

SR.8. Flight crew shall contact ATC when they are no longer able to maintain PTM separation.

SR.9. Flight crew shall attempt to contact designated aircraft via VHF radio when unable to maintain PTM separation.

SR.10. Flight crew shall use the Strategic Lateral Offset Procedure when in their judgment, doing so will increase safety margins and reduce the risk of collision.

SR.11. When dealing with an emergency, the flight crew of the PTM aircraft shall implement contingency procedures as specified in International Civil Aviation Organization (ICAO) Procedures for Air Navigation Services – Air Traffic Management (PANS-ATM) Document 4444.

SR.12. When dealing with non-nominal conditions, the flight crew of the PTM aircraft shall use the PTM traffic display to the maximum extent possible to gain situational awareness and prevent a potential near mid-air collision or collision.

SR.13. In the event of a PTM equipment failure, the flight crew shall maintain the last speed guidance provided by the PTM equipment.

SR.14. The PTM equipment shall provide conflict detection and alerting independent of the speed guidance function.

3 Discussion of Safety Requirements

SR.1. The operations that present the highest risk are operations where an aircraft climbs behind a leading aircraft or when an aircraft descends in front of a trailing aircraft. A mitigation strategy to reduce the risk of a wake turbulence encounter could be used. The mitigation strategy is based on using ICAO PANS-ATM Doc. 4444 Strategic Lateral Offset Procedure (SLOP). This procedure allows an aircraft to offset to the right of center line by one or two nautical miles (NM), at the flight crew's discretion, without having to request or obtain approval from air traffic control (ATC). Depending on the cross wind component, the aircraft will fly the track center line or an offset. An example of the offset rule is:

- If there is a left crosswind component or a right crosswind component that is equal to or greater than 15 knots (kts), remain centerline.
- If there is a crosswind component of less than 15 kts, offset 1 NM to the right.

Figure 1-1 illustrates the offset rule to avoid the wake turbulence during PTM operations.

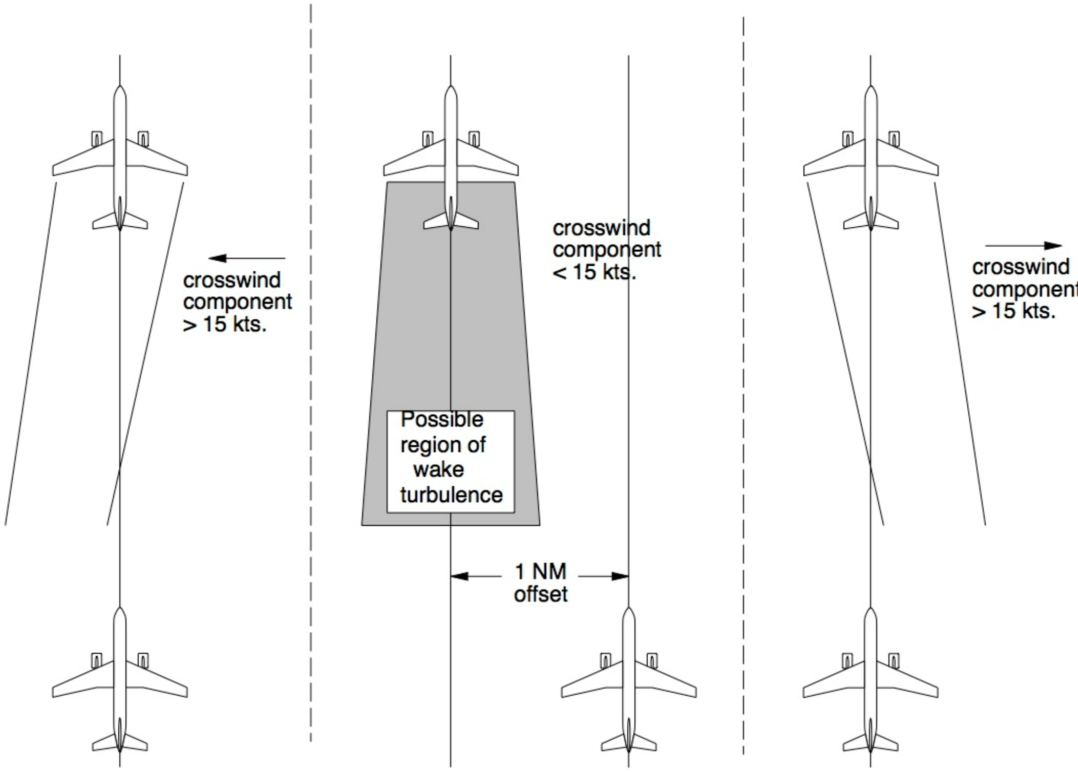


Figure 1-1. Rule illustration to avoid wake turbulence.

The rule could be implemented when a PTM aircraft receives a PTM clearance and the PTM automation on-board the aircraft advises the flight crew of the need to offset or to remain centerline.

SR.2. FAA Order JO 7110.65, Section 5-5-4 paragraph f defines wake turbulence minimum distances between aircraft operating in-trail at the same flight level and where radar separation is being applied. There are no wake turbulence rules or guidelines for ocean operations. The smallest oceanic separation standard in-trail is currently 30 NM. This oceanic separation standard minimum is significantly larger than the wake turbulence minimum specified in JO 7110.65. Any separation standard that defines a smaller separation standard minimum than currently exists should be limited to distances as specified in JO 7110.65 for wake turbulence mitigation.

SR.3. The PTM airborne equipment has an accurate position report from the potentially designated aircraft. The PTM airborne equipment also has an accurate position of the ownship. From these position reports, an accurate determination of the distance between the PTM and designated aircraft can be made. The ground automation and controller have a less accurate estimation of the distance between the aircraft. Therefore, the PTM airborne automation should make the determination if the distance between the aircraft meet the PTM operational requirements and should notify the flight crew that the clearance should not be accepted if the distance is less than the required spacing. See also safety requirement SR.4.

SR.4. Human-in-the-Loop testing conducted at NASA Langley showed that there were several instances of events where the PTM airborne automation determined that the flight crew should reply “Unable.” However, the flight crew selected the “accept” button of the system interface. There was confusion amongst the participants where they thought that “accept” meant that they were accepting the “Unable” guidance. However, this meant that the flight crew was accepting the PTM clearance when the operation did not meet the PTM operational requirements.
Accepting a clearance that does not meet the PTM operations requirements could have severe consequences. For example, if the along-track distance between the aircraft is less than the separation standard minimum and the flight crew accepts the clearance, the controller could clear the PTM aircraft to climb or descend to the flight level of the designated aircraft, and a loss of separation will result.

SR.5. A traffic display will provide situational awareness to the flight crew. Situational awareness will allow the flight crew to deal with non-nominal conditions and contingency procedures enhancing safety. Instances of non-nominal conditions that will benefit from a traffic display include:

- Erroneous speed guidance produced by the PTM equipment
- Lateral deviation of the designated aircraft from its intended trajectory
- Implementation of contingency procedures by PTM aircraft due to emergency
- Weather deviation by the designated aircraft
- Weather deviation by the PTM aircraft
- Change in speed of the designated aircraft to a non-assigned speed

SR.6. Training in the operations of the PTM equipment and interface will minimize potential human errors when implementing the PTM separation standard. The flight crew should be trained in the Controller Pilot Data Link Communication (CPDLC) data set used for PTM operations, receiving PTM clearances, responding to PTM clearances, and terminating PTM operations. The flight crew should also have knowledge of how the PTM equipment determines speed guidance to reduce possible unexpected situations.

SR.7. Training in the utilization of the PTM separation standard and the Advanced Technologies & Oceanic Procedures (ATOP) ground automation interface will minimize potential human errors. Controllers should be trained in the efficient use of the PTM separation standard to maximize its benefit. Controllers should be trained in the CPDLC data set used for PTM operations, formulating PTM clearances, terminating PTM clearances, and in the handling of non-nominal conditions.

SR.8. There are non-nominal conditions when a PTM aircraft, which is maintaining separation from one or more designated aircraft, can no longer maintain separation. Examples of these conditions are: A designated aircraft ahead of a PTM aircraft slows down to a speed that makes it impossible for the

PTM aircraft to receive and implement a valid speed guidance to maintain separation. The speed needed to maintain separation could be below the PTM aircraft minimum operational speed. The PTM equipment on-board will give the minimum operational speed as guidance to maintain the largest possible distance from the designated aircraft. The flight crew of the PTM aircraft should contact ATC to inform of the situation and ATC will provide an alternate means of separation.

SR.9. Depending on the nature of the non-nominal condition, the urgency, and severity, the flight crew could inform and coordinate with designated aircraft in proximity that might represent a threat of near mid-air collision or collision. The flight crew could use the emergency communication frequency (VHF 121.5 MHz) or the air to air communication frequencies (VHF 122.75 MHz).

SR.10. The Strategic Lateral Offset Procedure will allow the flight crew to establish a lateral distance between the PTM aircraft and the designated aircraft while communicating with ATC to establish alternate means of separation.

SR.11. Contingency procedures for oceanic operations are defined in the International Civil Aviation Organization, Procedures for Air Navigation Services, Air Traffic Management, Document 4444, Chapter 15. These include:

- Unlawful interference and aircraft bomb threat
- Emergency descent
- General contingency (medical diversion, airport/airspace closure diversion, mechanical)
- Weather deviation procedures
- Air-ground communications failure
- Strayed or unidentified aircraft
- Interception of civil aircraft
- Fuel dumping
- Fuel emergency and minimum fuel
- Procedures for volcanic ash cloud

Contingencies during PTM operations should be handled in the same manner as other separation standards.

SR.12. The PTM traffic display provides an additional tool that the flight crew could use to have situational awareness of the environment. The flight crew will be able to know where traffic aircraft are, both designated and other traffic aircraft, and their direction of flight and altitude. The PTM traffic display will aid in both PTM contingency procedures and other non-PTM contingency procedures.

SR.13. The PTM speed guidance is determined as a function of the along-track distance. A PTM aircraft that is farther from the designated aircraft will be given guidance that allows for a higher closure rate. As a result, any speed guidance at a given time is at least 30 minutes (min) from a potential collision with the designated aircraft. As the along-track distance is reduced, the guidance is reissued such that the closure rate is reduced. For example, if the PTM aircraft is in-trail of the designated aircraft, the designated aircraft has a speed of 0.82 Mach, and the along-track distance is 14 NM, the guidance for the PTM aircraft is 0.77 to 0.85 Mach. The upper speed of the guidance of 0.85 Mach will produce a closure rate of approximately 17.3 kts. With this closure rate, it will take 31.2 min to lose separation and 48.6 min to have a potential collision. As the PTM aircraft gets closer to the designated aircraft, the guidance upper speed and the closure is reduced. At approximately 6.7 NM from the designated aircraft, the speed guidance will be 0.77 to 0.83 Mach. The upper speed of the guidance of 0.83 Mach will produce a closure rate of approximately 5.8 kts. With this closure rate, it will take 17.6 min to a loss of separation and 69.3 min to a potential collision. By maintaining the last speed guidance given by PTM equipment before the failure, there will be at least 30 min before a potential collision exists. This assertion assumes that no other changes occur such as a change in the designated aircraft speed.

SR.14. The PTM equipment interface provides for indications when the flight crew is ignoring or not following the speed guidance. A conflict detection and alerting function will provide an additional layer of safety in cases of malfunctions or human errors.

Appendix G: Effect of Strategic Lateral Offset Procedure (SLOP) on Pairwise Trajectory Management (PTM) Along-Track Operations

Victor Carreño
v.1
3 Oct 2016

1 Introduction

Aircraft in oceanic operations can perform the Strategic Lateral Offset Procedure (SLOP) without contacting Air Traffic Control and requesting a clearance. The SLOP procedure allows aircraft to fly an offset route of 1 mile or 2 miles from the nominal route centerline.

This technical note discusses the effect that the SLOP procedure will have on PTM along-track operations. The effect of SLOP on PTM crossing operations has been previously analyzed and reported on a separate technical paper.

2 Worst-case scenario

A scenario is developed that is considered the worst-case scenario. In this scenario, there are two aircraft performing a PTM along-track operation with a 45-degree waypoint turn to the left and where the leading aircraft is offset to the right by 2 nautical miles. Figure 2-1 shows a diagram of the scenario geometry.

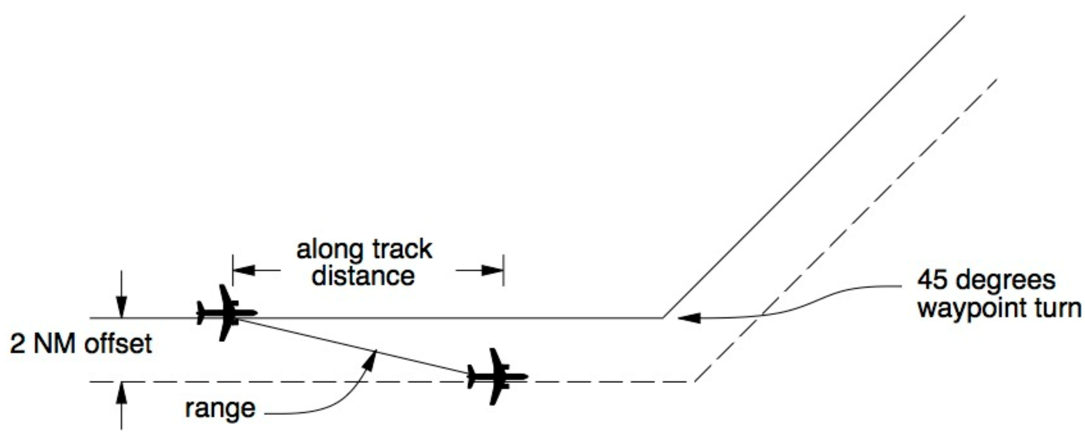


Figure 2-1. Scenario 1, turn to the left, leading aircraft offset to the right.

3 Effects on along-track distance and range

The effects of the 2 nautical miles offset are analyzed in this section. Figure 3-1 shows an expanded view of the waypoint turn.

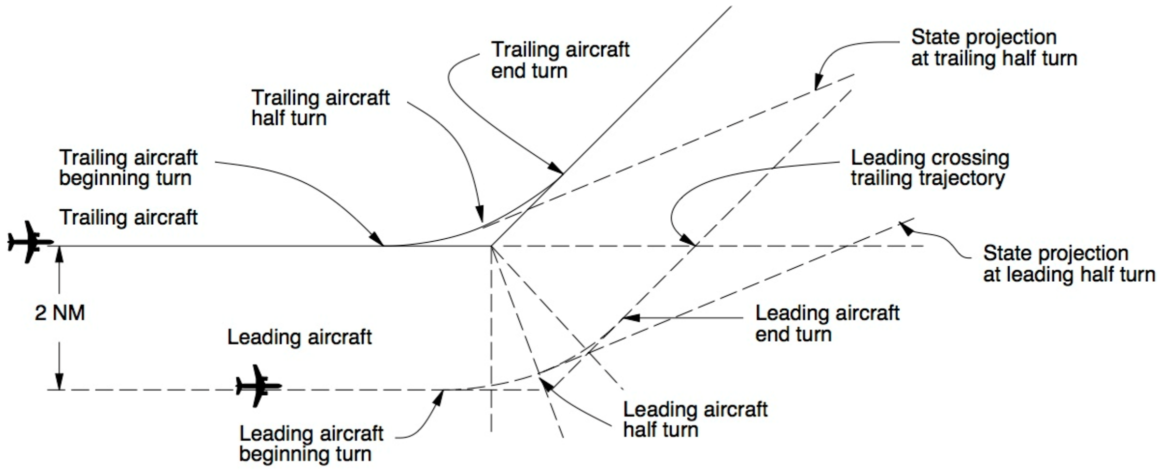


Figure 3-1. Points of calculations of along-track and rage distances.

The scenario assumes an initial along-track distance of 6.5 nautical miles and turns by the waypoint (not over the waypoint). Table 3-1 shows the along-track and range distance at different points in the operation. For the calculations of Table 3-1, it is assumed that the speeds of the aircraft remain constant.

Table 3-1. Distances at different points in the operation.

State	Along-Track, NM	Range, NM	Speed Guidance for trailing*
Before the turn	6.5	6.8	= Leading
Leading beginning turn	< 6.5	6.8	Reduce speed below leading
Leading half turn	6.165	6.45	Reduce speed below leading
Leading end of turn	5.853	6.30	Reduce speed below leading
Leading crossing trailing trajectory	5.828	5.828	Reduce speed below leading
Trailing beginning turn	< 5.828	5.49	Reduce speed below leading
Trailing half turn	5.242	5.29	Reduce speed below leading
Trailing end of turn	4.969	5.36	Reduce speed below leading

*Note: if the PTM aircraft is the leading aircraft, the leading aircraft will get a speed guidance to increase its speed to maintain spacing.

The along-track distance gets reduced from 6.5 nautical miles to 4.969 nautical miles with the assumption that the trailing aircraft ignores the speed guidance to slow down. The minimum range is 5.29 nautical miles, which occurs at the time that the trailing aircraft is halfway through its turn at the waypoint.

The trailing aircraft will get a speed guidance to slow down (assuming the trailing aircraft is the PTM aircraft) when the leading aircraft starts its turn. If the trailing aircraft were to implement the speed guidance immediately, the along-track and the range will increase by approximately 0.2 nautical miles at the time the trailing aircraft finishes its turn, to 5.169 and 5.56 nautical miles, respectively. The aircraft will continue to get speed guidance until the spacing is re-established.

4 Summary and conclusion

The case presented is considered worst-case because 45-degree turns in the oceanic environment are rare or non-existent, the initial condition is with the minimum spacing, and the waypoint turn to the left and leading aircraft offset to the right produces the largest reduction in along-track distance and range. Waypoint turns in the ocean are typically around 3 to 5 degrees. In cases where the waypoint turn is in the order of 5 degrees, the SLOP and turn will have a negligible effect.

Another possible consideration is if the leading aircraft returns to the course centerline immediately after turning at the waypoint. In that case, the range will be reduced to the same as the along-track distance, and the along-track distance will be reduced to approximately 4.5 nautical miles.

From the safety point of view, a reduction in along-track distance and range to 4.5 nautical miles will be a loss of separation. The severity of a loss of separation is evaluated based on the separation standard minimum and other criteria as outlined in the FAA’s safety management system. For the loss of separation presented in sections 2 and 3 of this paper, the loss of separation, as rated in the safety management system manual, will be Minimal.

Appendix H: Description of the airborne Pairwise Trajectory Management (PTM) algorithm

Victor Carreño
Version 1
31 December 2016

1 Introduction

Pairwise Trajectory Management (PTM) is a cockpit-based operation where the controller clears an aircraft to maintain spacing from one or more designated aircraft. On-board PTM tools will aid the flight crew in implementing the PTM spacing. The tools are expected to consist of a traffic display, decision support to accept or reject a PTM clearance, speed guidance to maintain spacing, conflict detection and alerting logic, Automatic Dependent Surveillance-Broadcast (ADS-B) in capabilities, and Controller-Pilot Data Link Communications (CPDLC).

There are two types of PTM operations:

1. One-dimensional in-trail where the PTM aircraft maintains spacing from an aircraft in front and/or behind that is flying the same route as the PTM aircraft,

2. Two-dimensional where the PTM aircraft maintains spacing from crossing or merging aircraft.

This paper describes the algorithm that implements the PTM functionality on-board a PTM aircraft. The PTM algorithm is a collection of algorithms and functions. There are three main PTM algorithms:

1. PTM executive
2. PTM along-track
3. PTM intent

The PTM executive is the interphase between the airborne functionality and the other elements of the PTM operation.

2 PTM executive

The PTM executive performs the following functions:

- Receives PTM clearances from the controller (ground automation) and determines if the clearance and system state meet the PTM operational requirements. If the operational requirements are met, the flight crew receives speed guidance and can accept the clearance. If the operational requirements are not met, the flight crew receives an advisory to reject the clearance
- Accepts a clearance
- Rejects a clearance
- Receives PTM clearances from the controller to add additional designated aircraft to an existing PTM operation
- Continuously provides speed guidance to an existing PTM operation
- Terminates a PTM operation for a given aircraft
- Terminates all PTM operations
- Detects projected losses of spacing and/or separation
- Alerts the flight crew when a projected loss of spacing and/or separation is within some time horizon

2.1 Clearance function

The clearance function receives clearances from the controllers and give guidance to the flight crew. There are five types of PTM operations and five types of PTM clearances:

1. PTM aircraft ahead of designated aircraft, same route. Maintain spacing from designated aircraft in-trail
2. PTM aircraft behind designated aircraft, same route. Maintain spacing from designated aircraft leading
3. PTM aircraft crossing track of designated aircraft. PTM algorithm determines if PTM aircraft will cross in front or behind designated aircraft
4. PTM aircraft merge ahead of designated aircraft
5. PTM aircraft merge behind of designated aircraft

The clearance function can receive PTM clearance for one or more designated aircraft. When the clearance function receives a clearance, it performs a series of checks, for each designated aircraft in the clearance, to determine if the clearance meets the PTM operational requirements.

2.1.1 Order

For clearances of type 1, 2, 4, and 5, the clearance specifies whether the PTM aircraft will be in front or behind the designated aircraft. For example, a clearance of type 5 instructs the PTM aircraft to merge behind the designated aircraft. For clearances of type 3, the clearance function makes the determination.

For clearances of type 1 and 2, the clearance function checks if the order of the clearance matches the actual geometry of the PTM and designated aircraft. The clearance function uses a distance and order function to make the determination. The distance and order function is described in Section 4. If the order of the clearance does not match the actual order of the aircraft for clearances of types 1 and 2, the clearance is invalid and the clearance function returns unable PTM.

For clearances of type 3, the clearance function determines whether the PTM aircraft is going to pass in front or behind the designated aircraft. The current position, the next and next-plus-one waypoints and the estimated times of arrival (ETA) at waypoints are used to make the determination. Crossing behind is the preferred operation with a system configurable bias parameter. For example, if using the ETAs (ground speeds) the PTM aircraft will cross in front of the designated aircraft by 2 NM or less, the selection will be to cross behind. If using the ETAs (ground speeds) the PTM aircraft will cross more than 2 NM in front of the designated aircraft, the selection is to cross in front. In this example, the system configurable bias parameter is 2 NM. Note that if it is determined that with the ETAs (ground speeds) the PTM aircraft will cross in front by slightly more than 2 NM, the PTM aircraft will have to speed-up to achieve the needed spacing (in the order of 8.5 NM). Whether the PTM aircraft can speed-up sufficiently to achieve the spacing is determined by the speed guidance sub-function, Section 2.1.6.

2.1.2 Track angle

A restriction of PTM operations is that the angle between the aircraft tracks must be less than 45 degrees. At the time of a clearance, the clearance function checks that the angle between the tracks is less than 45 degrees. If the angle is 45 degrees or more, the function returns unable.

2.1.3 Existing along-track distance

Along-track distance is the one dimensional distance between two aircraft that are following the same route. Figure 2-1 shows an example of along-track distance between two aircraft.

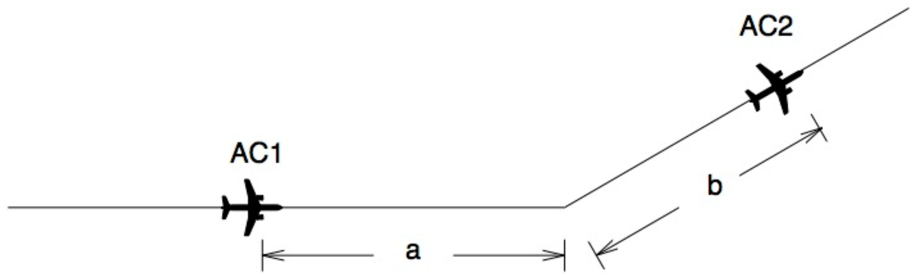


Figure 2-1. Example of along-track distance between aircraft.

The along-track distance between aircraft AC1 and AC2 is the sum of the distances “a” and “b”. How aircraft projections, intersecting points, and along-track distances are calculated is presented in the following sections. For clearances of type 1 and 2, the along-track distance between the PTM and designated aircraft at the time of the clearance must be greater than or equal to the PTM minimum spacing. If the along-track distance is less than the PTM minimum spacing, the clearance function returns unable PTM.

2.1.4 Existing range

Range is the two dimensional geometric horizontal distance between two aircraft. Figure 2-2 shows an example of horizontal range between two aircraft.

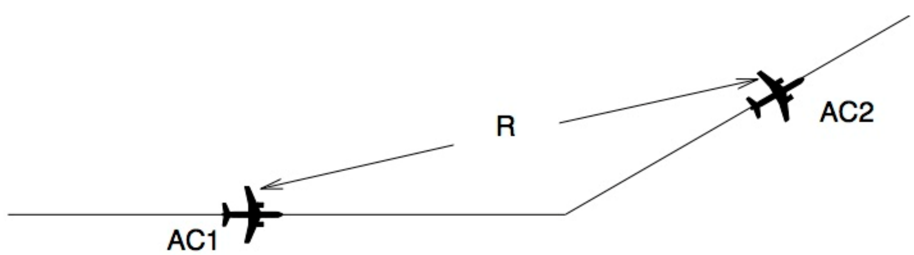


Figure 2-2. Example of range between aircraft.

For clearances of type 3, 4 or 5, the range between aircraft at the time of the clearance must be greater than or equal to the PTM minimum spacing. If the range is less than the PTM minimum spacing, the clearance function returns unable PTM.

2.1.5 Type of algorithm

There are two types of algorithms used for the calculation of speed guidance:

1. The PTM along-track algorithm (Section 5),
2. The PTM intent algorithm (Section 6)

Which algorithm is used depends on the type of clearance, the geometry of the aircraft and if there are waypoints before the projected point of intersection. Figure 2-3 shows the selection logic used when a clearance is received.

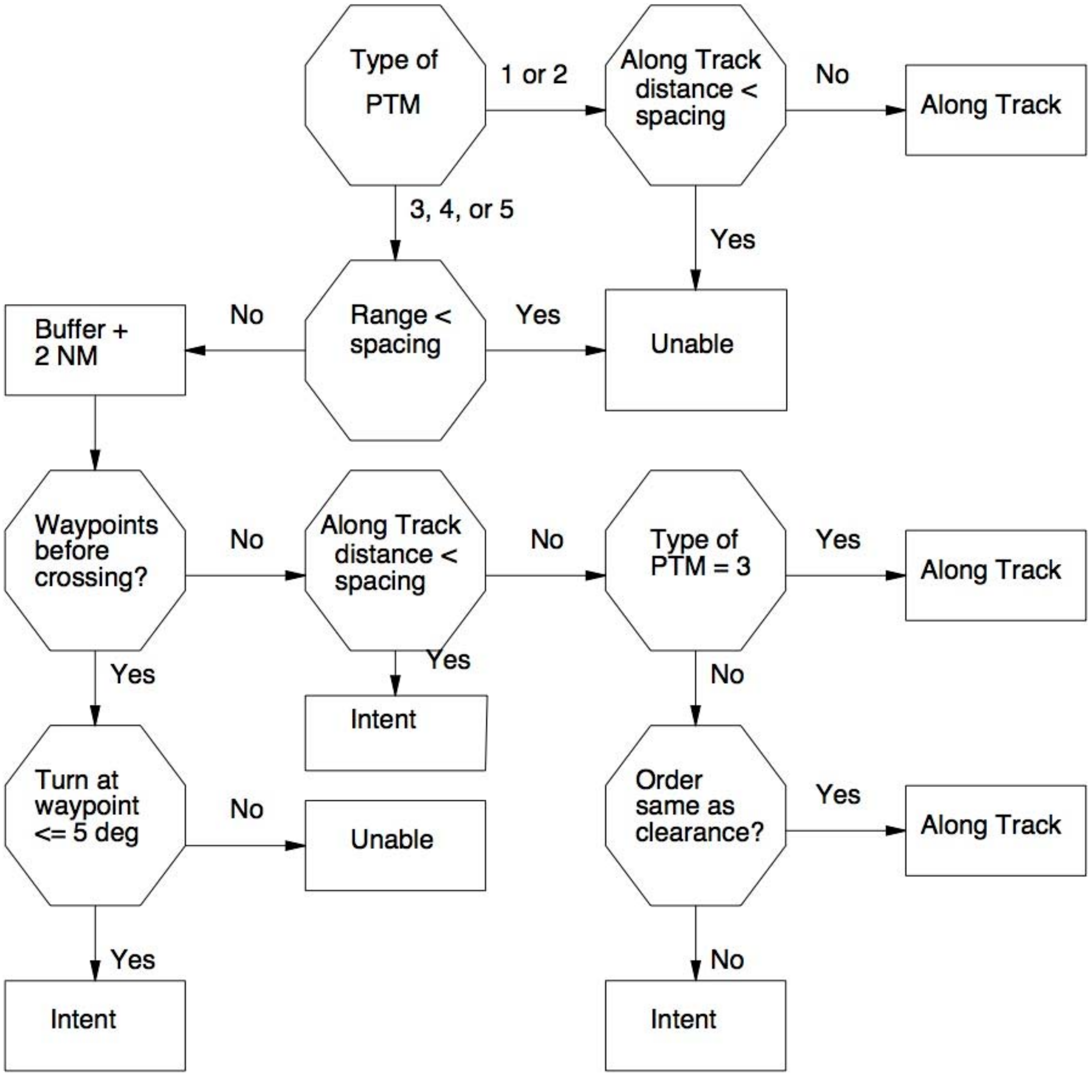


Figure 2-3. Logic to determine type of algorithm to use for speed guidance.

When the clearance is of type 3, 4, or 5, and there are waypoints before the projected crossing point, the clearance function checks if the turn at the waypoint has an angle of more than 5 degrees. A turn of more than 5 degrees will make the clearance invalid and the function will return unable.

2.1.6 Speed guidance

The clearance function uses the selected algorithm (along-track or intent) to calculate a speed guidance for each designated aircraft in the PTM clearance. The clearance function uses the conjunction of each designated aircraft speed guidance to calculate the overall speed guidance. The following equations are used:

Lower Guidance = Maximum(desig1(lower), desig2(lower), … desigN(lower))   (2-1)

Upper Guidance = Minimum(desig1(upper), desig2(upper), … desigN(upper))   (2-2)

where,

desigN(lower) denotes the lower speed guidance of the Nth designated aircraft in the clearance, and
desigN(upper) denotes the upper speed guidance of the Nth designated aircraft in the clearance.

Table 2-1 contains an example of speed calculations with two designated aircraft, each aircraft's speed guidance, and the resulting speed guidance for the PTM aircraft.

Table 2-1. Example speed guidance.

	Lower speed guidance	Upper speed guidance
Designated aircraft 1	0.77 Mach	0.82 Mach
Designated aircraft 2	0.78 Mach	0.83 Mach
Resulting speed guidance	0.78 Mach	0.82 Mach

It is possible that the lower guidance be greater than the upper guidance, in which case there is no solution and the clearance function returns unable. Table 2-2 contains an example of speed calculations with 2 designated aircraft and no solution.

Table 2-2. Example of speed guidance calculations with no solution.

	Lower speed guidance	Upper speed guidance
Designated aircraft 1	0.82 Mach	0.87 Mach
Designated aircraft 2	0.78 Mach	0.81 Mach
Resulting speed guidance	0.82 Mach	0.81 Mach

For the example of Table 2-2, the clearance function will return unable and the flight crew will not see the invalid speed guidance. Once the flight crew receives a valid speed guidance from the clearance function, they must decide if the clearance is accepted or rejected.

2.2 Accept and reject functions

A clearance that produces a valid PTM operation and a valid speed guidance will create a "pending PTM" state in the system. The accept function converts the list of pending designated aircraft to designated aircraft and the state of the system becomes "operating PTM."

The reject function clears the list of pending designated aircraft and the state of the system is "no PTM operations."

2.3 Add function

The add function is used to add additional designated aircraft to an existing PTM operation. When the add function is invoked, the function performs the same checks as the clearance function on the new designated aircraft that are going to be added. It does not perform the checks on the existing aircraft that are already performing the PTM operation.

If the new designated aircraft are valid for PTM operations, the add function calculates a speed guidance including all the designated aircraft, the existing designated aircraft and the new designated aircraft. If the speed guidance is valid, the speed guidance is presented to the flight crew and the flight crew can accept or reject the clearance to add additional aircraft. If the speed guidance is not valid, the add function returns unable PTM for the addition of the new designated aircraft. However, the existing designated aircraft remain as active PTM designated aircraft and the PTM operation continues.

2.4 Operations function

The operations function is used to calculate speed guidance once a PTM operation is taking place. The operations function does not check for the validity of the operation. The operations function produces a speed guidance event when the angle between the tracks is 45 degrees or greater, the along-track distance or range is less than the required spacing or separation minimum, or when the conjunction of the solutions of each designate aircraft produces no valid solution. If the resulting lower speed guidance is greater than the upper speed guidance, the operations function will take the average of the lower and upper guidance rounded up to the nearest one hundredth of a Mach.

During a call to the operations function, if the resulting speed guidance is similar to the example shown in Section 2.1.6, Table 2-2, the operations function would take the average of 0.82 (lower guidance) and 0.81 (upper guidance). The average of 0.815 would be rounded up to 0.82 and the speed guidance to the flight crew will be a fix value of 0.82 Mach. This guidance will try to maintain spacing and separation as best as possible from all designated aircraft, even when a loss of spacing or separation has occurred.

2.5 Termination function

There are two termination functions that can be used to terminate a PTM clearance. The first function terminates a single PTM operation, using the designated aircraft's identifier, in a single or multiple PTM operation. The second function terminates all PTM clearances in a single or multiple PTM operation.

3 Geometric and dynamic calculations

The functions used to calculate ordering of aircraft pairs, along-track distance, range, Mach speed guidance, etc. perform the calculations in Cartesian coordinates. To utilize Cartesian coordinates, a mapping is performed from geodesic coordinates expressed in latitude and longitude into Cartesian coordinates.

3.1 Coordinates mapping

Geodesic coordinates are translated to Cartesian coordinates by mapping the latitude to the y-axis and the longitude to the x-axis. Figure 3-1 shows an example of two locations with aircraft ac1 at 44 degrees north, 43 degrees east and aircraft ac2 at 45 degrees north and 45 degrees east.

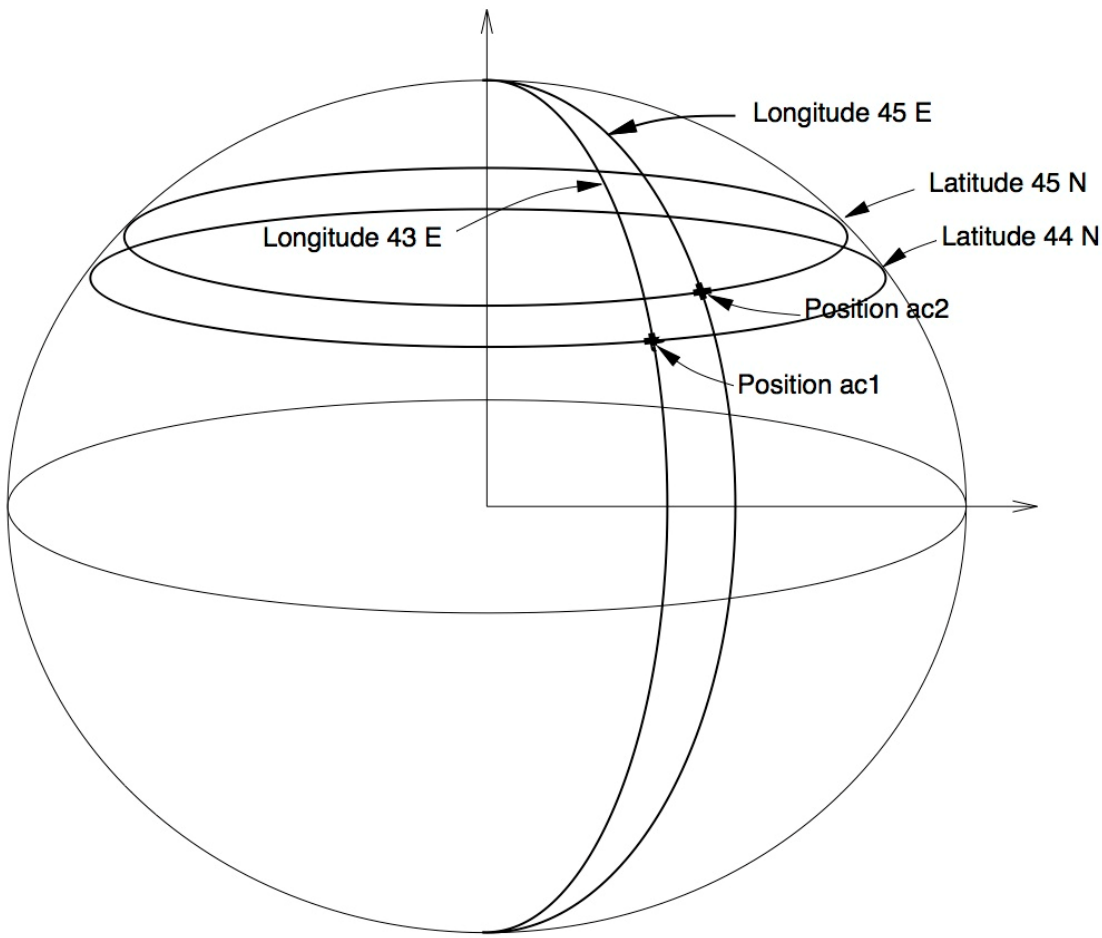


Figure 3-1. Example coordinate positions.

In the example shown in Figure 3-1, aircraft ac1 is defined as the PTM aircraft (ownship) and aircraft ac2 as the designated aircraft (traffic). The ownship is set at the origin of the Cartesian coordinate system, as shown in Figure 3-2.

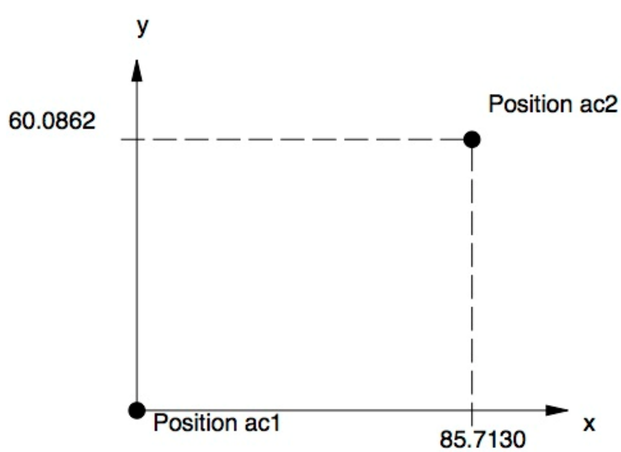


Figure 3-2. Location of aircraft in Cartesian coordinates.

The location of aircraft ac2 is relative to ac1. The y component of the location of ac2 is the difference in latitude between the two aircraft. The x component of the location of ac2 is the difference in longitude of the two aircraft at the average latitude. That is, the distance for the y component is the distance between longitude 43 degrees east and 45 degrees east at the average latitude of 44.5 degrees north.

The distance for the latitude is calculated by determining the difference in latitude angle between the aircraft and multiplying the angle by the radius from the center of the earth. The radius is the average radius of the earth plus the aircraft altitude. For the example shown in Figure 3-1, the latitude difference in distance is given by,

$$y = 1 \times \frac{2\pi}{360} \times (3437.74677 + 4.93746) \text{ nautical miles} \tag{3-1}$$

where,

3437.74677 is the average radius of the earth in nautical miles,
4.93746 is an altitude of 30,000 feet in nautical miles.

The distance for the longitude is calculated by determining the difference in longitude angle between the aircraft and multiplying by the radius of a plane normal to the earth axis that dissects the earth at the average latitude, as shown in Figure 3-3. For the example shown in Figure 3-1, the longitude difference in distance is given by,

$$x = 2 \times \frac{2\pi}{360} \times (3437.74677 + 4.93746)\sin(90 - ave\_latitude) \text{ nautical miles} \tag{3-2}$$

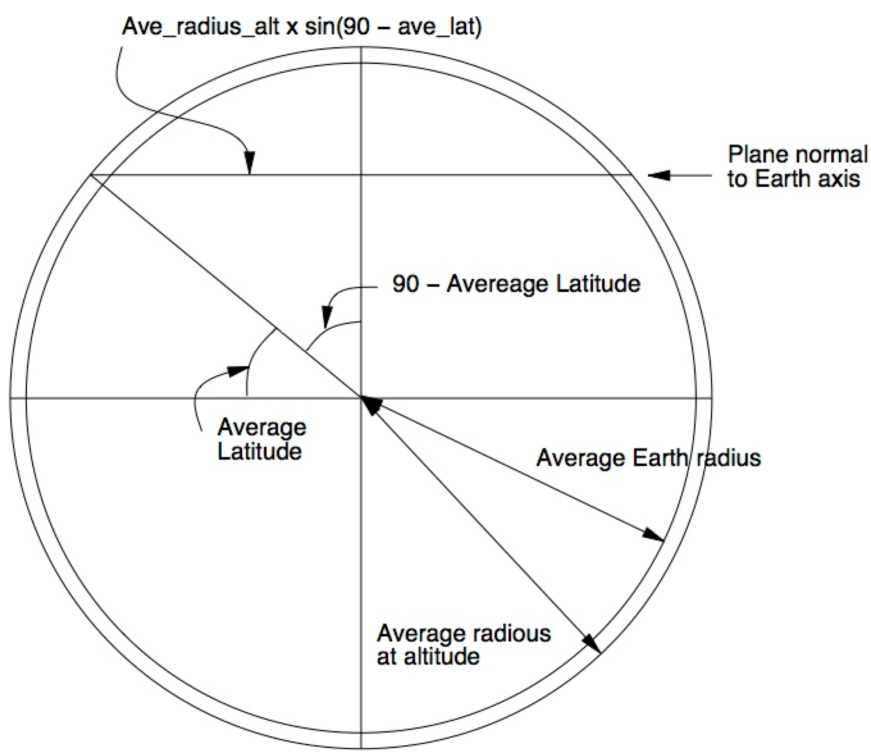


Figure 3-3. Calculation of longitudinal distance at average latitude.

3.2 Velocity vectors

The velocity vectors of the aircraft are mapped to the Cartesian coordinates system with the north component to the y-axis and the east component to the x-axis. Figure 3-4 shows an example of velocity vectors and utilizes the position of the example of Figure 3-2. The velocity vector for aircraft ac1 is 333.75 knots north and 333.75 knots east. The velocity vector for aircraft ac2 is 286.08 knots north and 381.43 knots east. Aircraft ac1 and ac2 speeds are 472.0 knots and 476.79 knots, respectively.

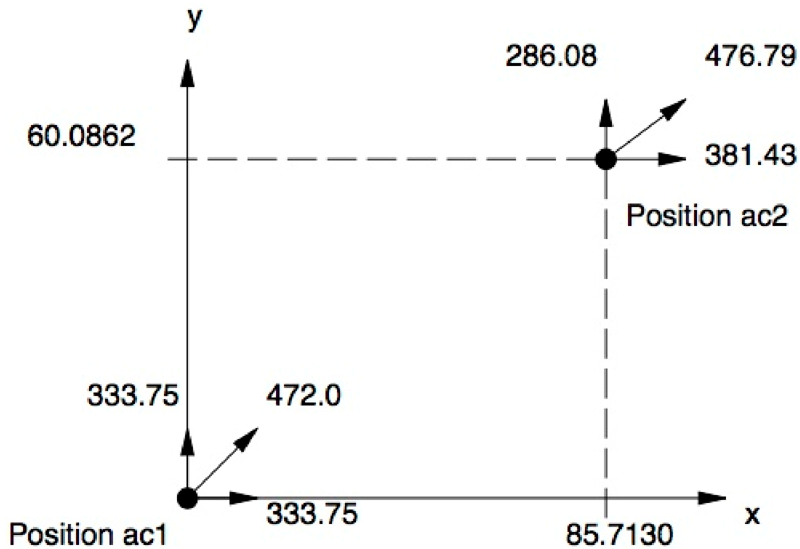


Figure 3-4. Example of velocity vectors on the Cartesian plane.

4 Along-track distance, intersection point and parallel tracks

4.1 Along-track distance and intersection point

To determine the along-track distance between the aircraft, the intersecting point of the aircraft tracks is determined. There is a possibility that there is no intersecting point between the tracks. This occurs when the velocity vectors are parallel and will be covered in the next sub-section.

The intersection point is determined by projecting the velocity vectors of the aircraft from the aircraft positions. Figure 4-1 shows the intersecting point for the position and velocity vector example.

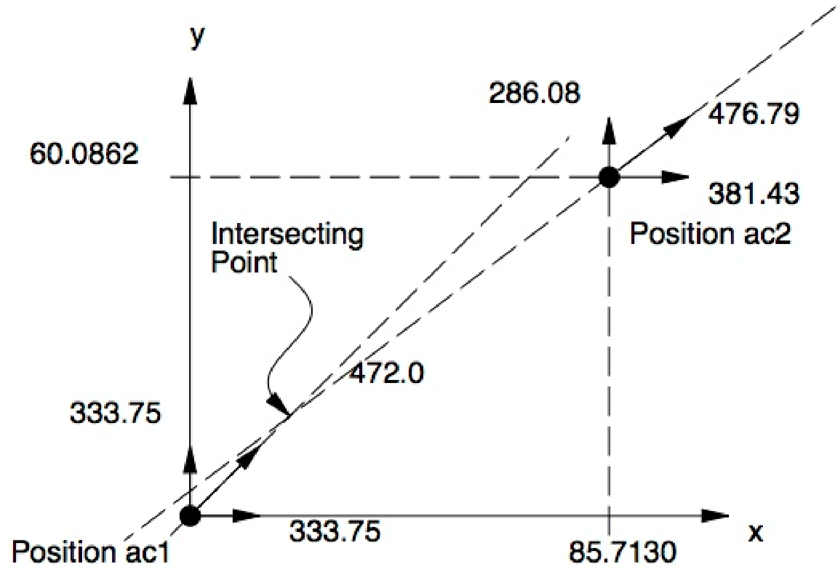


Figure 4-1. Intersecting point of the tracks.

There are four cases when determining the relative location of the intersecting point with respect to the aircraft:

- Aircraft ac1 is after the intersection and ac2 is before
- Aircraft ac2 is after the intersection and ac1 is before (Example of Figure 4-1)
- Both aircraft are after the intersection point
- Both aircraft are before the intersection point

Using the intersecting point of the tracks, the leading and trailing aircraft can be determined and the along-track distance can be calculated.

Case 1. Aircraft ac1 is after the intersection and ac2 is before

When aircraft ac1 is after the intersecting point and ac2 is before, ac1 is the leading aircraft. The along-track distance is the sum of the distances from each aircraft to the intersecting point.

Case 2. Aircraft ac2 is after the intersection and ac1 is before

When aircraft ac2 is after the intersecting point and ac1 is before, ac2 is the leading aircraft. The along-track distance is the sum of the distances from each aircraft to the intersecting point.

Case 3. Both aircraft are after the intersection point

When both aircraft are after the intersection point, the aircraft with the longest distance to the intersection point is the leading aircraft. The along-track distance is the difference of the leading aircraft distance minus the trailing aircraft distance to the intersection point.

Case 4. Both aircraft are before the intersection point

When both aircraft are before the intersection point, the aircraft with the shortest distance to the intersection point is the leading aircraft. The along-track distance is the difference of the trailing aircraft distance minus the leading aircraft distance to the intersection point.

4.2 Along-track distance and parallel tracks

When the velocity vectors are parallel, there is no intersection point. A perpendicular vector to the velocity vector of ac2 is calculated as shown in Figure 4-2.

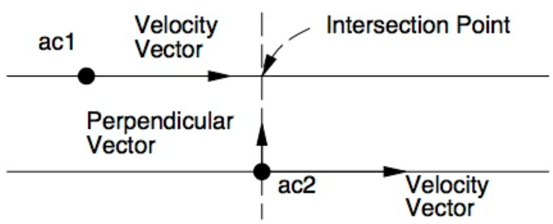


Figure 4-2. Aircraft on parallel tracks.

The intersection point for the parallel tracks scenario is the point a-beam of aircraft ac2. When aircraft ac1 is before the projected intersection point, aircraft ac2 is the leading aircraft. When aircraft ac1 is ahead of the intersection point, ac1 is the leading aircraft. The along-track distance is the distance between aircraft ac1 and the projected intersection point.

5 PTM along-track algorithm

The objective of the PTM along-track algorithm is to produce a speed guidance that will allow the flight crew of the PTM (ownship) aircraft to maintain spacing from one or multiple designated aircraft in a safe an efficient manner. The spacing is the sum of a separation standard minimum and buffer distance.

The algorithm gives speed guidance that permits the flight crew to select a speed from a range of speeds that will maintain or achieve the PTM spacing. If the along-track distance is greater than the spacing, the algorithm will give speed guidance such that the along-track distance could be reduced if the flight crew choses. If the along-track distance is at or near the spacing, the algorithm will give speed guidance to maintain the spacing. Depending on the limit Mach, the algorithm could also give speed guidance such that the PTM aircraft can increase the along-track distance. See examples 1 and 2, Section 5-2, which illustrate a PTM Pair and a PTM String and the speed guidance associated with these operations.

The following parameters are used in the computation of the speed guidance:

- Separation standard distance – a minimum distance that shall never be infringed upon. The range between the aircraft shall never be less than the separation standard distance.

- Buffer distance – a distance used to achieve the operational goal of separation standard
- Spacing – the sum of the separation standard distance and the buffer distance.
- Along-track distance – The distance between the aircraft along the flight path of the aircraft over segments that might include turns at waypoints.
- Wind velocity – the velocity vector of the wind at the ownship location.
- Assigned Mach – the speed that has been assigned to the designated aircraft.
- Time to achieve spacing – the time used to calculate the speed guidance and to achieve spacing.
- Time to achieve spacing when loss of spacing – the time used to calculate the speed guidance to achieve spacing when the along-track distance is less than the spacing.
- Maximum Mach – The maximum Mach that the algorithm will give as an upper bound. This value depends on the type of the aircraft. This maximum Mach does not mean that the aircraft can actually achieve this speed. It is a bound put on the algorithm guidance output.
- Minimum Mach – The minimum Mach that the algorithm will give as the lower bound. This value depends on the type of the aircraft. This minimum Mach does not mean that the aircraft can actually achieve this speed. It is a bound put on the algorithm guidance output.
- Limit Mach – The Limit Mach is an operational restriction placed on a PTM operation. The Limit Mach is transmitted to the PTM aircraft at the time of the clearance. When the PTM aircraft is the leading aircraft, the maximum Mach is set to the Limit Mach (except when loss of spacing/separation occurs). When the aircraft is trailing, the minimum Mach is set to the Limit Mach (except when a loss of spacing/separation occurs). A Limit Mach is not used for clearances of type 3.

The speed guidance is calculated starting with the ground speed of the aircraft. A new ground speed is calculated for the PTM aircraft. When the PTM aircraft is leading, the new ground speed is,

$$new\_gs = gs_d - \frac{D_{AT} - spacing}{T_s} \text{ knots} \tag{5-1}$$

where,

gs_d is the ground speed of the designated aircraft,
D_{AT} is the along-track distance between the aircraft,
T_s is the time to achieve spacing.

When the PTM aircraft is trailing, the new ground speed is,

$$new\_gs = gs_d + \frac{D_{AT} - spacing}{T_s} \text{ knots} \tag{5-2}$$

From the new ground speed, a new True Air Speed (TAS) is calculated taking into account the wind velocity vector at the ownship location. The vectorial components of the TAS are calculated from the new ground speed.

$$tas_x = new\_gs \times \sin(heading) - wind_x \tag{5-3}$$

$$tas_y = new\_gs \times \cos(heading) - wind_y \tag{5-4}$$

The magnitude of the TAS is calculated from the vectorial components.

$$TAS = \sqrt{tas_x^2 + tas_y^2} \tag{5-5}$$

In order to calculate the Mach speed, the speed of sound is calculated by,

$$s_{sound} = \frac{3600}{1852} \times 331.3 \times \sqrt{1 + \frac{temp}{273.15}} \quad \text{knots} \tag{5-6}$$

where *temp* is the temperature of the air in degrees Celsius.

The new Mach number is the new True Air Speed divided by the speed of sound at altitude,

$$new\_Mach = \frac{TAS}{s_{sound}} \tag{5-7}$$

The new Mach speed is rounded to the nearest one hundredth of a Mach. The speed guidance is determined from new Mach speed, the maximum and minimum Mach, whether the ownship is leading or trailing the designated aircraft.

When the ownship is leading, the guidance is,

Lower Mach = New Mach
Upper Mach = Maximum Mach

When the ownship is trailing, the guidance is,

Lower Mach = Min Mach
Upper Mach = New Mach

5.1 Non-linearity to account for Incremental Nature of Guidance

The speed guidance in units of Mach speed is given to the flight crew in 0.01 Mach increments. This is the typical resolution of the Mach command in the flight control panel. That is, Mach guidance in thousandth of Mach increments cannot be selected in the flight control panel of the aircraft. For example, a Mach guidance of 0.834 would not be possible to implement in a typical aircraft flight control panel.

To be able to achieve spacing closer to the desired spacing objective, a non-linear characteristic is designed into the algorithm. The non-linearity is added into the algorithm by determining if the along-track distance is less than the spacing requirement or more than the spacing requirement plus a hysteresis parameter. If the along-track distance is less than the spacing requirement, the Mach guidance is adjusted by 0.01 Mach to increase the distance between the aircraft. If the along-track distance is more than the spacing requirement plus the hysteresis parameter, the Mach guidance is adjusted by 0.01 Mach to decrease the distance between the aircraft.

5.2 Performance of the along-track algorithm and examples

This section presents three examples and what speed guidance is produced for a given set of parameters. The parameters used for the examples are shown in Table 5-1.

Table 5-1. Parameters Used for the Examples.

Parameter	Value
Separation Standard distance	5 nautical miles
Buffer	1.5 nautical miles
Spacing	6.5 nautical miles
Hysteresis	0.2 nautical miles
Limit Mach	0.82
Time to achieve spacing	30 minutes
Time to achieve spacing when loss of spacing exists	10 minutes
Minimum Mach	0.77
Maximum Mach	0.86

Example 1

Example 1 is a PTM Pair where the PTM aircraft is trailing the designated aircraft as shown in Figure 5-1. In this figure, the black aircraft (A) is the PTM aircraft and the white aircraft (B) is the designated aircraft. Aircraft A is maintaining spacing from B.

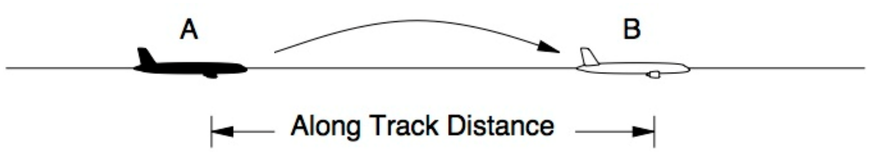


Figure 5-1. Example 1, PTM Pair with PTM aircraft trailing.

The speed guidance as a function of along-track distance is shown in Figure 5-2.

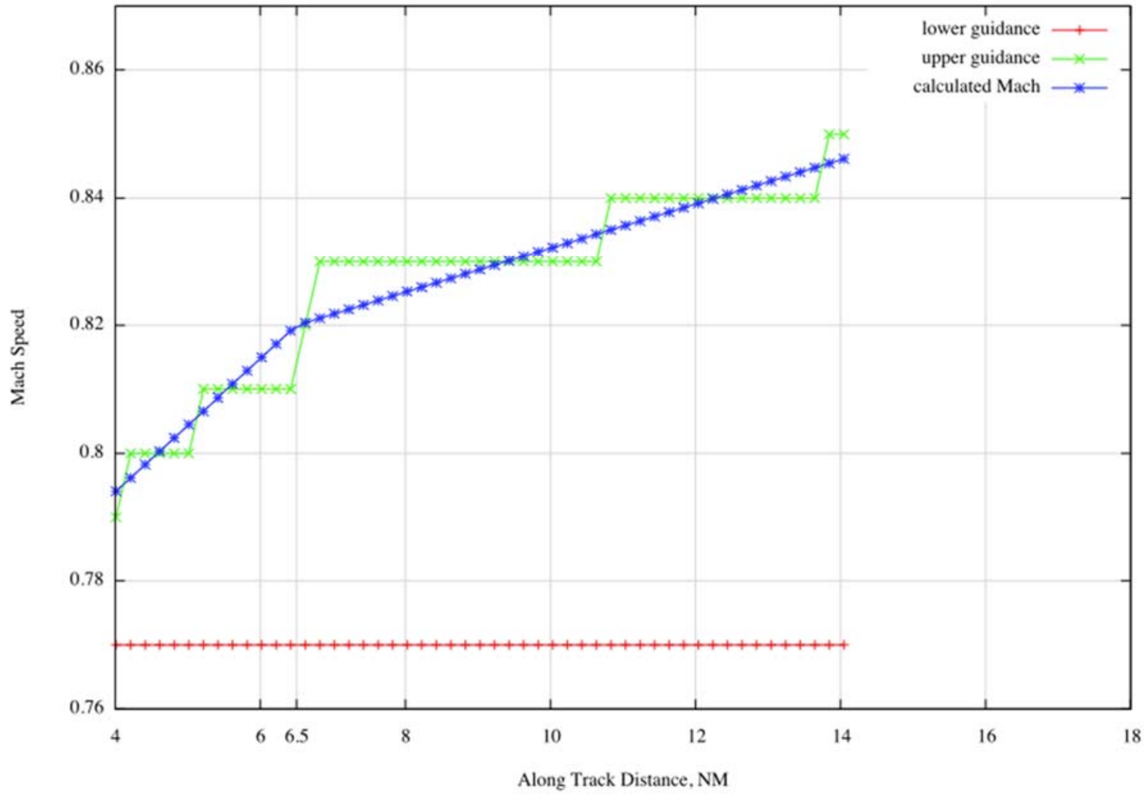


Figure 5-2. Mach guidance for aircraft A as a function of along-track distance.

When the along-track distance is 6.4 NM, the calculated guidance is 0.77 to 0.81 Mach. The minimum Mach is set to the Limit Mach and the system will provide a guidance of 0.82 to 0.81 under nominal conditions. The lower bound is greater than the upper bound and not achievable. However, because a loss of spacing exists, the algorithm will give a guidance that is lower than the Limit Mach and produce a guidance of 0.81 to 0.81 (a fixed guidance).

When the along-track distance is 6.6 NM, the calculated guidance is 0.77 to 0.82 Mach, which will increase or maintain the present distance. The guidance produced by the PTM algorithm is 0.82 to 0.82 because the minimum Mach is set to the Limit Mach.

When the along-track distance is 6.8 NM, the calculated guidance is 0.77 to 0.83 Mach, which allows for the PTM aircraft to go faster than the designated aircraft and reduce the along-track distance. The guidance produced by the algorithm is 0.82 to 0.83 Mach because the minimum Mach is set to the Limit Mach. The flight crew also has the option of going slower than 0.83 Mach to maintain the distance.

<u>Example 2</u>

Example 2 is a PTM String where 2 PTM aircraft are in trail of the designated aircraft as shown in Figure 5-3. Aircraft B is the designated aircraft for aircraft A and aircraft A is the designated aircraft for aircraft C. Aircraft A is maintaining spacing from aircraft B and aircraft C is maintaining spacing from aircraft A.

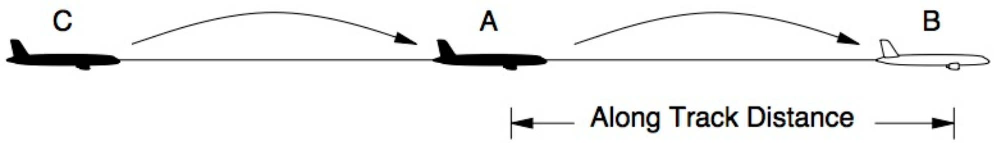


Figure 5-3. Example 2, PTM String with PTM aircraft trailing.

The speed guidance for PTM aircraft A as a function of along-track distance between aircraft A and B is shown in Figure 5-4. In the example of Figure 5-4, the minimum Mach speed for aircraft A has been set to the Limit Mach.

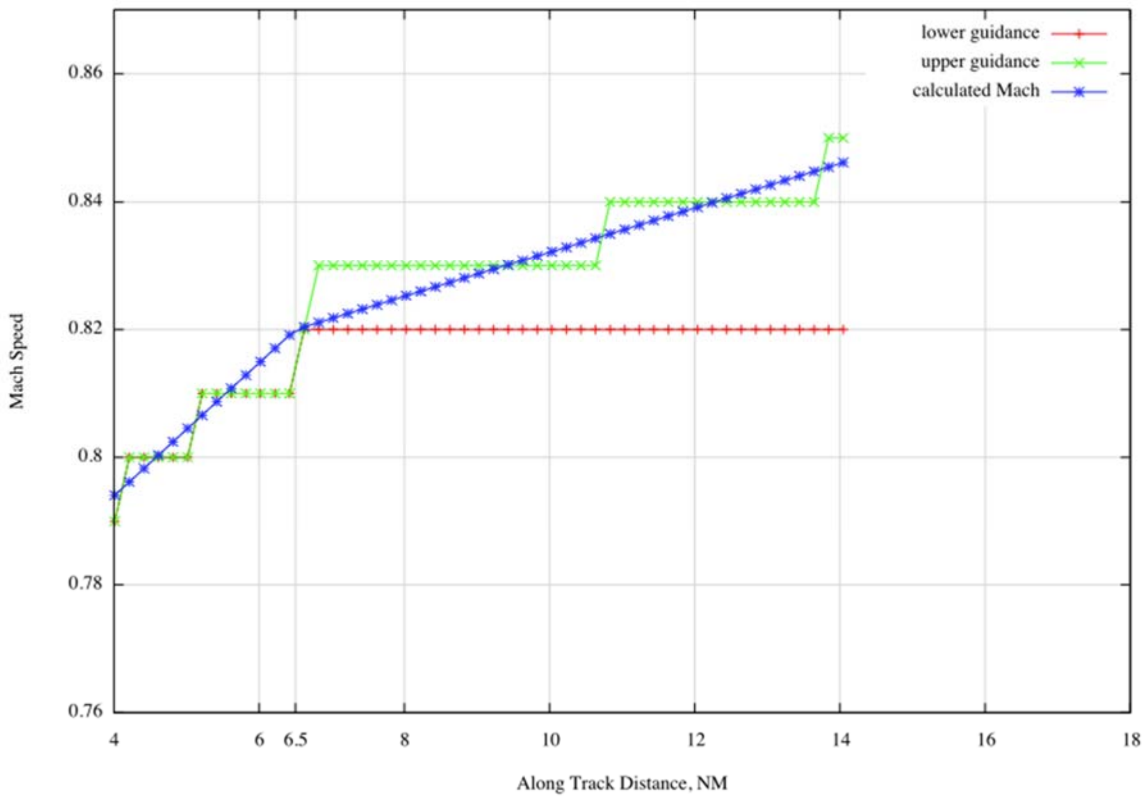


Figure 5-4. Mach guidance for aircraft A as a function of along-track distance.

Table 5-2 shows the distances and times for Example 1 when the PTM aircraft follows the upper guidance speed and the Time to Achieve Spacing parameter is set to 30 minutes. When the initial distance is 14 NM and the PTM aircraft follows the upper guidance, the aircraft will achieve spacing in 57.4 minutes.

Table 5-2. Time and Distance Between the PTM and Designated Aircraft, with Time to Achieve Spacing set at 30 minutes.

Time	Distance	PTM aircraft speed	Closure rate
0 minutes	14 NM	0.85 Mach	17.3 knots
1.4 minutes	13.6 NM	0.84 Mach	11.5 knots
17.1 minutes	10.6 NM	0.83 Mach	5.8 knots
57.4 minutes	6.7 NM	0.82 Mach	0 knots

Table 5-3 shows the distance and times for Example 1 when the PTM aircraft follows the upper guidance speed and the Time to Achieve Spacing parameter is set to 15 minutes. When the initial distance is 14 NM and the PTM aircraft follows the upper guidance, the aircraft will achieve spacing in 38.6 minutes.

Table 5-3. Time and Distance Between the PTM and Designated Aircraft, with Time to Achieve Spacing set at 15 minutes.

Time	Distance	PTM aircraft speed	Closure rate
0 minutes	14 NM	0.86 Mach	23.1 knots
6.8 minutes	11.4 NM	0.85 Mach	17.3 knots
11.6 minutes	10.0 NM	0.84 Mach	11.5 knots
18.9 minutes	8.6 NM	0.83 Mach	5.8 knots
38.6 minutes	6.7 NM	0.82 Mach	0 knots

Example 3

Example 3 is a PTM Chain where a PTM aircraft is between two designated aircraft as shown in Figure 3-5. Aircraft B and C are the designated aircraft for aircraft A. Aircraft A is maintaining spacing from aircraft B and C.

Figure 5-5. Example 3, PTM Chain.

The calculated speed guidance for aircraft pairs A-B and A-C are shown in Figure 5-6.

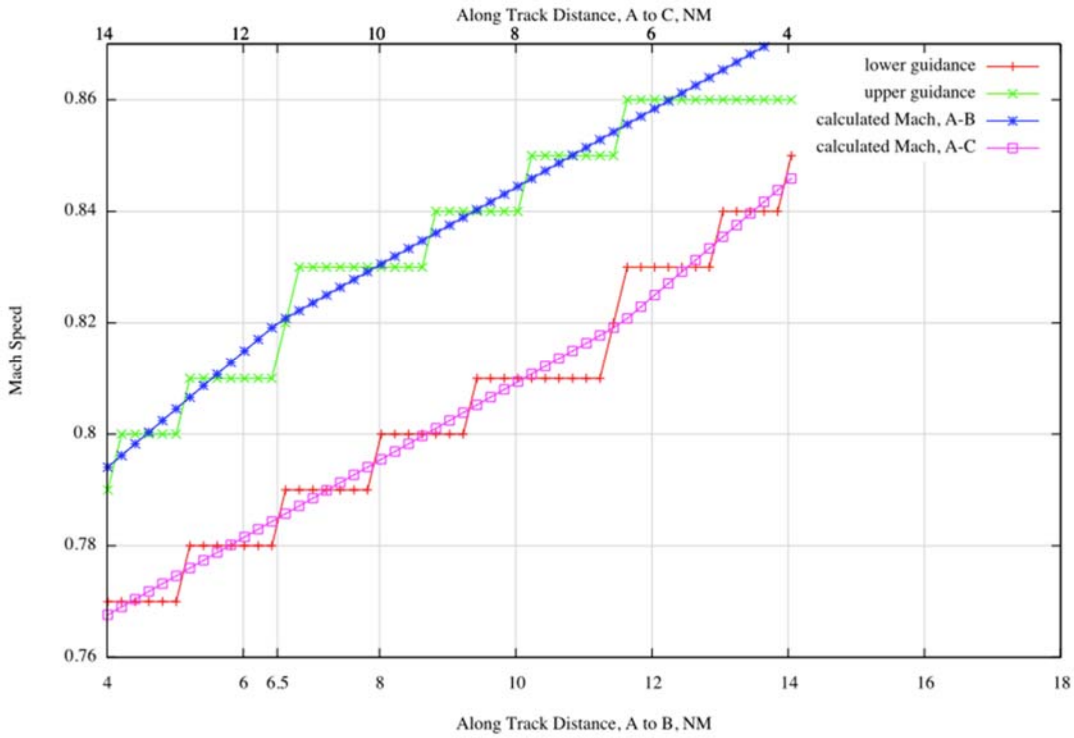


Figure 5-6. Mach guidance for aircraft A as a function of along-track distance between aircraft A and B, lower x-axis, and aircraft A and C, upper x-axis.

However, in a PTM Chain operation, the algorithm will generate a fix guidance equal to the Limit Mach. An exception occurs if there is a loss of spacing or loss of separation and the calculated guidance between the pairs will override the Limit Mach.

5.3 Accuracy, errors, and other considerations

Radius of the Earth

The calculations of distances from one position to another are performed using the average radius of the Earth. Because the earth is not a perfect sphere, this can result in calculation errors of distance. The radius of the earth at the equator is taken for WGS84 as 3,443.918466 nautical miles. The radius at the pole is 3,432.371660 for WGS84. The average radius used in the calculation of along-track distance is 3437.746771. When calculating the distance between two aircraft, which are approximately 15 nautical miles apart, an error of up to 0.0269 nautical miles or 49.87 meters could result. The error increases as the distance between the aircraft increases and decreases as the distance between the aircraft decreases, where it is more critical. At 5 nautical miles apart, the maximum error will be 0.00898 nautical miles or 16.62 meters. A function to estimate the Earth radius as a function of latitude has been added which makes this error negligible.

Coordinates Transformation

The transformation from latitude and longitude to Cartesian coordinates could result in a distances error. To map the east-west longitude to the x-axis, the average latitude is used. When the aircraft are 15 nautical miles apart, the worst error is 0.00006265 nautical miles or 0.116 meters. This error is negligible.

Range vs. Along-Track Distance

A requirement for 1-dimensional PTM operations is that aircraft are same direction. Same direction aircraft are aircraft with headings whose angular difference is less than 45 degrees. The objective of the algorithm described in this paper is to maintain along-track spacing. For separation standards and safety, the range between the aircraft is considered the metric of importance rather that the along-track distance.

When the along-track distance is, for example, 6.5 nautical miles and the leading aircraft turns 45 degrees at a waypoint, the range between the aircraft will become 6.005 nautical miles at the closes point of approach.

Round of Mach Guidance

The PTM Along-Track algorithm will calculate Mach guidance to many digits of precision. However, it is not practical to give to the flight crew Mach guidance that is more than one hundredth of a Mach. For example, a Mach guidance of 0.82 to 0.823176 cannot be implemented in the flight control panel. The need for giving guidance no more precise than hundredths of a Mach results in the optimal spacing not being achieved.

The algorithm currently rounds the guidance to the nearest hundredth of a Mach. It is possible to modify the algorithm to round up or round down (truncate) to the nearest hundredth of the Mach. This modification will change the algorithm performance. If rounding up, the guidance will allow the aircraft to get closer together when the PTM aircraft is trailing and maintain the aircraft farther apart when the PTM aircraft is leading. When rounding up, the opposite effect will occur.
The algorithm could also round depending on whether the PTM aircraft is trailing or leading and be designed such that the guidance will allow for the distances to be reduced further or the distances to remain longer.

Pressure Altitude vs. Geometric Altitude

The mapping of latitude and longitude to Cartesian coordinates take into account the aircraft altitude. The altitude is added to the radius of the Earth to determine distances. If the altitude used as input to the algorithm is the flight level of the aircraft rather than the geometric altitude, then an error will result. When the sea level barometric pressure is 29.92 inches of mercury (1013 hPa), the flight level is approximately the geometric altitude. Variations in atmospheric pressure will make the flight level and geometric altitude differ. To estimate the error, a lower atmospheric pressure than average is assumed. A lower atmospheric pressure will cause the aircraft to fly at lower geometric altitudes for a given pressure altitude. This in turn will result in a larger calculated distance than the actual distance. Assuming a barometric pressure of 25.10 inches of mercury (850 hPa), which is the lowest barometric pressure recorded on Earth, and the aircraft at FL350, the geometric altitude will be approximately 30,500 feet.

When the aircraft are at a distance of 15 nautical miles, the difference between flight level and geometric altitude for this worst-case condition will result in an error of 0.003231 nautical miles or 5.98 meters.

GPS and ADS-B Position Errors

The algorithm accuracy will depend in the accuracy of the data being provided by the GPS data of the PTM (ownship) aircraft and the ADS-B data of the Reference aircraft. The source data of the ADS-B data of the designated aircraft is expected to also be GPS.
The distance calculation errors resulting from position errors will depend on the magnitude of the position errors and whether the errors are correlated between the PTM and designated aircraft (correlated bias errors) or independent errors.

The provision of 5 nautical miles separation in the U.S. National Airspace System using ADS-B requires a Navigation Accuracy Category for position of 7. This NACp level correspond to an accuracy of 0.1 nautical miles or 185.2 meters at a 95% level.

6 PTM intent algorithm

The PTM intent algorithm is used to calculate speed guidance when the PTM and designated aircraft are not following the same route and there are waypoints before the projected crossing point. The PTM intent algorithm uses the PTM and designated aircraft's next and next-plus-one waypoint and the Estimated Time of Arrival (ETA) at the waypoints to calculate the speed guidance needed to maintain spacing and separation.

6.1 Speed guidance calculation logic

The PTM intent algorithm uses an iterative strategy and the Langley Research Center Formal Methods Conflict Detection with Intent Information (CDII) algorithm [2] to calculate the speed guidance. There are two cases for the speed guidance calculation: 1. The PTM aircraft will pass in front of the designated aircraft; 2. The PTM aircraft will pass behind the designated aircraft. The logic shown in Figure 6-1 is used to calculate the speed guidance for the first case where the PTM aircraft will pass in front.

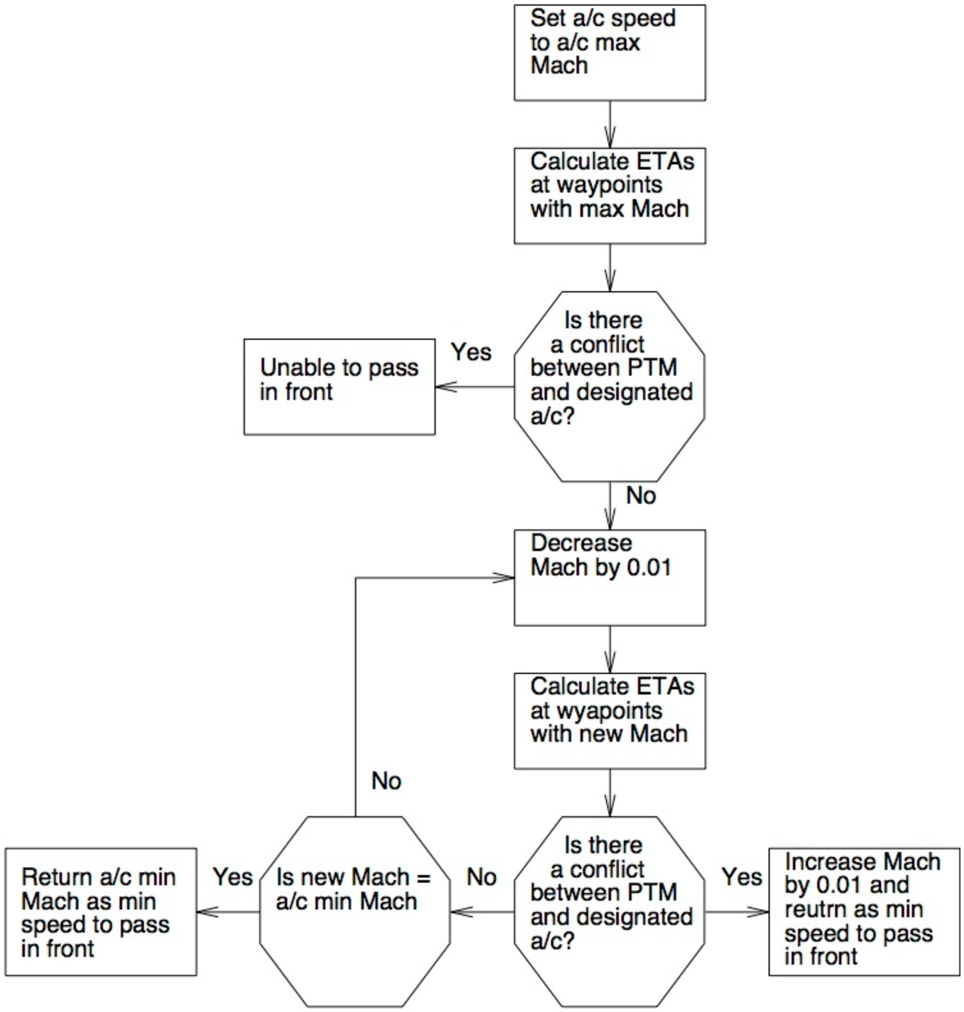


Figure 6-1. Logic to determine speed guidance for PTM aircraft passing in front.

The logic shown in Figure 6-2 is used to calculate the speed guidance for the second case where the PTM aircraft will pass behind.

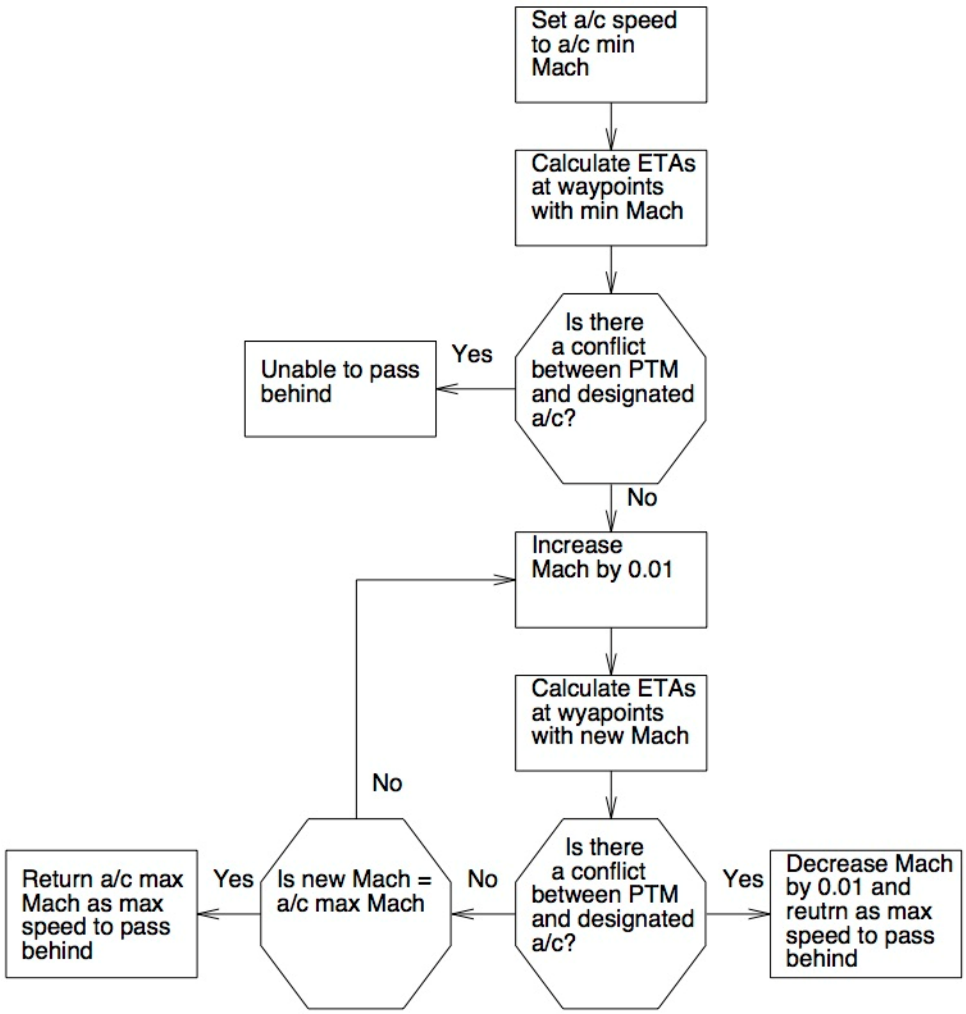


Figure 6-2. Logic to determine speed guidance for PTM aircraft passing behind.

6.2 Detection function

The PTM intent algorithm uses the Langley Research Center Formal Methods Conflict Detection with Intent Information (CDII) algorithm. The detection function of the CDII algorithm takes:

- Ownship set of waypoints and ETA at waypoints
- Designated aircraft set of waypoints at waypoints
- Start time of look ahead
- End time of look ahead

The function returns:

- True if there is a conflict and false if there is not

The existence or non-existence of a conflict is used by the PTM intent algorithm logic to vary the PTM aircraft to produce the guidance, as shown in the previous sub-section in Figures 6-1 and 6-2.

6.3 Calculating ground speed and TAS (True Air Speed) components

The PTM intent algorithm relies on the recalculation of the ground speed along the tracks to determine new times to waypoints. The new ground speed is calculated from the new Mach speed and the wind velocity vector. Figure 6-3 is a graphical example of the vectors involved in the calculation.

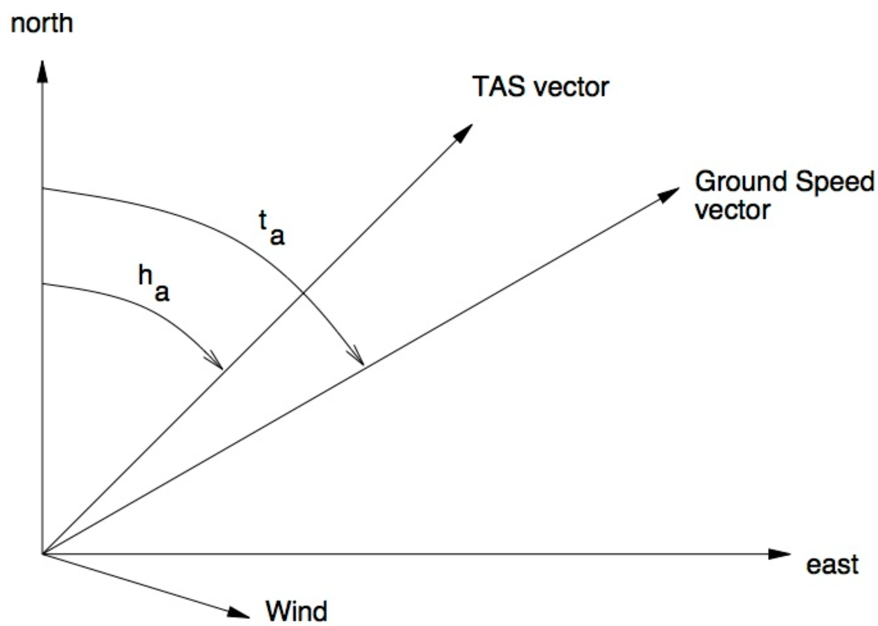


Figure 6-3. TAS vector, GS vector, wind vector, track angle and heading angle.

The following parameters are used in the calculation:

- Magnitude of TAS, known (new Mach times speed of sound)
- TAS_n, north component of True Air Speed, unknown
- TAS_e, east component of True Air Speed, unknown
- gs_n, north component of the ground speed, unknown
- gs_e, east component of the ground speed, unknown
- W_n, north component of wind, known
- W_e, east component of wind, known
- h_a, heading angle, unknown
- t_a, track angle, known (direction from current location to next waypoint)
- Magnitude of new ground speed, unknown

Although the individual components of the ground speed and the magnitude of the ground speed are unknown and must be calculated, the ratio of the ground speed components is known from the track angle.

$$\frac{gs_e}{gs_n} = \tan(t_a) \qquad (6\text{-}1)$$

The ground speed velocity vector is the vectorial sum of the true air speed velocity vector and the wind velocity vector, as shown in Figure 6-1,

$$gs_e = TAS_e + W_e \tag{6-2}$$

$$gs_n = TAS_n + W_n \tag{6-3}$$

inserting equations (6-2) and (6-3) into (6-1),

$$\frac{TAS_e+W_e}{TAS_n+W_n} = \tan(t_a) \tag{6-4}$$

let $\tan(t_a) = T$ in equation (6-4),

$$TAS_e + W_e = T(TAS_n + W_n) \tag{6-5}$$

$$TAS_n = \sqrt{TAS^2 - TAS_e^2} \tag{6-6}$$

inserting equation (6-6) into equation (6-5),

$$TAS_e + W_e = T(\sqrt{TAS^2 - TAS_e^2} + W_n) \tag{6-7}$$

squaring and rearranging the terms we get the quadratic equation,

$$(T^2 + 1)TAS_e^2 + 2(W_e - T \cdot W_e)TAS_e + (W_e - T \cdot W_n)^2 - T^2TAS^2 = 0 \tag{6-8}$$

From equation (6-8), the east component of the TAS can be calculated. When the track angle is between 0 (zero) degrees and 180 degrees, the first root of the solution to the quadratic equation is used. When the track angle is between 180 and 360 degrees, the second root of the solution is used.

In a similar manner, the north component of the TAS can be calculated,

$$(T^2 + 1)TAS_n^2 + 2(T^2W_n - T \cdot W_e)TAS_n + T^2W_n^2 + W_e^2 - 2T \cdot W_nW_e - TAS^2 = 0 \tag{6-9}$$

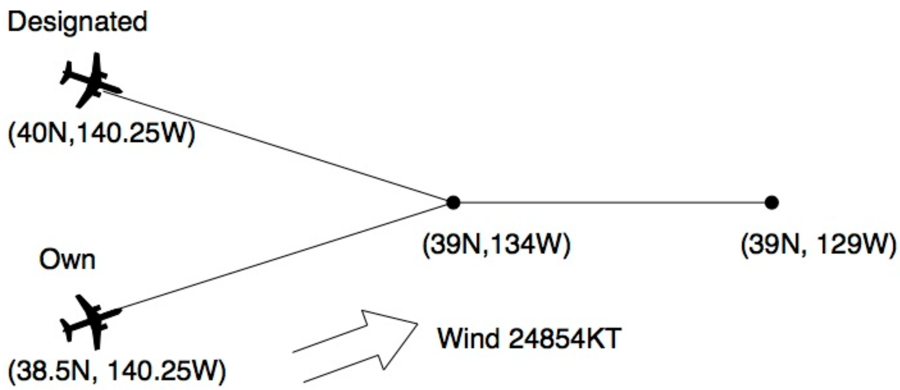
When the track angle is between 270 (-90) degrees and 90 degrees, the first root of the solution is used. When the track angle is between 90 degrees and 270 degrees, the second root of the solution is used.

Once the components of the TAS are calculated, the components of the ground speed can be calculated from equations (6-2) and (6-3) and the magnitude of the ground speed is the square root of the sum of the squares of the ground speed components. The ground speed magnitude is then used to calculate the new Estimated Times of Arrival to waypoints and whether or not there are conflicts.

6.4 Test cases

This section defines test cases for the PTM intent algorithm and shows the results given by the algorithm. The PTM separation standard is set to 5.0 NM and the target spacing is set to 6.5 NM for the test cases in this section. The flight level of the aircraft is FL350 and the air temperature -54.18 degrees Celsius.

Test Case 1



Own Mach speed: 0.83
Designated Mach speed: 0.84
Wind components: 20 kts North, 50 kts East
Distance between aircraft at initiation: 90.18 NM

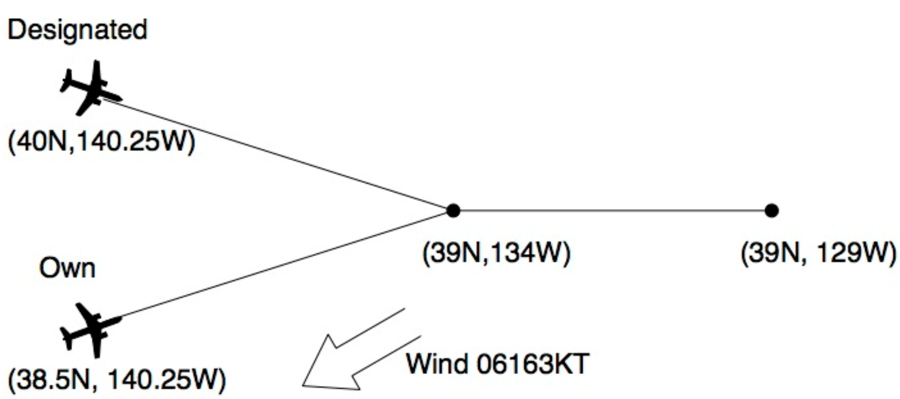
Waypoint	Distance to next waypoint, NM	Time at waypoint, seconds
Own, 38.5N, 140.25W	0	0
Own, 39N, 134W	294.527	1996.56
Own, 39N, 129W	233.584	3585.71
Designated, 40N, 140.25W	0	0
Designated, 39N, 134W	296.037	2011.44
Designated, 39N, 129W	233.584	3583.46

Conflict? Yes
Time to conflict: 1871.72 seconds
Distance at CPA: 0.00163 NM

Guidance

Mach speed to pass behind designated	0.80 Mach maximum
Mach speed to pass in front designated	0.85 Mach minimum

Test Case 2



Own Mach speed: 0.83
Designated Mach speed: 0.84
Wind components: -30 kts North, -55 kts East
Distance between aircraft at initiation: 90.18 NM

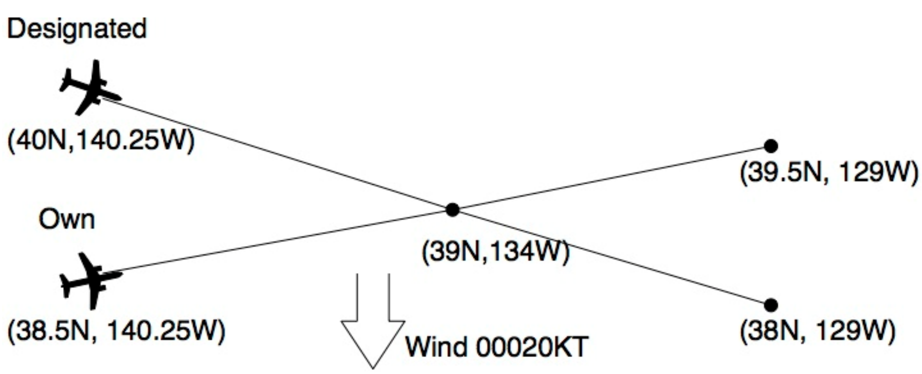
Waypoint	Distance to next waypoint, NM	Time at waypoint, seconds
Own, 38.5N, 140.25W	0	0
Own, 39N, 134W	294.527	2521.97
Own, 39N, 129W	233.584	4510.30
Designated, 40N, 140.25W	0	0
Designated, 39N, 134W	296.037	2452.54
Designated, 39N, 129W	233.584	4414.14

Conflict? No
Time to conflict: N/A
Distance at CPA: > 6.5 NM

Guidance

Maintain current speed	0.83 Mach

Test Case 3



Own Mach speed: 0.83
Designated Mach speed: 0.84
Wind components: -20 kts North, 0 kts East
Distance between aircraft at initiation: 90.18 NM

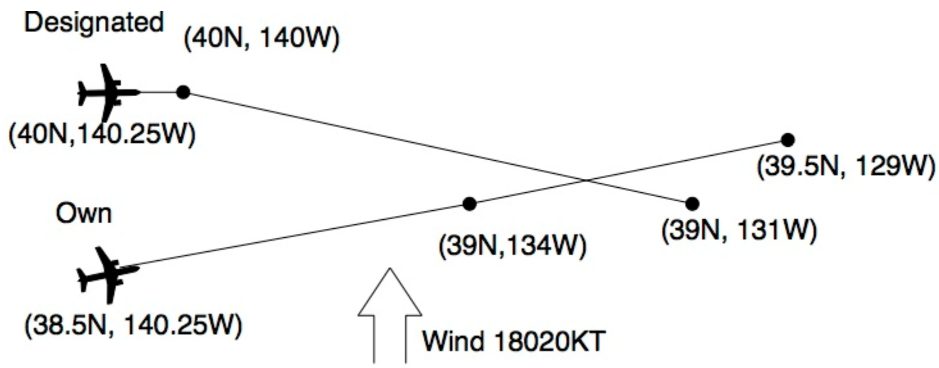
Waypoint	Distance to next waypoint, NM	Time at waypoint, seconds
Own, 38.5N, 140.25W	0	0
Own, 39N, 134W	294.527	2228.17
Own, 39.5N, 129W	234.685	4005.07
Designated, 40N, 140.25W	0	0
Designated, 39N, 134W	296.037	2185.14
Designated, 38N, 129W	242.784	3973.37

Conflict? Yes
Time to conflict: 2123.21
Distance at CPA: 4.915 NM

Guidance

Mach speed to pass behind designated	0.82 Mach maximum
Mach speed to pass in front designated	0.87 Mach minimum

Test Case 4



Own Mach speed: 0.83
Designated Mach speed: 0.84
Wind components: 20 kts North, 0 kts East
Distance between aircraft at initiation: 90.18 NM

Waypoint	Distance to next waypoint, NM	Time at waypoint, seconds
Own, 38.5N, 140.25W	0	0
Own, 39N, 134W	294.527	2203.01
Own, 39.5N, 129W	234.685	3956.99
Designated, 40N, 140.25W	0	0
Designated, 40N, 140W	11.5134	85.571
Designated, 39N, 131W	421.627	3231.44

Conflict? Yes
Time to conflict: 2659.01
Distance at CPA: 2.6281 NM

Guidance

Mach speed to pass behind designated	0.82 Mach maximum
Mach speed to pass in front designated	0.86 Mach minimum

7 Conflict detection and alerting

The conflict detection and alerting function calculates along-track distance and closure rate to determine if a loss of spacing or separation will occur in a given look ahead time. The function provides 6 different levels of alerting:

- Loss of spacing in L1 seconds (Predicted loss of spacing)
- Loss of spacing in L2 seconds (Imminent loss of spacing)
- Loss of spacing (Current loss of spacing)
- Loss of separation in L1 seconds (Predicted loss of separation)
- Loss of separation in L2 seconds (Imminent loss of separation)
- Loss of separation (Current loss of separation)

The parameters L1 and L2 are system configurable and represent the time thresholds. The values of L1 and L2 are such that L1 is greater than or equal to L2.

8 Summary and conclusion

The PTM algorithm is a collection of algorithms that implement the airborne functionality of PTM operations. The PTM executive is the interphase between the airborne functionality and the flight crew and ground automation. The PTM algorithm provides decision tools to the flight crew and allows the flight crew to accept or reject a PTM clearance. The PTM algorithm also provides speed guidance during PTM operations to maintain spacing and separation from designated aircraft.
The PTM algorithm also provides speed guidance during non-nominal conditions. If conditions result in a loss of spacing or separation, guidance will be given to re-establish the separation minima and the spacing. In cases were a solution is not available to re-establish spacing and/or separation minima, the guidance will provide the best possible distance between the PTM and designated aircraft.

9 References

[1] Carreño, V. and Graff, T.; Definitions, Theory and Operational Rules for Chains and Strings in the PTM Application, version 6, 2 September 2013.

[2] Geser, Alfons and Muñoz César; A Geometric Approach to Strategic Conflict Detection and Resolution, Proceedings of the 21st Digital Avionics System Conference, DASC 2001.

Appendix I: Design of an Airborne Human Machine Interface for Pairwise Trajectory Management (PTM)

INTRODUCTION

The airborne PTM HMI's iterative design process is depicted graphically in Figure I-1.

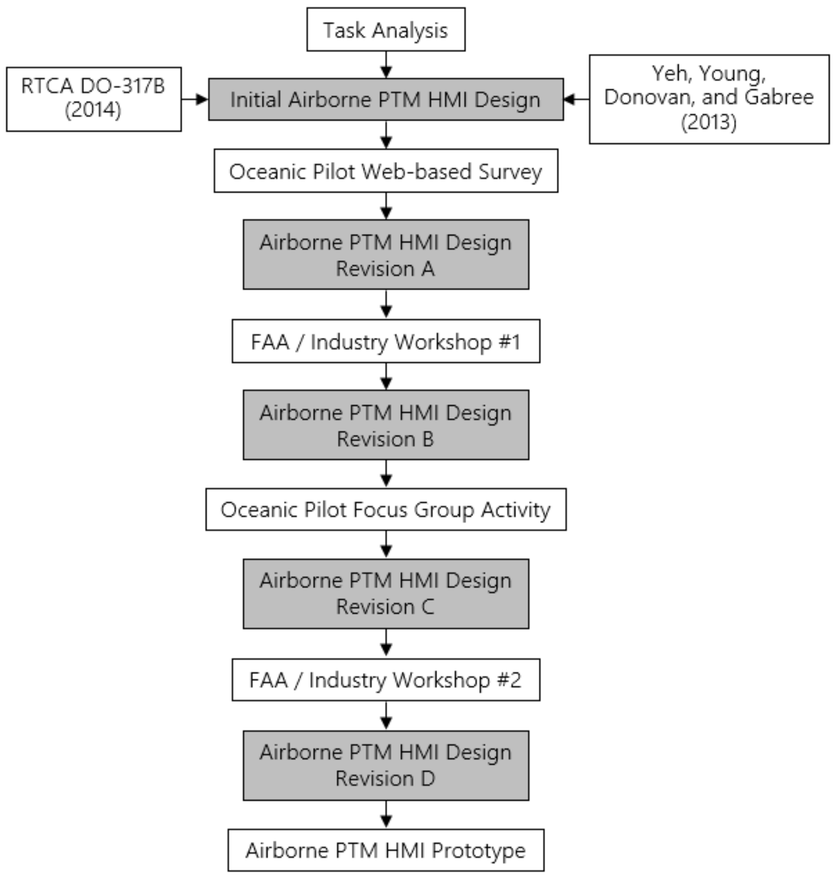


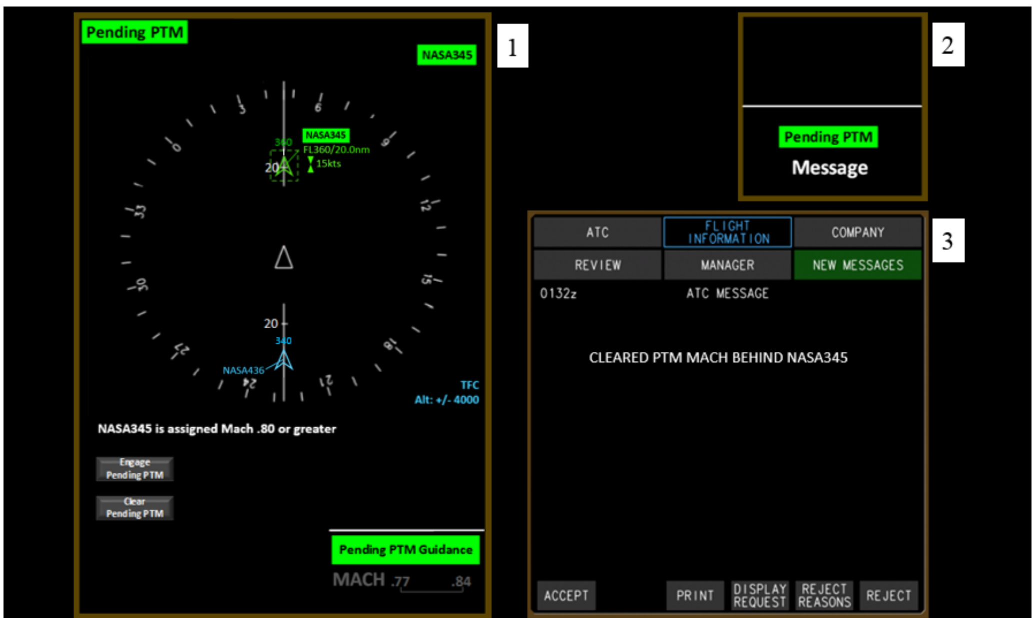
Figure I-1. Airborne PTM HMI iterative design process.

As shown in the figure above, the design process began with a task analysis that allowed the characterization of the HMI's functional requirements and the identification of its required information elements. Next, two key references were reviewed as it was deemed a requirement that their contents heavily influence and, in some instances, dictate the design of certain airborne PTM HMI features. These references include the RTCA minimum operational performance standards document DO-317B (ref. 1) and the work of Yeh, Young, Donovan, and Gabree (ref 2), which provides extensive guidance regarding the design and evaluation of flight deck displays and controls.

Requirements for and proposed design elements associated with airborne HMIs intended for use with Interval Management (IM) operations conducted in the terminal environment, such as those developed for Flight-deck Interval Management (FIM) (refs 3 and 4), were also reviewed. However, the PTM concept is the first application that allows the flight crew to maintain spacing from controller assigned aircraft in oceanic airspace. As such, it was anticipated that innovative HMI design features might be required to support the flight crew during the conduct of PTM given that these operations will take place in an oceanic environment. Therefore, rather than constrain the airborne PTM HMI's design by adhering to design philosophies associated with currently proposed airborne HMIs intended to support IM terminal operations, the decision was made to begin the airborne PTM HMI design process without reference to existing displays, fully realizing that harmonization with other applications making use of side mounted display and configurable graphics display (CGD) hardware will likely be necessary in the future.

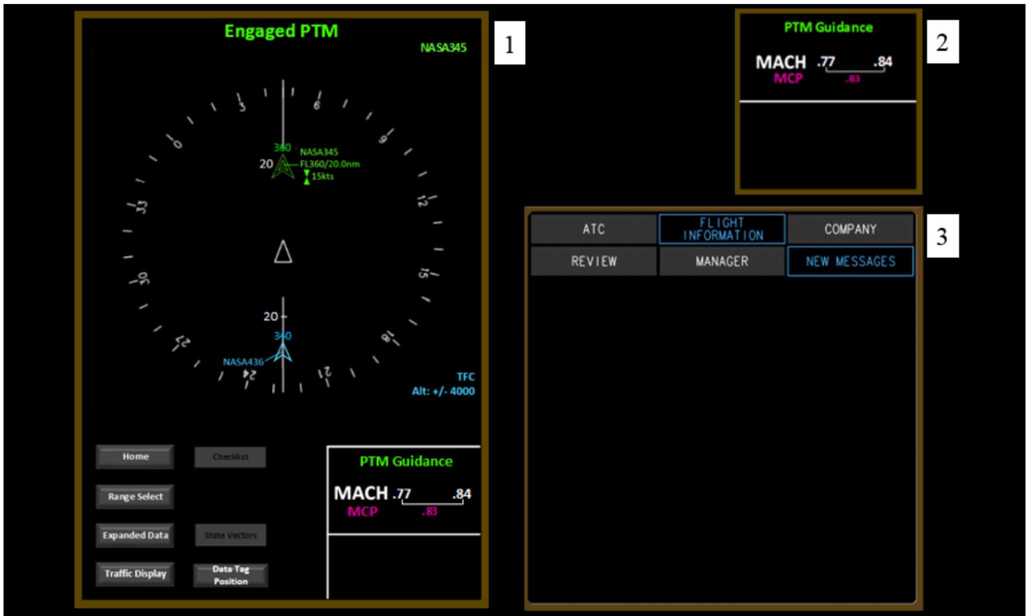
To facilitate a comprehensive evaluation of the airborne PTM HMI design, a series of user scenarios representative of flight crew tasks involving the HMI's use during various PTM operations were defined, and an HMI storyboard prototype was developed using commercially available presentation software. Then, various user scenarios and accompanying HMI storyboard graphics were presented to subject matter experts (SMEs) to gather their feedback and guidance regarding the HMI's design.

Example airborne PTM HMI storyboard graphics, presented here to provide an overview of the HMI displays' general layout and contents rather than a detailed view of their features and information elements, are shown in Figures I-2 and I-3. Although not part of the airborne PTM HMI, a flight deck multi-function display (MFD) is included in these figures to show a sample PTM clearance received from air traffic control (ATC).



1) Side-Mounted Auxiliary Display; 2) Configurable Graphics Display; 3) Multi-Function Display

Figure I-2. Example airborne PTM HMI upon receipt of a PTM clearance.



1) Side-Mounted Auxiliary Display; 2) Configurable Graphics Display; 3) Multi-Function Display

Figure I-3. Example airborne PTM HMI during a PTM operation.

As shown in the process depicted above in Figure I-1, the initial airborne PTM HMI design was evaluated by a small group of oceanic pilots through completion of a web-based survey. These survey responses assisted with the creation of airborne PTM HMI design revision A, which was reviewed during a small-scale workshop conducted with SMEs from the Federal Aviation Administration (FAA) and the U.S. aerospace industry. Feedback obtained from SMEs during this workshop was used to create airborne PTM HMI design revision B, which was shared with oceanic pilot focus group participants. Feedback from these oceanic pilots assisted with the creation of airborne PTM HMI design revision C, which was reviewed during a second small-scale FAA and industry workshop. Feedback obtained during this final SME data collection activity assisted with the creation of airborne PTM HMI design revision D.

The design of airborne PTM HMI revision D considered RTCA DO-317B requirements, followed guidelines set forth within the work of Yeh et al., and incorporated guidance provided by a large and appropriate sample of SMEs. Therefore, this version of the HMI design was used to generate specifications for a functional HMI prototype constructed by software developers at NASA Langley Research Center. This functional prototype was used in focus group and initial human-in-the-loop (HITL) testing activities, described in Appendix J of "Pairwise Trajectory Management (PTM) Concept Description and Doumentation", that assessed the ability of oceanic pilots to execute PTM flight crew procedures using the proposed airborne PTM HMI.

METHOD

Data used to successively refine and improve the airborne PTM HMI design were not collected during a formal experiment. Instead, data that guided the HMI's iterative design process were gathered from SMEs through the systematic conduct of a series of data collection activities.

Participants

Web-based survey respondents. Eight pilots employed by a major U.S. air carrier completed a web-based survey to provide feedback regarding the airborne PTM HMI's initial design. On average, these pilots had 26 years of airline experience and over 11,000 hours of commercial airline flight time. All pilots reported having significant experience flying oceanic routes, primarily using organized track systems in the North Atlantic, Pacific, and Central East Pacific.

Workshop #1 participants. An FAA Aviation Safety Inspector from Flight Standards and two senior engineers, one affiliated with Operations and Human Factors and the other with Flight Deck Research, employed by a major U.S. aircraft manufacturer participated in airborne PTM HMI workshop #1.

Focus group participants. Twenty pilots employed by five major U.S. air carriers participated in airborne PTM HMI design focus group activities. On average, these pilots had 24 years of airline experience and over 17,000 hours of commercial airline flight time. All pilots had significant experience flying oceanic routes, with the majority of their experience being obtained during the use of organized track systems in the North Atlantic and Pacific as well as the West Atlantic Route System.

Workshop #2 participants. Four individuals from the FAA participated in workshop #2. They included the Aviation Safety Inspector from Flight Standards who also participated in workshop #1, an Air Traffic Systems SME from the Surveillance and Broadcast Services Program, an Avionics Systems and Surveillance SME from Aircraft Certification, and an SME from the Engineering Development Services Division. Additionally, a Systems Engineer employed by a U.S. aerospace development and manufacturing company also participated in airborne PTM HMI workshop #2.

Materials

Web-based survey. A 37-item questionnaire consisting of forced-choice, multiple-choice, short answer, and open-ended questions was constructed using a commercially available web-based survey tool. Questionnaire items were preceded by a statement of the survey's purpose, survey completion instructions, an overview of the PTM concept, and a detailed description of the airborne PTM HMI's design. A simple user scenario was presented with accompanying HMI storyboard graphics, then questionnaire items were presented. Approximately half of the questionnaire items referred to specific aspects of the user scenario and its related display graphics while the remaining questionnaire items gathered survey respondent demographic information.

Workshops and focus group sessions. Information regarding the PTM concept, the airborne PTM HMI design process, and the HMI's design features was presented to SMEs via a slide show. Then, one version of the airborne PTM HMI design (either HMI design revision A, B, or C) was presented as a storyboard prototype to each group of workshop participants and to all of the focus groups' participants.

HMI storyboard graphics were presented using a laptop computer, a projector, and two projection screens. The side mounted display was presented on one projection screen, and the PTM guidance display was presented on a second projection screen. This presentation format was used to remind SMEs that the proposed retrofit implementation will require the HMI displays to be physically separated within the flight deck, as shown in Figure 27 of "Pairwise Trajectory Management (PTM) Concept Description and Documentation". A second laptop computer, a second projector, and a third projection screen were used to display a graphical representation of a flight deck MFD.

SMEs identified the airborne PTM HMI design's strengths and weaknesses and provided suggestions for design revisions. These data were collected by the research team via paper-and-pencil notes.

Procedure

Web-based survey. The URL associated with the web-based survey was shared via email with eight oceanic pilots by a point of contact affiliated with a major U.S. air carrier. All pilots accessed and completed the survey using computers available to them at a location and time of their choosing. All survey responses were saved by the pilots and were retrieved by the research team using the web-based survey tool.

Workshops. Workshops #1 and #2 were conducted as single-day meetings held in conference rooms at NASA Langley. Each workshop began with the presentation of introductory material. Then, several airborne PTM HMI user scenarios and corresponding HMI storyboard graphics were reviewed to provide SMEs with the opportunity to closely examine and comment upon the HMI's design multiple times.

Focus group sessions. Single-day focus group activities were conducted in a conference room at NASA Langley. A different group of five oceanic pilots served as participants during each of four interactive focus group sessions. Each session began with the presentation of introductory material. Then, a series of airborne PTM HMI user scenarios and corresponding HMI storyboard graphics were shown to and discussed in detail with each group of pilot SMEs.

RESULTS

Web-based Survey

Oceanic pilot survey respondents indicated that information elements associated with the side mounted display's CDTI were legible and that the intended use of buttons located in the lower left of the display's touchscreen was intuitive from their design. Additionally, the content of aircraft data tags presented within the CDTI (i.e., indications of flight identification, altitude, distance from ownship, and along-track closure and speed relative to ownship) was rated as being appropriate and useful given the nature of PTM operations.

All survey respondents rated information provided on the side mounted display as being useful in supporting the flight crew decision making process required when a PTM clearance is received. Additionally, most pilots reported that "reverse video" (an example of which is shown in Figure I-2) was appropriately used to highlight various information elements during this decision making process.

One suggested improvement associated with the airborne PTM HMI's use during ongoing PTM operations focused on the presentation of the PTM algorithm's commanded speed guidance. These speed commands, presented as "PTM Guidance" on the primary FOV CGD and in the lower right portion of the side mounted display's screen, must be followed by the flight crew to maintain spacing from controller assigned aircraft. Based on pilot feedback, the decision was made to surround commanded speed changes consisting of a single required Mach value with a white box for 10 seconds to draw the flight crew's attention to the necessity of altering the speed of their aircraft.

Workshop #1

In general, the SMEs participating in workshop #1 found the airborne PTM HMI to be well designed and appropriate for use by flight crews authorized to conduct PTM operations. They agreed with the survey respondents' conclusion that information provided on the side mounted display supports flight crew decision making when a PTM clearance is received. Additionally, the use of reverse video was found to be acceptable given that its use is limited to displays shown when the flight crew must provide ATC with a timely response regarding a PTM clearance.

Other topics of interest were also discussed with SMEs during workshop #1. For example, the use of mixed case letters for text presented on the airborne PTM HMI's displays, rather than the use of upper case letters as is traditional in flight deck display design, was deemed to be acceptable.

Another discussion with SMEs focused on the number of button presses required to display and remove background traffic information presented within the side mounted display's CDTI. A "Traffic Display" button (shown in Figure I-3) can be used to access a "Background Traffic On/Off" button, with a subsequent "Return" button press being used to return to the default screen shown on the side mounted display during an ongoing PTM operation. It was recommended, however, that the flight crew be able to turn background traffic information "on" and "off" via a single button press. In accordance with this SME guidance, the decision was made to use the background traffic / altitude range indicator, located below and to the right of the CDTI's compass rose, as a touchscreen "hot spot" to provide the recommended single-button press functionality.

Focus Group Sessions

Overall, the focus group participants discussed the airborne PTM HMI's design in favorable terms, and they identified several strengths of the design. Examples include the appropriateness of providing units of measure in aircraft data tags presented within the side mounted display's CDTI (i.e., flight level (FL), nautical miles (NM), and knots (kts)) and the utility of information regarding traffic altitude relative to ownship that is conveyed via traffic data tag position. The use of 2 o'clock and 10 o'clock data tag positions, relative to a traffic symbol, as indications of traffic being located above ownship and the use of 4 o'clock and 8 o'clock data tag positions as indications of traffic being located below ownship was identified as an extremely effective information coding scheme. As a result of focus group discussions, the decision was made to further extend this coding scheme to include the use 3 o'clock and 9 o'clock data tag positions as indications of traffic being co-altitude with ownship.

Discussions with focus group participants revealed a desire for pilots to know when and for whom the ownship serves as a designated target aircraft during a PTM operation as well as a desire for the presentation of a chime whenever the flight crew fails to respond to ATC within 1 minute of having received a PTM clearance. To address these areas of interest, the decision was made to add an element to the data tags of aircraft for whom the ownship serves as a PTM designated target aircraft, and the decision was made to investigate the appropriateness of providing an aural prompt to ensure a flight crew's timely response to ATC when PTM clearances are received.

Workshop #2

SMEs participating in workshop #2 generally found the airborne PTM HMI to be well designed and capable of supporting flight crews during the conduct of PTM operations. One topic of interest addressed with this group of SMEs focused on the appropriateness of providing checklists within an area of the side mounted display that would overwrite the right column of buttons shown in Figure I-3. Another topic of interest focused on the potential utility of presenting state vectors, associated with ownship and designated target aircraft, on the side mounted display's CDTI during the conduct of PTM operations involving specific aircraft route geometries. A third topic of interest involved the possible need for increased "PTM Guidance" saliency, perhaps conveyed by flashing speed commands, if a flight crew fails to implement commanded speed guidance within a given timeframe.

Feedback regarding the use of checklists, on a limited basis, to guide flight crew actions during PTM operations influenced the design of HMI revision D, and the decision was made to permit the presentation of aircraft state vectors during a subset of PTM operations. Additionally, the decision was made to investigate the saliency of "PTM Guidance" during upcoming HITL experiments.

DISCUSSION

Data collected from 35 SMEs drove the airborne PTM HMI's iterative design process forward, with the ultimate result being the creation of an HMI design that was used to generate specifications for a functional prototype constructed by NASA Langley software developers. Collectively, the SMEs possessed extensive knowledge of oceanic flight operations as well as the design, evaluation, operational use, implementation, and certification of flight deck displays and controls and aircraft avionics systems. SMEs were asked to critically assess all aspects of the HMI's design and were discouraged from thinking of the HMI as being too far along its development path to warrant suggestions for major revisions.

Although they were encouraged to share candid and comprehensive feedback, the SMEs did not suggest that major revisions be made to the airborne PTM HMI design. Perhaps this is a result of the design's adherence to DO-317B (RTCA, 2014) and its reliance on guidance provided by Yeh *et al.* (2013). Oceanic pilot SMEs reported that the HMI's design follows flight deck design philosophies with which they are very familiar, and its innovative design features follow a design philosophy that is consistent with accepted standards.

While a robust airborne PTM HMI design has been created, the HMI's iterative design process will continue as future challenges are encountered and addressed. For example, HITL experiments evaluating the ability of oceanic pilots to accurately execute PTM flight crew procedures using the airborne PTM HMI may reveal that pilot assessments of the HMI's usability significantly differ from the SME feedback gathered through the web-based survey, workshops, and interactive focus group sessions. Furthermore, the airborne PTM HMI will need to be harmonized with other applications, such as FIM, that make use of flight deck side mounted display and CGD hardware. Lastly, it must also be acknowledged that the airborne PTM HMI may ultimately be redesigned to support a future integrated flight deck solution.

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Appendix J: Pairwise Trajectory Management (PTM) Pilot Training Requirements Focus Group and Human-in-the-Loop (HITL) Testing Activities

INTRODUCTION

A research team at NASA Langley Research Center conducted a series of focus group and human-in-the-loop (HITL) testing activities with active oceanic airline pilots in order to:

- Assess the effectiveness of a Pairwise Trajectory Management (PTM) training materials (i.e., a Pilot Guide and computer-based training (CBT) package) developed by NASA Langley researchers and subject matter experts (SMEs)
- Gather oceanic pilot input regarding the PTM concept, proposed flight crew procedures, and prototype airborne HMI design
- Collect additional qualitative data from pilot participants after they had flown a series of in-trail PTM scenarios using a medium fidelity desktop simulator

An overview of the methodology used during and the results obtained from the focus group and HITL testing activities are provided in the sections that follow.

METHOD

Participants

Twelve pilots employed by three major U.S. air carriers participated in the PTM pilot training requirements focus group and HITL testing activities. On average, these pilots had 25 years of airline experience and over 15,000 hours of commercial airline flight time. All pilots were currently flying Boeing aircraft (i.e., B757, B777, and B787). All pilots had significant experience flying oceanic routes, with the majority of their experience being obtained during the use of organized track systems in the North Atlantic and Pacific as well as the West Atlantic Route System.

Materials

A PTM Pilot Guide (Appendix L of Pairwise Trajectory Management (PTM) Concept Decription and Documentation) and a six-module CBT package served as training materials provided to the pilot participants prior to their arrival at NASA Langley. The Pilot Guide included an overview of the PTM concept and provided details regarding PTM avionics, procedures, clearance types, flight deck displays, and modes. The Pilot Guide also included a section describing potential “irregular and non-normal” situations that might be experienced during PTM operations [e.g., loss of an Automatic Dependent Surveillance-Broadcast (ADS-B) signal during a PTM operation] and provided checklists associated “Loss of ADS-B Signal” and “Loss of Spacing.” The CBT training package was accessible via a web browser and included six modules with the following titles: “Introduction,” “Operations,” “Clearances,” “Displays,” “Displays 2,” and “Irregular Operations.”

Instructor-led PTM training materials, presented to pilot participants within a classroom setting at NASA Langley, consisted of a slide show presentation that included information pertaining to the PTM concept, procedures, and airborne HMI. Within this classroom setting, pilot participants used personal computer workstations equipped with headphones to individually review the CBT package’s modules.

Pilot participants flew as single pilots, as opposed to flying as a crew, using NASA Langley's Aircraft Simulation for Traffic Operations Research (ASTOR) aircraft, a medium fidelity desktop simulator (ref 1). As shown in Figure J-1, ASTOR aircraft were equipped with a functional prototype of the PTM HMI that was used to complete simulated PTM operations.

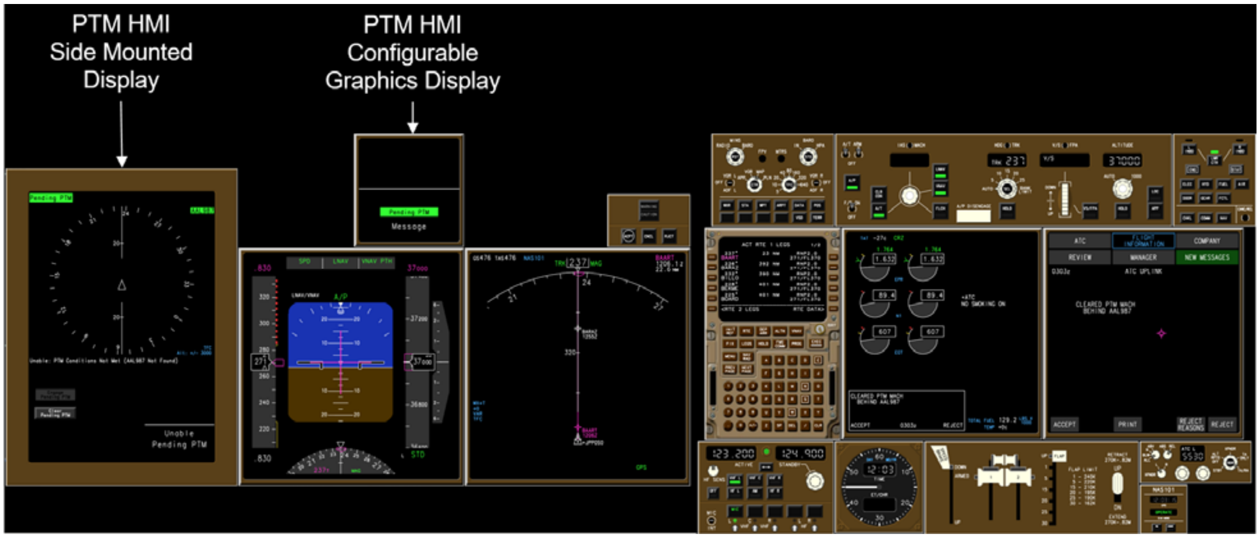

Figure J-1. Aircraft Simulation for Traffic Operations Research (ASTOR) aircraft equipped with functional airborne PTM HMI prototype.

Qualitative data were recorded from the pilot particpants using paper-and-pencil questionnaires. Additional information (e.g., comments regarding the HMI design's strengths and weaknesses and suggestions for design revisions) were collected by the research team via paper-and-pencil notes. No quantitative data recording took place.

Procedure

Three groups of four oceanic pilots each spent one day with the research team at NASA Langley. Eleven of the 12 pilot participants reported reading the Pilot Guide and completing the CBT package prior to arriving at NASA Langley. Immediately following the completion of an Informed Consent form, each pilot participant provided an initial assessment of the Pilot Guide and CBT package. Specifically, the pilots completed a 17-item questionnaire, comprised of forced-choice, multiple-choice, and check-all-that-apply questions, designed to assess the degree of knowledge and understanding that they had acquired through their independent review of the Pilot Guide's contents and the CBT package's six modules.

After completing the initial training materials assessment questionnaire, the pilots received instructor-led classroom training that involved detailed discussions of the PTM concept and procedures as well as the functionality and use of the airborne PTM HMI. As part of the instructor-led training session, pilot participants were asked to identify and comment upon anything presented by the instructor (i.e., a pilot SME and core member of the team responsible for designing the PTM concept, procedures, and HMI) that was not adequately covered within the Pilot Guide or CBT package.

Following the instructor-led training session, each pilot evaluated the CBT package in terms of its effectiveness, completeness, clarity, and speed of information presentation. Using a personal computer workstation equipped with headphones, pilots individually reviewed each of the six CBT modules and completed one 5-item questionnaire, comprised of 7-point likert-type rating scale and free response questions, in conjunction with each module. Then, the CBT package was presented in its entirety on a large projection screen, and the pilot participants engaged in a group discussion, facilitated by the research team, regarding specific aspects (both strengths and weaknesses) of the training materials' content and structure.

At this point, the pilot participants and research team moved from a classroom setting to a laboratory setting. Pilot participants were assigned to fly an ASTOR aircraft equipped with a prototype of the PTM HMI and were provided with an overview of the ASTOR aircraft's functionalty. Then, pilots flew three in-trail PTM scenarios. All three scenarios were presented to the pilot participants in the same order (i.e., Scenario 1, then Scenario 2, then Scenario 3). Neither counterbalancing nor partial counterbalancing was employed since this activity served as a HITL testing effort rather than a formal experiment.

Scenario 1 consisted of a PTM operation involving a Pair of aircraft. At scenario start up, the ownship (a PTM aircraft) is flying at cruise at Flight Level (FL) 360 (as shown in Figure J-2) during an oceanic crossing and has requested a flight level change to FL370.

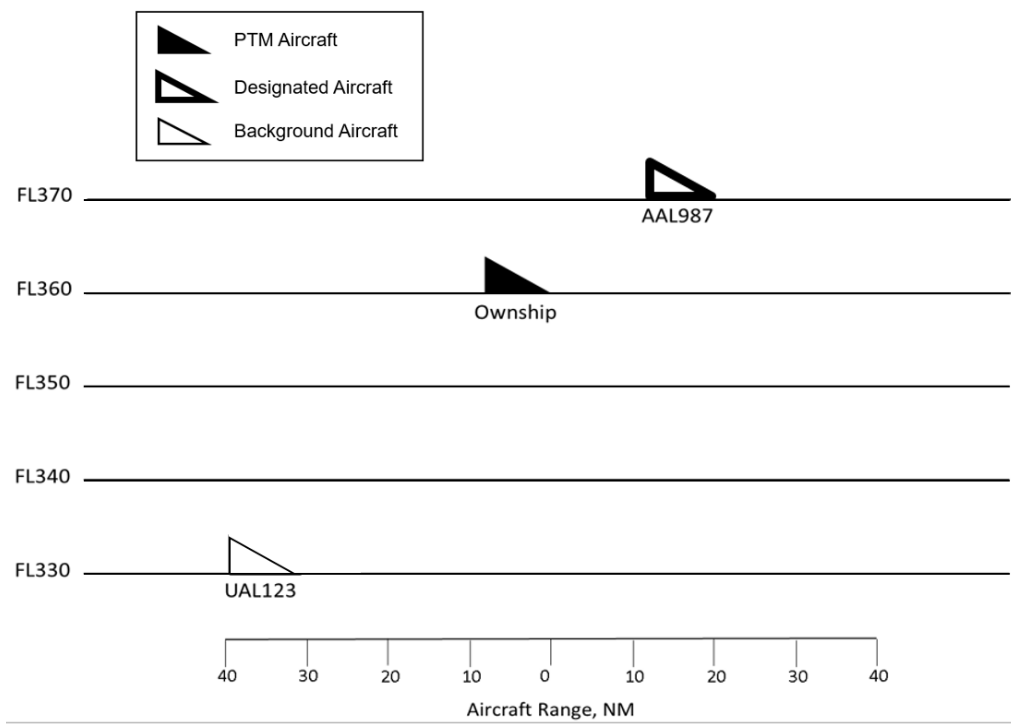

Figure J-2. HITL testing scenario 1: PTM operation involving a Pair of aircraft.

The ownship received the following PTM clearance from air traffic control (ATC) via controller-pilot data link communications (CPDLC): CLEARED PTM MACH BEHIND AAL987. The pilot engaged the PTM avionics (via the PTM HMI's side mounted display), accepted the PTM clearance (via CPDLC), and followed PTM Mach Guidance (presented on the PTM HMI's configurable graphics display). After two minutes, the following clearance was received from ATC and accepted by the ownship's pilot: CLIMB TO AND MAINTAIN FL370 REPORT REACHING FL370. The ownship's pilot climbed to, maintained, and reported reaching FL370. Ultimately, AAL987 (the designated aircraft) climbed, and (after five minutes) the following clearance was received from ATC and accepted by the ownship's pilot: CANCEL PTM RESUME MACH 0.83.

During Scenario 2, all conditions required to engage in a PTM operation were not met, therefore an “Unable PTM” situation was encountered by the ownship’s pilot. Specifically, the flight identifier of the designated aircraft (AAL987) was “not found” by the ownship’s FIM equipment. At scenario start up, the ownship (a PTM aircraft) was flying at cruise at FL370 (as shown in Figure J-3) during an oceanic crossing.

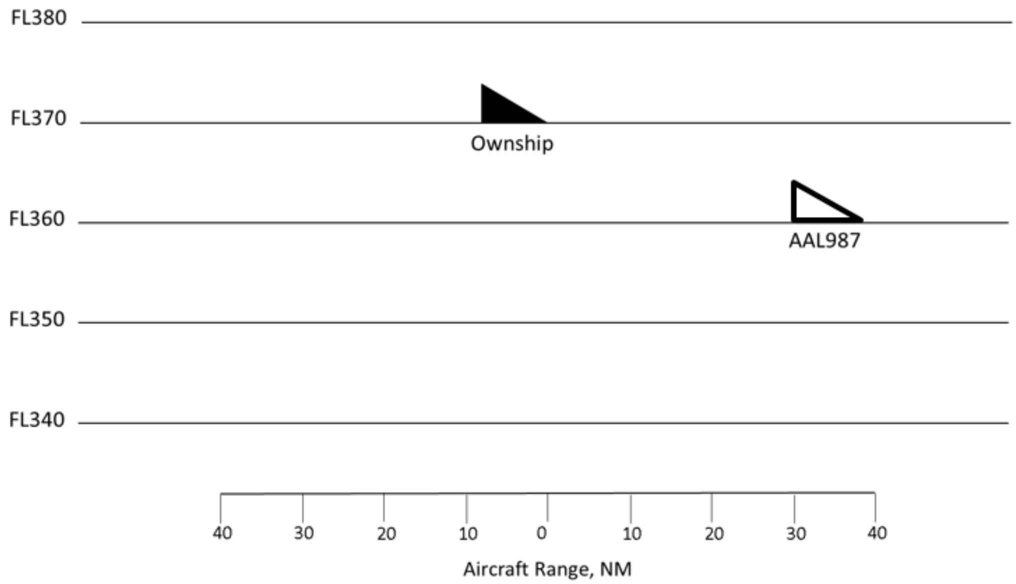

Figure J-3. HITL testing scenario 2: PTM conditions not met (flight identifier not found).

Another aircraft (AAL987) requested a flight level change to FL370. The following PTM clearance was received by the ownship’s pilot from ATC (via CPDLC): CLEARED PTM MACH BEHIND AAL987. The ownship’s PTM avionics did not receive a valid ADS-B Out signal from AAL987 and, as a result, presented the pilot with the following message (via the PTM HMI’s side mounted display): *Unable: PTM Conditions Not Met (AAL987 Not Found)*. The pilot cleared the pending PTM information from the PTM avionics (via the PTM HMI’s side mounted display), and the PTM avionics provided a message reminding the pilot to: *Reject PTM clearance with ATC*. The pilot rejected the PTM clearance with ATC (via CPDLC) and pressed the “Confirm Message Sent” button on the PTM HMI’s side mounted display.

Scenario 3 consisted of a PTM operation involving a Chain of three aircraft. At scenario start up, the ownship (a PTM aircraft) is flying at cruise at FL360 (as shown in Figure J-4) during an oceanic crossing and has requested a flight level change to FL370.

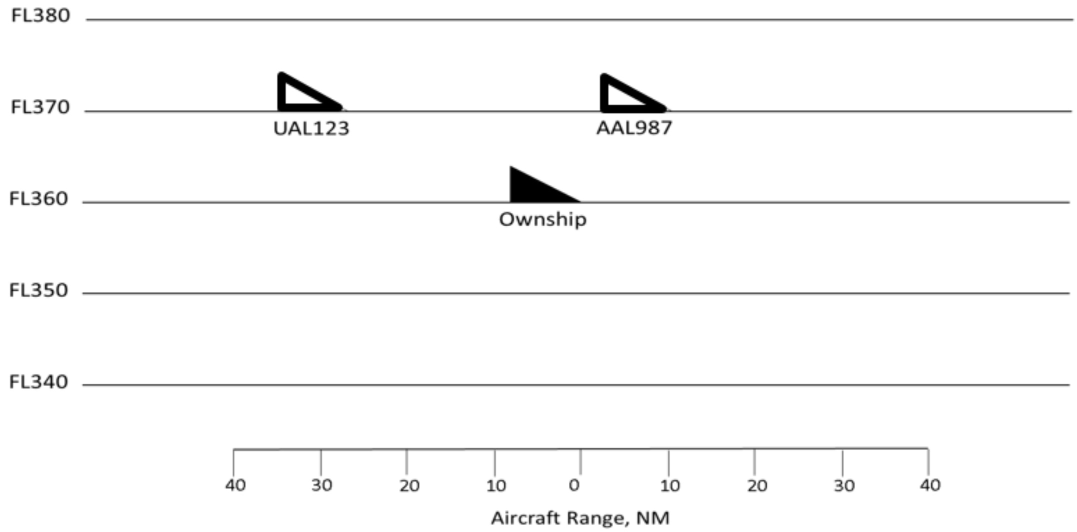

Figure J-4. HITL testing scenario 3: PTM operation involving a Chain of three aircraft.

The following PTM clearance was received by the ownship's pilot from ATC (via CPDLC): CLEARED PTM MACH AHEAD UAL123 BEHIND AAL987. The ownship's pilot engaged the PTM avionics (via the PTM HMI's side mounted display), accepted the PTM clearance (via CPDLC), and followed PTM Mach Guidance (presented on the PTM HMI's configurable graphics display). The following clearance was received from ATC and accepted by the ownship's pilot: CLIMB TO AND MAINTAIN FL370 REPORT REACHING FL370. The ownship's pilot climbed to, maintained, and reported reaching FL370. Ultimately, AAL987 (one of the two designated aircraft) climbed to FL380. The following clearance was received from ATC and accepted by the ownship's pilot: CONTINUE PTM AHEAD OF UAL123, REMOVE PTM AAL987. The ownship's pilot continued to follow PTM Mach Guidance (presented on the PTM HMI's configurable graphics display) until the scenario was concluded.

Following each scenario, pilot participants completed a 5-item questionnaire consisting of the Modified Cooper-Harper Subjective Workload Rating Scale (ref 2), two 7-point Likert-type rating scale questions (each coupled with free response), a forced-choice question (coupled with free response), and an additional free response item requesting that "any additional comments" be provided. Through these post-run questionnaires, qualitative data were collected in the form of subjective assessments of: workload; the acceptability of tasks required to complete a sample of PTM operations; the HMI's presentation of information needed to support pilot performance prior to, during, and following the conduct of a sample of PTM operations.

After completing their third and final post-run questionnaire, pilot participants provided responses to a 29-item post-experiment questionnaire comprised of forced-choice, Likert-type rating scale, and free response questions. This questionnaire was designed to gather pilot feedback regarding the PTM concept, integration of PTM into oceanic flight procedures, the PTM HMI, and final comments regarding the adequacy of the PTM training materials after having flown a sample of simulated PTM operations. The day's events concluded with a structured group debrief session facilitated by members of the research team.

RESULTS

Initial Pilot Knowledge of PTM and Feedback regarding PTM Training Materials

As mentioned previously, pilot participants were instructed to review the Pilot Guide and CBT package prior to their arrival at NASA Langley. Eleven of the 12 pilot participants reported reading the Pilot Guide in its entirety and completing the CBT package's six modules as instructed. Furthermore, soon after arriving at NASA Langley, each pilot completed an initial "training materials assessment" questionnaire designed to gauge the degree of knowledge and understanding that the pilots obtained through their independent review of the PTM training materials.

This initial "training materials assessment" questionnaire was scored as a "quiz," since each questionnaire item was developed such that it had a single correct response. On average, the pilots correctly answered 82% of the questionnaire's items [Standard Deviation (SD) = 0.116; minimum (min) score = 61%; maximum (max) score = 98%]. When asked to share initial impressions regarding the quality and effectiveness of the Pilot Guide and CBT modules, the pilots generally described the training materials as being well-designed, useful learning tools.

Pilot Assessment of the CBT Package

Overall, pilot participants found the CBT package's six modules to be effective, complete, and clear. Additionally, as shown in Table J-1, the pilots generally reported that information provided within the modules was presented at an appropriate rate or speed.

Table J-1. Pilot assessment of the PTM CBT package.

	Effectiveness of PTM CBT materials*	Completeness of PTM CBT materials**	Clarity of PTM CBT materials***	Speed of information presentation within PTM CBT materials****
Mean	6.167	6.417	6.250	3.833
SD	0.718	0.669	0.622	0.937
Min	5	5	5	1
Max	7	7	7	5
Sample size (N)	12	12	12	12

* Likert-type rating scale ranged from 1 (Not at all effective) to 7 (Very effective)
** Likert-type rating scale ranged from 1 (Not at all complete) to 7 (Very complete)
*** Likert-type rating scale ranged from 1 (Not at all clear) to 7 (Very clear)
**** Likert-type rating scale ranged from 1 (Much too slow) to 7 (Much too fast), with 4 corresponding to a rating of "Just Right"

Analysis of data collected through the post-experiment questionnaire showed that one-quarter of the pilot participants reported that self-guided PTM training, involving the use of a pilot guide document and CBT package, served as an appropriate level of required training. However, three-quarters of the pilots reported that instructor-led classroom and/or simulator training should also be required as part of a "minimum PTM training package."

HITL Testing Scenario 1: PTM Operation Involving a Pair of Aircraft

In general, the pilot participants found the PTM operation involving a Pair of aircraft to be straightforward and easily accomplished. As shown in Table J-2, pilots reported a mean workload rating of 1.583 (SD=0.669), using a scale of 1 to 10, with a rating of 10 corresponding to an impossibly difficult workload level. Furthermore, pilots reported a maximum workload rating of 3, indicating that they found the PTM operation involving a Pair of aircraft to be associated with a fair, mild level of difficulty and that an acceptable level of operator mental effort was required to attain adequate system performance.

Table J-2. Pilot feedback regarding a simulated PTM operation involving a Pair of aircraft.

	Workload Rating*	Overall acceptability of tasks required to complete the PTM operation**	Did the PTM HMI provide all of the information you needed?	Was information provided on the PTM HMI presented in an intuitive manner?
Mean	1.583	7	Yes: 100%	Yes: 100%
SD	0.669	0		
Min	1	7		
Max	3	7		
N	12	12	12	12

* Modified Cooper-Harper workload rating scale ranges from 1 to 10:
- "1" corresponds to "Very Easy, Highly Desirable Level of Difficulty; Operator Mental Effort is Minimal and Desired Performance is Easily Attainable"
- "3" corresponds to "Fair, Mild Level of Difficulty; Acceptable Operator Mental Effort Required to Attain Adequate System Performance"
- "10" corresponds to "Impossible; Instructed Task Cannot be Accomplished Reliably"

** Likert-type rating scale ranged from 1 (Completely Unacceptable) to 7 (Completely Acceptable)

When asked to assess the acceptability of the tasks required to complete the PTM operation involving a Pair of aircraft, all 12 pilots provided a qualitative rating of "completely acceptable." When asked to assess the PTM HMI's presentation of information, the pilot participants unanimously reported that the HMI provided all of the information that they needed to accomplish a PTM operation involving a Pair of aircraft, and they described the HMI's information presentation as being intuitive.

HITL Testing Scenario 2: PTM Conditions Not Met (Flight Identifier Not Found)

When the pilot participants encountered an "Unable PTM" situation as a result of all conditions required to engage in a PTM operation not being met, they reported a mean workload rating of 2.250 (SD=1.913) and a maximum workload rating of 7, using a scale that ranged from 1 to 10. As described in the "notes section" of Table J-3 below, a workload rating of 7 indicates that some of the pilots experienced “major difficulty” and felt that they were required to exert “maximum operator mental effort” in order to control or mitigate errors.

Table J-3. Pilot feedback regarding a simulated PTM operation during which PTM conditions were not met.

	Workload Rating*	Overall acceptability of tasks required to complete the PTM operation**	Did the PTM HMI provide all of the information you needed?	Was information provided on the PTM HMI presented in an intuitive manner?
Mean	2.250	5.917	Yes: 83.3% No: 16.67%	Yes: 63.64% Neutral / Undecided: 36.36%
SD	1.913	1.505		
Min	1	3		
Max	7	7		
N	12	12	12	11***

* Modified Cooper-Harper workload rating scale ranges from 1 to 10:
- “1” corresponds to “Very Easy, Highly Desirable Level of Difficulty; Operator Mental Effort is Minimal and Desired Performance is Easily Attainable”
- “3” corresponds to “Fair, Mild Level of Difficulty; Acceptable Operator Mental Effort Required to Attain Adequate System Performance”
- “7” corresponds to “Major Difficulty; Maximum Operator Mental Effort is Required to Bring Errors to Moderate Level”
- “10” corresponds to “Impossible; Instructed Task Cannot be Accomplished Reliably”

** Likert-type rating scale ranged from 1 (Completely Unacceptable) to 7 (Completely Acceptable)

*** One pilot participant did not complete the last page of the post-run questionnaire for HITL Testing Scenario 2

As outlined previously, the flight ID of the designated aircraft in HITL Testing Scenario 2 was “not found” by the ownship’s FIM equipment. Therefore, the pilot was required to clear the pending PTM information from the PTM avionics (via the PTM HMI’s side mounted display), and the PTM avionics provided a message reminding the pilot to: *Reject PTM clearance with ATC*. Following this, the pilot was required to reject the PTM clearance with ATC (via CPDLC) and press the “Confirm Message Sent” button on the PTM HMI’s side mounted display.

Several of the pilot participants reported that the ability to accept a PTM clearance with ATC using the flight deck communication system should not be possible when the PTM avionics determines that PTM conditions are not met. The potential for pilot acceptance of a PTM clearance, which indicates to ATC that a PTM operation is being conducted when, in fact, it is not possible for that PTM operation to occur, presents an opportunity for the occurrence of a very serious error that can – and should – be rendered impossible by the design of the HMI. As a result of the findings associated with the pilot participants’ conduct of HITL Testing Scenario 2, an important design requirement was identified with respect to the need for integration between PTM avionics and the flight deck communication system to ensure that it is impossible for a pilot to accept a PTM clearance when the PTM avionics indicates “Unable PTM.”

HITL Testing Scenario 3: PTM Operation Involving a Chain of Three Aircraft

Pilot participants described the PTM operation involving a Chain of aircraft as being “very workable” and as requiring a “‘normal’ adjustment period for proper scan and procedures.” As shown in Table J-4, pilots reported a mean workload rating of 1.417 (SD=0.669) and a maximum workload rating of 3. These workload rating indicate that the pilots found the PTM operation involving a Chain of aircraft to be associated with, at most, a fair or mild level of difficulty, requiring an acceptable level of operator mental effort to attain adequate system performance.

A slightly lower mean workload rating was reported by the pilot participants following the conduct of a PTM operation involving a Chain of three aircraft (i.e., 1.417) when compared with the mean workload rating that was reported following the conduct of a PTM operation involving a Pair of aircraft (i.e., 1.583). Although this difference may, at first, appear to be somewhat interesting, it is important to note that the difference between workload ratings associated with HITL Testing Scenarios 1 and 3 is probably not statistically significant, and it bears repeating that scenarios were presented to all pilot participants in the same order (i.e., Scenario 1, then Scenario 2, then Scenario 3) during the HITL testing effort. As such, learning effects are very likely influencing these workload rating data.

Table J-4. Pilot feedback regarding a simulated PTM operation involving a Chain of three aircraft.

	Workload Rating*	Overall acceptability of tasks required to complete the PTM operation**	Did the PTM HMI provide all of the information you needed?	Was information provided on the PTM HMI presented in an intuitive manner?
Mean	1.417	6.833	Yes: 100%	Yes: 100%
SD	0.669	0.389		
Min	1	6		
Max	3	7		
N	12	12	12	11***

* Modified Cooper-Harper workload rating scale ranges from 1 to 10:
- “1” corresponds to “Very Easy, Highly Desirable Level of Difficulty; Operator Mental Effort is Minimal and Desired Performance is Easily Attainable”
- “3” corresponds to “Fair, Mild Level of Difficulty; Acceptable Operator Mental Effort Required to Attain Adequate System Performance”
- “10” corresponds to “Impossible; Instructed Task Cannot be Accomplished Reliably”

** Likert-type rating scale ranged from 1 (Completely Unacceptable) to 7 (Completely Acceptable)

*** One pilot participant did not complete the last page of the post-run questionnaire for HITL Testing Scenario 3

When asked to assess the acceptability of the tasks required to complete the PTM operation involving a Chain of aircraft, the pilot participants provided a mean rating of 6.833 (0.389), using a scale of 1 to 7, with a rating of 7 corresponding to “completely acceptable.” When asked to assess the PTM HMI’s presentation of information, all 12 pilots reported that the HMI provided all of the information that they needed to accomplish a PTM operation involving a Chain of aircraft. Statements such as “all information was readily available”, and “all information was there to support my performance” were provided. Additionally, all 11 of the pilots that completed the final page of the post-run questionnaire for HITL Testing Scenario 3 described the HMI's information presentation as being intuitive.

Pilot Feedback regarding the PTM Concept and Integration of PTM into Oceanic Flight Procedures

Pilot participants unanimously reported that, based on their experience flying in oceanic airspace, they believed that improvements to the operation of a flight could be realized through the use of PTM. One pilot predicted that "fuel savings alone could pay for the efficiency that this system [i.e., PTM] could provide." When asked whether PTM would degrade or improve the efficiency and capacity of oceanic airspace, the pilot participants provided a mean rating of 6.917 (SD = 0.289), using a scale of 1 to 7, with a rating of 7 corresponding to "significantly improve."

When asked how difficult it would be for a typical oceanic flight crew to learn and integrate PTM into their oceanic flight procedures, the pilots provided a mean rating of 6.5 (SD=0.789), using a scale of 1 to 7, with a rating of 7 indicating that it would be "very easy" for an oceanic flight crew to learn and integrate PTM into their oceanic flight procedures. When asked to comment on the perceived change in workload for an oceanic flight crew authorized to incorporate PTM operations into their oceanic flight procedures, when compared to duties associated with current day operations, the pilot participants provided a mean rating of 4.083 (SD=1.165), using a scale of 1 to 7. As described in the "notes section" of Table J-5 below, a rating of 4 corresponded to "no change in workload." Furthermore, one pilot provided the following additional comment: "There might be a slightly higher workload [associated with the use of PTM]. However, the benefits outweigh the additional duties/tasks."

Table J-5. Pilot feedback regarding the PTM concept and integration of PTM into oceanic flight procedures.

	Based on your experience flying in oceanic airspace, do you believe that PTM can offer any improvement(s) to the operation of a flight?	In your opinion, would PTM degrade or improve the efficiency and capacity of oceanic airspace?*	How difficult would it be for a typical oceanic flight crew to learn and integrate PTM into their oceanic flight procedures?**	Perceived change in workload for an oceanic flight crew who incorporates PTM operations into their oceanic flight procedures***
Mean	100% Yes	6.917	6.5	4.083
SD		0.289	0.789	1.165
Min		6	5	3
Max		7	7	6
N	12	12	12	12

* Likert-type rating scale ranged from 1 (Significantly degrade) to 7 (Significantly improve)
** Likert-type rating scale ranged from 1 (Very difficult) to 7 (Very easy)
*** Likert-type rating scale ranged from 1 (Significant increase in workload) to 7 (Significant decrease in workload), with 4 corresponding to a rating of "No change in workload"

CONCLUSIONS

As a result of the PTM pilot training requirements focus group and HITL testing activities, several important conclusions were drawn. These are outlined below.

- It is recommended that a minimum PTM training package consist of self-guided training, involving the use of a pilot guide document and CBT package, as well as instructor-led classroom and/or simulator training.
- Pilots provided favorable ratings of workload, task acceptability, and HMI design after completing simulated PTM operations involving a Pair of aircraft (during HITL Testing Scenario 1) and a Chain of three aircraft (during HITL Testing Scenario 3).
- The conduct of HITL Testing Scenario 2 (Unable: PTM Conditions Not Met) highlighted the importance of integrating PTM avionics with the flight deck communication system to ensure that it is impossible for a flight crew to accept a PTM clearance with ATC when the PTM avionics indicates “Unable PTM.”
- All pilot participants reported that PTM has the potential to improve the efficiency and capacity of oceanic airspace and indicated that it would be relatively easy for a typical oceanic flight crew to learn and integrate PTM into their oceanic flight procedures.

Additionally, two examples of feedback received from pilots following their participation in the PTM pilot training requirements focus group and HITL testing activities are also noteworthy. The first example comes from a Boeing 787 Check Airman: “The [PTM] product is well developed, concise, easy to understand and will be a game changer when ‘it’ hits the streets. I would love to have the ability to use PTM today!” The second example comes from a Boeing 777 First Officer: “I am flying to London later this evening and will miss my PTM crossing the North Atlantic.”

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Appendix K: Rules for Determining Limit Mach for Clearances and Pairwise Trajectory Management (PTM) Operations

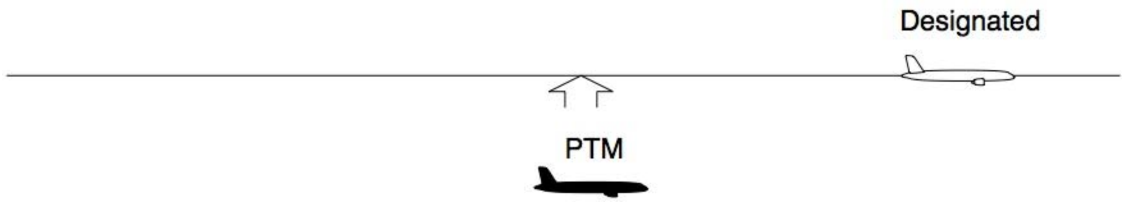
Version 2
21 September 2016
Victor Carreño

1. Introduction

This paper summarizes the rules that will determine the limit Mach that will be transmitted to a Pairwise Trajectory Management (PTM) aircraft during a clearance.

2. Rules for limit Mach determination

2.1. PTM Pair trailing



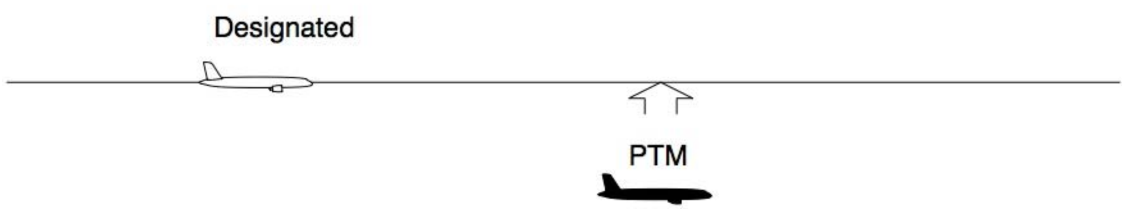
R.1. The limit Mach is the minimum of the designated aircraft's assigned Mach speed and the PTM aircraft current speed.

Limit $Mach_{PTM}$ = MIN($Mach_{desig}$, Current $Mach_{PTM}$)

If the designated aircraft has a range of speeds assignment, for example Mach 0.81 or greater, the limit Mach calculation will use the lower speed or 0.81 for $Mach_{desig}$.

Note: If the designated aircraft is leading and has an assigned speed, which allows it to arbitrarily slow down (for example 0.81 Mach or less), air traffic control (ATC) should not issue a PTM in-trail operation clearance.

2.2. PTM Pair leading



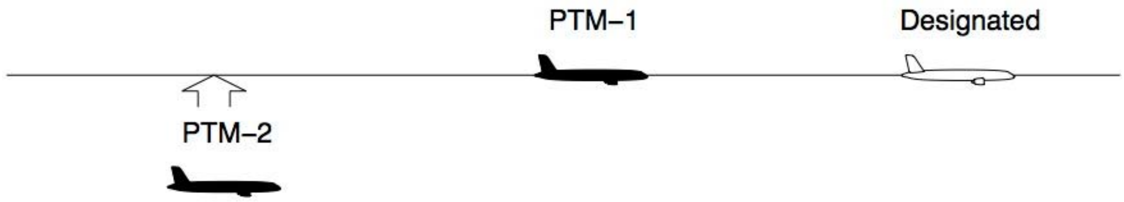
R.2. The limit Mach is the maximum of the designated aircraft's assigned Mach speed and the PTM aircraft current speed.

Limit $Mach_{PTM}$ = MAX($Mach_{desig}$, Current $Mach_{PTM}$)

If the designated aircraft has a range of speeds assignment, for example Mach 0.81 or less, the limit Mach calculation will use the upper speed or 0.81 for $Mach_{desig}$.

Note: If the designated aircraft is trailing and has an assigned speed, which allows it to arbitrarily speed-up (for example 0.81 Mach or greater), ATC should not issue a PTM leading operation clearance.

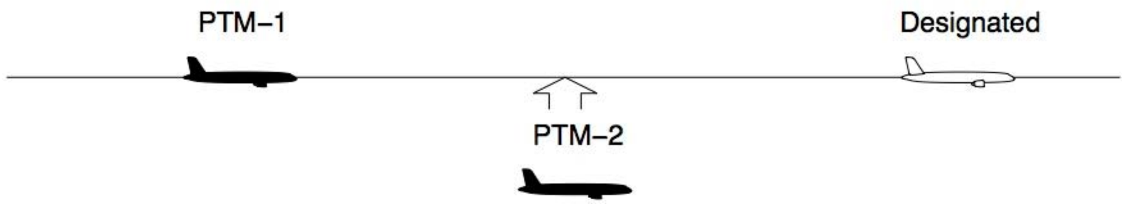
2.3. Forming a PTM String from a trailing PTM Pair, new aircraft at the end



R.3. The limit Mach for the new aircraft (PTM-2) is the minimum of the limit Mach of the trailing aircraft (PTM-1) and the new aircraft's current speed (PTM-2).

Limit $Mach_{PTM-2}$ = MIN(Limit $Mach_{PTM-1}$, Current $Mach_{PTM-2}$)

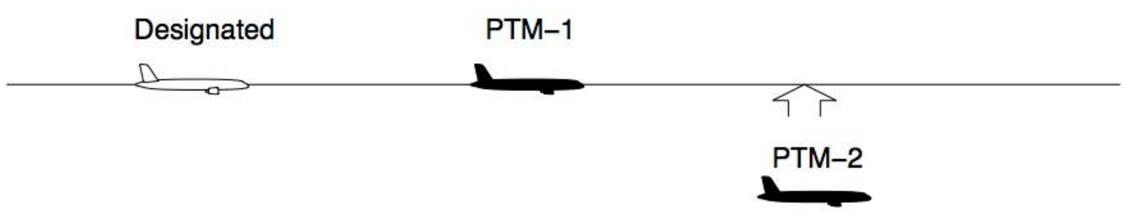
2.4. Forming a PTM String from a trailing PTM Pair, new aircraft in the middle



R.4. The limit Mach of the new aircraft inserted in the middle (PTM-2) is the limit Mach of the aircraft behind in the string (PTM-1).

Limit $Mach_{PTM-2}$ = Limit $Mach_{PTM-1}$

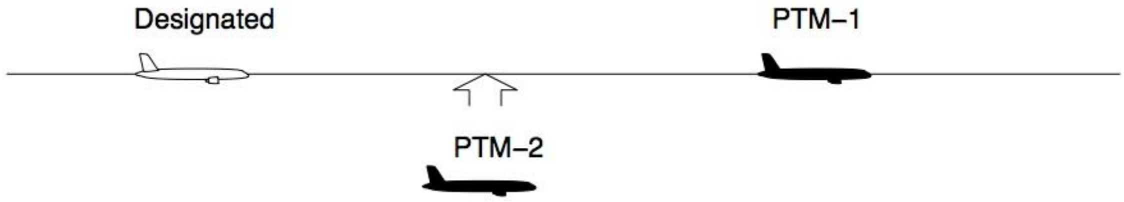
2.5. Forming a PTM String from a leading PTM Pair, new aircraft in the front



R.5. The limit Mach of the new aircraft (PTM-2) is the maximum of the limit Mach of the leading aircraft (PTM-1) and the new aircraft's current speed (PTM-2).

Limit $Mach_{PTM-2}$ = MAX(Limit $Mach_{PTM-1}$, Current $Mach_{PTM-2}$)

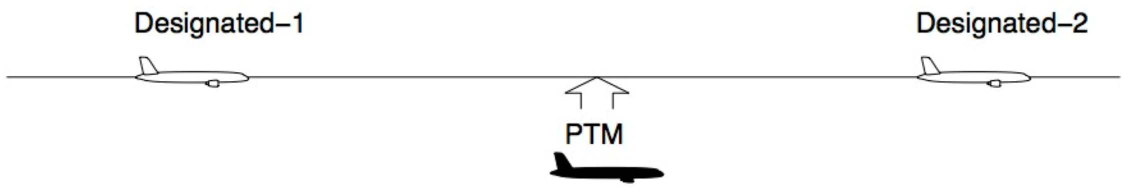
2.6. Forming a PTM String from a leading PTM Pair, new aircraft in the middle



R.6. The limit Mach of the new aircraft inserted in the middle (PTM-2) is the limit Mach of the aircraft in front in the string.

Limit $\text{Mach}_{\text{PTM-2}}$ = Limit $\text{Mach}_{\text{PTM-1}}$

2.7. Forming a PTM Chain



R.7. The limit Mach of the PTM aircraft is given by:

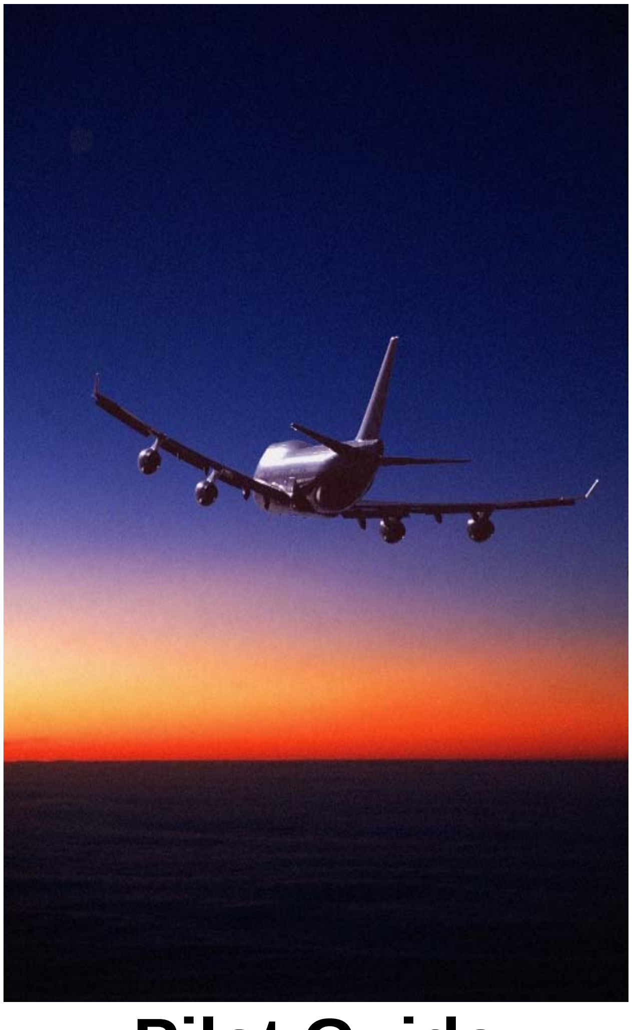
Limit $\text{Mach}_{\text{PTM}} = \text{MIN}(\text{MAX}(\text{Current Mach}_{\text{PTM}}, \text{Mach}_{\text{desig-1}}), \text{Mach}_{\text{desig-2}})$

2.8. Inserting an aircraft into a PTM Chain

R.8. The limit Mach of the new aircraft inserted in the Chain (PTM-2) is the limit Mach of the existing PTM aircraft in the Chain (PTM-1).

Limit $\text{Mach}_{\text{PTM-2}}$ = Limit $\text{Mach}_{\text{PTM-1}}$

Pairwise Trajectory Management (PTM)



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OVERVIEW OF PAIRWISE TRAJECTORY MANAGEMENT (PTM)

Future traffic predictions indicate there will be continued growth in oceanic operations. Even with recent improvements to oceanic surveillance and communications systems, required separation standards in oceanic airspace are still large enough to cause aircraft operational inefficiencies. These inefficiencies include flights being unable to operate at their desired altitude and speeds for extended periods of time, flights being unable to operate on their desired routes, and flights being required to change altitudes for crossing traffic. These system inefficiencies increase flight time and fuel burn and may cause aircraft to operate at altitudes with an undesirable ride.

Pairwise Trajectory Management (PTM) is designed to allow aircraft to resolve a specific traffic conflict (or conflicts), identified by an oceanic controller, with reduced spacing between aircraft. The oceanic controller, using ground automation system support, issues a pair-specific PTM clearance to a PTM equipped aircraft. When accepted, this PTM clearance will resolve the conflict for the specific pair of aircraft, and the controller's ground system will no longer display the conflict. The PTM clearance requires the flight crew of the PTM equipped aircraft to use their Automatic Dependent Surveillance Broadcast (ADS-B) enabled on-board avionics to manage their spacing relative to an "engaged" aircraft. The PTM avionics will provide speed guidance to ensure spacing distances are maintained that are no closer than the PTM spacing[1]. When the controller determines (with ground automation system support) that PTM is no longer required, the controller ends the PTM operation by issuing a clearance to the PTM equipped aircraft.

PTM will support same track operations (typically found in oceanic organized track systems) and crossing track operations (typically found with oceanic user preferred routes). Since PTM spacing is less than ground-based separation, a PTM equipped aircraft may not be required to modify its current speed in many crossing situations. PTM operations should save fuel and reduce delays by improving operations that increase time on an aircraft's optimal trajectory (track and altitude). PTM operations can allow for higher throughput and generally more efficient aircraft operations.

PTM operations are employed, depending on local constraints and traffic characteristics, to support several different types of operations. For example, a PTM clearance may be used to resolve a short-term conflict (such as one aircraft climbing through the altitude of another), or it may be used for an extended period of time (same track, same altitude).

The availability to use PTM to resolve a conflict does not necessarily make it the preferred option for the controller. PTM is not intended to take away the oceanic controller's discretion in managing the traffic in their sector. Likewise, the flight crew always has the option to refuse a PTM clearance if they determine it is not the best course of action.

[1] PTM spacing is 6.5 NM to account for the PTM separation standard distance (currently proposed to be 5 NM), plus an additional 1.5 NM buffer.

DEFINITIONS

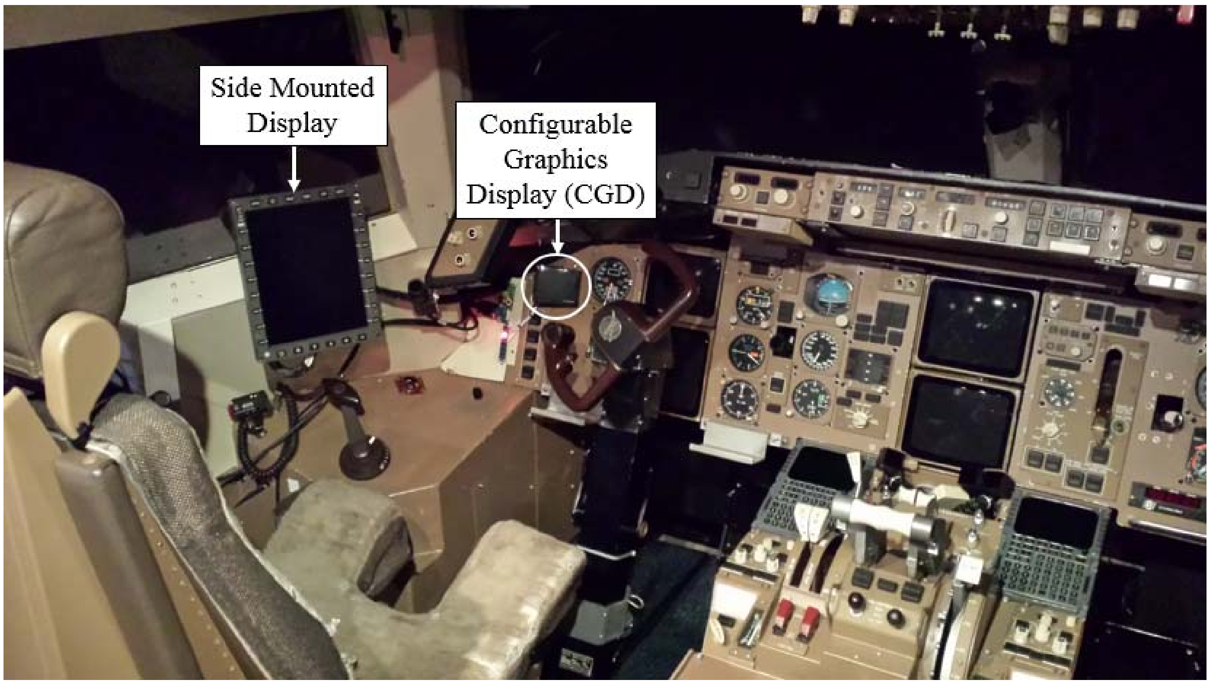
Add PTM Mach	Clearance from air traffic control (ATC) to increase the number of engaged aircraft included in an ongoing PTM operation.
Ahead of	PTM clearance geometry in which the PTM equipped aircraft is physically located in front (ahead) of an engaged aircraft.
Automatic Dependent Surveillance Broadcast (ADS-B)	A means by which aircraft, aerodrome vehicles, and other objects can automatically transmit and/or receive data such as identification, position, and additional data, as appropriate, in a broadcast mode via a data link.
Automatic Dependent Surveillance Contract (ADS-C)	A means by which the terms of an ADS-C agreement will be exchanged between the ground system and the aircraft, via a data link, specifying under what conditions ADS-C reports would be initiated, and what data would be contained in the reports.
Background aircraft	Any ADS-B Out aircraft, within ADS-B signal range, not serving as a pending or engaged aircraft in the ownship's PTM operation.
Behind	PTM clearance geometry in which the PTM equipped aircraft is physically located behind an engaged aircraft.
Cancel PTM	Clearance from ATC to stop performing PTM on all engaged aircraft.
Cancelled PTM	A mode within the airborne PTM avionics that occurs when a Cancel PTM clearance is received.
Cleared PTM Mach	Clearance from ATC to initiate a PTM operation.
Cockpit Display of Traffic Information (CDTI)	A pilot interface that includes, at a minimum, a graphical plan-view (top down) traffic display. The CDTI receives position information of traffic and ownship from an airborne surveillance and separation assurance processing (ASSAP) function, which receives such information from surveillance sensors and ownship position sensors.
Configurable Graphics Display (CGD)	A flight deck display located in the primary field of view that can be used by multiple applications to convey information necessary for performing the current operation. During PTM operations, the CGD will be used to display PTM Guidance, notifications, and alerts.
Continue PTM	Clearance from ATC requiring the PTM equipped aircraft to maintain a PTM operation with a specific engaged aircraft.
Controller-Pilot Data Link Communication (CPDLC)	A means of communication between controller and pilot, using data link for ATC communications.
Crossing	PTM clearance geometry in which the PTM equipped aircraft and engaged aircraft are not located in-trail of each other and their routes will intersect.
Engaged Aircraft	An aircraft from which the PTM equipped aircraft must maintain PTM spacing during a PTM operation.

Engaged PTM	A mode within the airborne PTM avionics that occurs when a PTM clearance has been accepted by the flight crew and PTM is being actively performed with one or more engaged aircraft.
Ground automation system	Computer automation that assists the controller by providing a means for communication, separation, and decision support.
Legacy Separation (or Non-PTM Separation)	Separation applied by ATC for a given airspace and aircraft equipage level. For example, 50 NM longitudinal and lateral separations can be applied with ADS-C reporting in intervals of 27 minutes and Required Navigation Performance 10 (RNP10) aircraft. Legacy separation specifically refers to a separation standard that is not associated with PTM separation.
Merge Ahead of	PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located in front (ahead) of the engaged aircraft once both aircraft are on the same track.
Merge Behind	PTM clearance geometry in which the PTM equipped aircraft is physically located on an intersecting track (initially) but will be located behind the engaged aircraft once both aircraft are on the same track.
No PTM	A mode within the airborne PTM avionics that occurs when either no PTM clearance has been received or after all PTM clearances have been cancelled.
Non-PTM Aircraft	An aircraft that has not been cleared to conduct a PTM operation. A non-PTM aircraft may serve as an engaged aircraft.
Pending Aircraft	An aircraft that has been included in a PTM clearance being reviewed by the flight crew. If the clearance is accepted, this aircraft will become an engaged aircraft. If the clearance is rejected, this aircraft will become a background aircraft.
Pending PTM	A mode within the airborne PTM avionics that occurs when a PTM clearance has been received, but the flight crew has not yet engaged the PTM avionics and begun conducting the PTM operation with the aircraft included in the clearance.
Pending PTM Guidance	During a Pending PTM mode, this guidance provides the flight crew with a preview of what the PTM Guidance will be if the PTM clearance is accepted.
Procedural Control	Term used to indicate that information derived from an air traffic services surveillance system is not required for the provision of ATC service.
Procedural Separation	Separation used when providing procedural control.
PTM Avionics	The on-board hardware, software, and displays necessary to perform PTM operations.
PTM Equipped Aircraft	An aircraft that has PTM avionics installed on-board.

PTM Guidance	A series of Mach commands and restrictions provided by the PTM avionics to ensure that PTM spacing is maintained for 30 minutes.
PTM Separation Standard	A procedure that, when applied, allows for PTM operations to be conducted while maintaining the required PTM separation standard distance.
PTM Separation Standard Distance	A horizontal distance (currently proposed to be 5 NM) that must be maintained during a PTM operation. The horizontal distance between a PTM equipped aircraft and an engaged aircraft shall never be less than the PTM separation standard distance while a PTM operation is in effect.
PTM Spacing	A distance comprising the PTM separation standard distance plus a distance buffer. The PTM avionics provides guidance to the flight crew to achieve the PTM spacing (Note: 5 NM PTM separation standard distance + 1.5 NM distance buffer = 6.5 PTM spacing).
Remove PTM	Clearance from ATC to stop performing PTM on a specific engaged aircraft.
Separation Standard	A procedure that ATC applies to aircraft traffic to maintain required separation between aircraft. When ATC is applying a separation standard, the distance between aircraft shall never be less than the separation standard distance.
Separation Standard Distance	A minimum distance that shall never be infringed upon during aircraft operations.
Side Mounted Display	A flight deck display that can be located outside of the flight crew’s forward field of view and is used for information that is not required to operate the aircraft. A CDTI can be hosted on a side mounted display. During PTM operations, this equipment will be used for situation awareness and to review, engage, and acknowledge cancelation of all PTM operations.

PTM AVIONICS

Two key pieces of avionics will be used in the flight deck to conduct PTM operations: a side mounted display and a forward mounted configurable graphics display (CGD). Pilots will use the side mounted display to review PTM clearances, engage or clear the PTM avionics, review displayed messages, indications, and alerts, and as a situation awareness display tool. The CGD will display the PTM Guidance as well as indications that advise the flight crew to review the side mounted display. The CGD is located in the flight crew's primary field of view and is intended to be the primary display used to ensure conformance with PTM Guidance during PTM operations. Controller-Pilot Data Link Communication (CPDLC) is also assumed to be in use during PTM operations.



PTM PROCEDURES

PTM operations are intended to be used anytime aircraft are projected to be closer than an available separation standard that the controller can apply using ground automation system support. This distance or time varies due to aircraft equipage and airspace, but as a rule of thumb is from 30 to 50 nautical miles (NM) on the Pacific Organized Track System (PACOTS) routes, 5 or 10 minutes on the North Atlantic Organized Track System (NATOTS) routes, and 30 NM to 10 minutes when flying the Central East Pacific (CEP) routes. If PTM operations are used, the separation standard decreases to 5 NM with the PTM avionics providing guidance to maintain a minimum 6.5 NM spacing. PTM Guidance will maintain the PTM spacing of 6.5 NM or greater. This spacing can be maintained on in-trail, merging, and crossing routes. This will greatly increase the available airspace at a given altitude on oceanic routes, permitting most equipped aircraft to fly at whatever altitude and airspeed is desired.

PTM clearances will always originate with the controller. The flight crew will never request a PTM clearance. The PTM clearance will be issued to allow a reduced separation standard between aircraft to satisfy a route or altitude request from either the PTM equipped aircraft or a non-PTM aircraft. Therefore, a non-PTM aircraft could request a clearance that requires a reduced separation standard, and a PTM clearance would be issued to the PTM equipped aircraft. The PTM equipped aircraft is never required to accept the PTM clearance and may reject it when it is issued, with the understanding that the clearance is usually beneficial to all aircraft involved.

One example of when a PTM clearance might be issued is when an aircraft requests a climb to or through an altitude that will place that aircraft at less than standard longitudinal separation from one or more aircraft. A PTM clearance might also be issued if a non-PTM aircraft requests to fly at or pass through a PTM equipped aircraft's altitude even though the PTM equipped aircraft did not originate the request. Additionally, aircraft on merging or crossing routes might receive a PTM clearance to allow the crossing to occur while both aircraft remain at the same altitude.

The engaged aircraft that the PTM avionics is basing guidance on can be located ahead of, behind, or both ahead of and behind a PTM equipped aircraft. In crowded airspace, this could mean that several aircraft serve as engaged aircraft. In operations, the PTM Guidance is determined by the closest engaged aircraft that is located in front of and behind ownship. Since a PTM clearance is a Mach clearance (the Mach being determined by on-board avionics), it is referred to as a "PTM Mach" clearance in the CPDLC messages. When the PTM Mach clearance is cancelled, the controller should issue a new assigned Mach (or resume normal Mach).

A PTM clearance will only be issued by ATC when a conflict using the separation standard available to the controller exists. The controller will end the PTM operation when it is no longer needed.

A sample PTM procedure is as follows:

1) The flight crew of a PTM equipped aircraft receives a PTM Mach clearance over CPDLC. The PTM clearance is shown on the communication system and information from the CPDLC message is auto-loaded into the PTM avionics and shown on the side mounted display.

2) The flight crew analyzes the Pending PTM information presented on the side mounted display to determine if the clearance is acceptable. As shown in the "PTM Flight Deck Displays" section of this Pilot Guide, the side mounted display shows the relative position of traffic on the CDTI and presents information regarding assigned Mach of all pending aircraft in the display's Message Area. The assigned Mach of a pending aircraft could become a limiting speed (maximum, minimum, or the only available speed, depending on geometry) at some time in the future.

3) The flight crew examines the Pending PTM Guidance to determine if they will be able to follow the guidance during the PTM operation for which they have been cleared.

4) If acceptable[2], the flight crew engages the PTM avionics using the side mounted display and accepts the PTM clearance using CPDLC.

5) The flight crew continues operations, making sure that the flight crew selected Mach complies with the PTM Guidance presented by the PTM avionics. Climbs, descents, and block altitudes can be requested by the flight crew and issued by ATC during PTM operations.

6) The flight crew receives a Cancel PTM clearance with a Mach assignment. The flight crew must accept the Cancel PTM clearance. The flight crew acknowledges the PTM cancellation using the side mounted display and accepts the clearance using CPDLC.

[2] If the PTM clearance was not acceptable when received, the flight crew rejects the clearance through CPDLC and clears the Pending PTM information from the side mounted display.

PTM CLEARANCE TYPES

PTM clearances will be delivered to the PTM equipped aircraft via CPDLC. Information from the clearance will be auto-loaded into the PTM avionics and displayed on the side mounted display. This information includes, among other items, the pending aircraft's flight identification (ID) and assigned Mach.

PTM clearances can clear a PTM equipped aircraft "AHEAD OF", "BEHIND", "MERGE AHEAD OF", "MERGE BEHIND", or "CROSSING" another aircraft. There can be multiple aircraft contained in a PTM clearance.

The controller may add or remove engaged aircraft from the PTM operation as necessary. The word "ADD" is used to add an engaged aircraft to an ongoing PTM operation while the word "REMOVE" is used to remove an engaged aircraft from an ongoing PTM operation. The word "CONTINUE" is used to identify engaged aircraft that remain the same in a new clearance. When PTM is no longer needed for any engaged aircraft, the controller issues a Cancel PTM clearance.

Example PTM clearances include:

- CLEARED PTM MACH AHEAD OF UAL345
  The PTM equipped aircraft is cleared to use PTM MACH ahead of aircraft UAL345. If the flight crew accepts the clearance, the PTM equipped aircraft will be located in front of engaged aircraft UAL345.

- CLEARED PTM MACH BEHIND UAL345
  The PTM equipped aircraft is cleared to use PTM MACH behind aircraft UAL345. If the flight crew accepts the clearance, the PTM equipped aircraft will be located behind engaged aircraft UAL345.

- CLEARED PTM MACH AHEAD OF UAL345, BEHIND UAL123
  The PTM equipped aircraft is cleared to use PTM MACH ahead of aircraft UAL345 and behind aircraft UAL123. If the flight crew accepts the clearance, the PTM equipped aircraft will be located in front of engaged aircraft UAL345 and behind engaged aircraft UAL123. PTM Guidance will ensure that PTM spacing is maintained with respect to both engaged aircraft.

- CONTINUE PTM MACH UAL345, UAL123
  ADD PTM MACH AHEAD OF UAL863, AHEAD OF UAL436
  The PTM equipped aircraft is cleared to continue PTM operation with engaged aircraft UAL345 and engaged aircraft UAL123 and to add aircraft UAL863 and aircraft UAL436 to the PTM operation. If the flight crew accepts the clearance, the PTM equipped aircraft will be located in front of all four of the engaged aircraft (UAL345, UAL123, UAL863, and UAL436). If the flight crew rejects the clearance, the PTM equipped aircraft will continue PTM operation with engaged aircraft UAL345 and engaged aircraft UAL123.

- CONTINUE PTM MACH UAL436, UAL863
  REMOVE PTM UAL123, UAL345
  The PTM equipped aircraft is cleared to continue PTM operation with engaged aircraft UAL436 and engaged aircraft UAL863 and to remove engaged aircraft UAL123 and engaged aircraft UAL345 from the PTM operation. The flight crew must accept a remover clearance. Therefore, only UAL436 and UAL863 will serve as engaged aircraft in the PTM operation.

- CLEARED PTM MACH MERGE AHEAD OF UAL345
  The PTM equipped aircraft is cleared PTM MACH with aircraft UAL345. The PTM equipped aircraft and UAL345 are not currently on the same route. However, at the point of the merge to a common route, the PTM equipped aircraft will be located in front of UAL345.

- CLEARED PTM MACH MERGE BEHIND UAL345
  The PTM equipped aircraft is cleared PTM MACH with aircraft UAL345. The PTM equipped aircraft and UAL345 are not currently on the same route. However, at the point of the merge to a common route, the PTM equipped aircraft will be located behind UAL345.

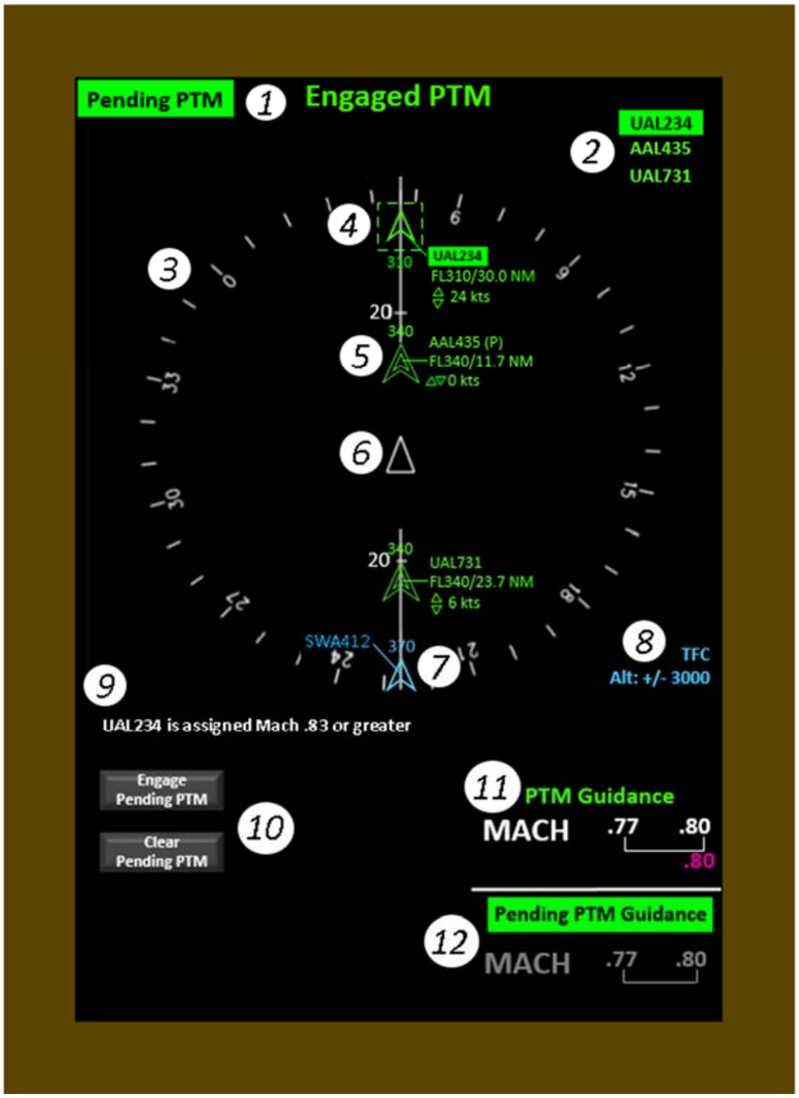
- CLEARED PTM MACH CROSSING UAL345
  The PTM equipped aircraft is cleared PTM MACH where its track crosses aircraft UAL345's track.

- CANCEL PTM, RESUME MACH .82
  A Cancel PTM clearance removes all engaged aircraft from the PTM operation. ATC will also include a new speed command (assigned Mach or other command) in a Cancel PTM clearance since the PTM equipped aircraft is no longer following PTM Guidance.

PTM FLIGHT DECK DISPLAYS

The PTM avionics contains two types of flight deck displays: a side mounted display and a CGD. These displays, which show information elements relating to PTM operations, are described in detail below.

SIDE MOUNTED DISPLAY



1 – PTM Mode Indicator. Displays current status of PTM. Can display one of the following five modes:

- “Pending PTM”
- “Engaged PTM”
- “Pending PTM” & ”Engaged PTM”
- “Cancelled PTM”
- “NO PTM”

2 – Flight Identification (ID) List. Displays flight ID of all aircraft that are or may become engaged in a PTM operation with the ownship. Normal text indicates engaged aircraft. Reverse video text indicates pending aircraft. Aircraft flight ID’s are listed in the order that aircraft symbols appear on the CDTI, from top to bottom.

3 – Cockpit Display of Traffic Information (CDTI). Displays ownship symbol and ADS-B traffic that is within ADS-B signal range. Current heading is shown in the compass rose located around the perimeter of the CDTI. Distance is shown by the tick marks on the center lubber line. Various range scales may be selected (as described later).

4 – Pending Aircraft Symbol and Data Tag. Each pending aircraft is displayed as a single green chevron surrounded by a dashed box. Flight ID is shown in reverse video text. The rest of the data tag is shown in green text.

5 – Engaged Aircraft Symbol and Data Tag. Each engaged aircraft is displayed as a double green chevron. The information in data tags associated with engaged aircraft can be reduced by the pilot, leaving only the flight ID.

6 – Ownship Aircraft Symbol. Ownship is displayed as a hollow white triangle.

7 – Background Aircraft Symbol and Data Tag. Each ADS-B Out aircraft not being used by ownship as pending or engaged aircraft in a PTM operation is displayed as a single cyan chevron. Only the flight ID is included in a background aircraft's data tag, and the flight ID can be removed by the pilot (as described later).

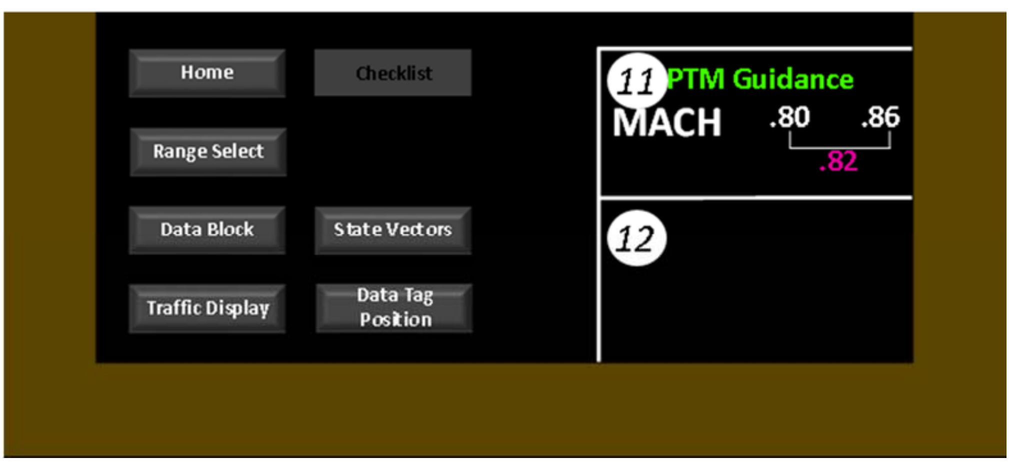
8 – Background Traffic Indicator. Shows the altitude filter applied to determine which background aircraft are displayed. The setting for the Altitude Filter is changed within the Traffic Display menu (as described later). The Background Traffic Indicator serves as a selectable area of the display screen and may be used to toggle background traffic off/on. When background traffic is off, **TFC OFF** is displayed.

9 – Message Area. PTM related messages are displayed in this area. White text is associated with information and indications; amber text is associated with cautions; and white text with red highlighting is associated with warnings.

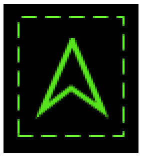
10 – Selectable Buttons. Various buttons, used to interact with the PTM avionics, are displayed depending on the PTM mode. Two columns of buttons are displayed during the "Engaged PTM" mode (in contrast to the combined "Pending PTM / Engaged PTM" mode shown above). During Engaged PTM operation, additional data associated with a pilot selected aircraft may be displayed in a data block that replaces the right column of buttons. The right column of buttons can also be replaced with a checklist during rare non-normal events.

11 – PTM Guidance. Displays Mach guidance (in white) that ownship is allowed to fly during Engaged PTM mode. Flight crew selected Mach for ownship is shown in magenta. During Engaged PTM mode, this area "repeats" the PTM Guidance shown on the CGD. When areas 11 and 12 display the exact same information as that shown on the CGD, areas 11 and 12 of the side mounted display are segregated by white border lines on the top and left.

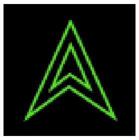
12 – Multi-Use Information Area. Displays information pertaining to PTM, but is normally blank. During the Pending PTM mode, "Pending PTM Guidance" is displayed (in grey) to show the flight crew the PTM Guidance that ownship will be required to fly if a pending PTM clearance is accepted. There are times (as described later), when the PTM avionics determines that PTM conditions are not met when ATC issues a PTM clearance. When this occurs, the words "Unable Pending PTM" are shown (in white) since the option to accept the PTM clearance is not available to the flight crew. Other than in a Pending PTM mode, the word "Message" is displayed in area 12 when a message is shown in the Message Area. Additionally, when areas 11 and 12 display the exact same information as that shown on the CGD, areas 11 and 12 of the side mounted display are segregated by white border lines on the top and left.



Details Regarding the Side Mounted Display's CDTI and Flight ID List



Pending Aircraft. Displayed as a single green chevron surrounded by a dashed box. Pending aircraft are included in a pending PTM clearance that has not yet been accepted or rejected by the flight crew.



Engaged Aircraft. Displayed as a double green chevron. Engaged aircraft are aircraft from which ownship must maintain PTM spacing.

Engaged Aircraft associated with a Caution. An engaged aircraft involved in a situation requiring immediate flight crew awareness and possible future corrective action (e.g., loss of the engaged aircraft's ADS-B signal for a period of time greater than 25 seconds but less than 5 minutes) will be displayed in amber.

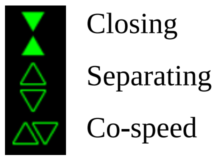
Engaged Aircraft associated with a Warning. An engaged aircraft involved in a situation requiring immediate flight crew action (e.g., an imminent loss of separation) will be displayed in red.

Engaged Aircraft State Vector. Displayed as a time line with a 5 NM (radius) circle drawn around the predicted point. Each dash on the timeline represents 30 seconds into the future.

Background Aircraft. Displayed as a single cyan chevron. Background traffic are aircraft with a received ADS-B signal that are not serving as engaged or pending aircraft in the ownship's PTM operation.

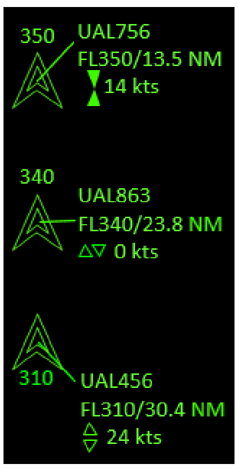
Altitude Above/Below Aircraft Symbol. Altitude is shown above an aircraft symbol (pending, engaged, or background) if the aircraft is located above ownship, and below the aircraft symbol if the aircraft is located below ownship. Altitude is shown either above or below if co-altitude based on the previous location of the aircraft relative to ownship.

Data Tag for Same Track Engaged Aircraft. Displays Flight ID, Altitude, Distance, and Closure information. Flight ID is shown in reverse video (UAL233) for pending aircraft. If ownship serves as an engaged aircraft for another aircraft (pending, engaged, or background), a (P) is included in that aircraft's data tag, following its flight ID. The (P) will be shown in reverse video for pending aircraft and will be cyan for background aircraft.



Data Tag Closure Symbology. Displays the relative closure between ownship and a pending or engaged aircraft. (Note: Closure symbology is also shown in conjunction with any engaged or background aircraft when additional information for that aircraft is displayed within a data block located on the side mounted display.)

Data Tag for Crossing Engaged Aircraft. Displays Flight ID, Altitude, and Projected Closest Distance (e.g., PCD 7.6 NM A). PCD is the distance between ownship and a pending or engaged aircraft at their closest point of approach. In this example, the ownship will cross a common point (common to ownship's and engaged aircraft's route) ahead of the engaged aircraft, therefore the letter "A" follows the PCD value of 7.6 NM. If the ownship were to cross a common point behind the engaged aircraft in this example, the letter "B" would follow the PCD value of 7.6 NM. Flight ID will be shown in reverse video (**UAL233**) for pending aircraft.



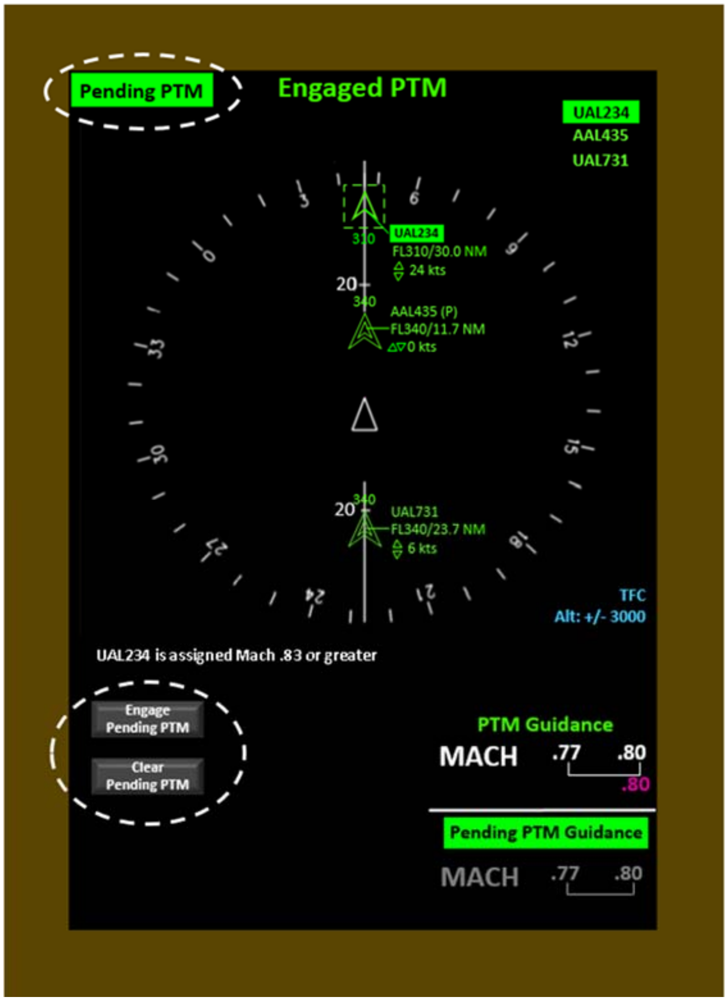
Data Tag Position. Data tag will change position in relation to an aircraft's (pending, engaged, or background) altitude with respect to ownship. If the aircraft is above ownship, the data tag will be above the aircraft symbol. If at same altitude, the data tag will be level with the aircraft symbol. If the aircraft is below ownship, then the data tag will be below the aircraft symbol. Flight ID will be shown in green reverse video for pending aircraft and will be cyan for background aircraft.

Flight ID List. Located in the upper right corner of the side mounted display. Displays flight IDs for all pending and engaged aircraft. Flight IDs for pending aircraft are shown in green reverse video, and flight IDs for engaged aircraft are shown in green. Amber flight IDs are displayed when engaged aircraft are involved in caution situations, and red highlighted flight IDs are displayed when engaged aircraft are involved in warning situations. Flight IDs are listed in the order that their corresponding aircraft symbols appear on the CDTI, from top to bottom.

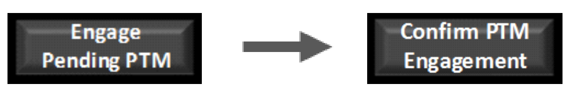
Details Regarding the Side Mounted Display's Selectable Buttons

Note: PTM modes are described in detail in a subsequent section of this Pilot Guide.

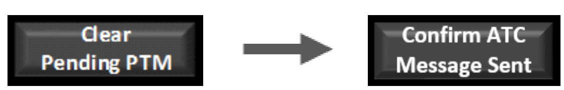
Buttons available for use during Pending PTM mode:



Engage Pending PTM. Appears whenever a pending PTM clearance is received and the PTM avionics enters a Pending PTM mode. If the clearance is acceptable, the flight crew presses this button and confirms PTM engagement with a subsequent button press to engage PTM avionics.

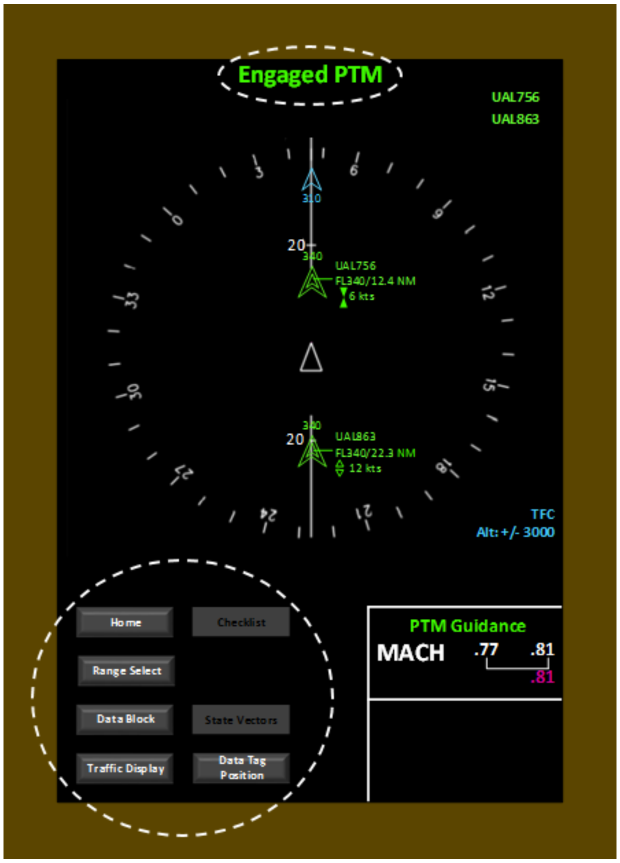


Clear Pending PTM. Appears whenever a pending PTM clearance is received and the PTM avionics enters a Pending PTM mode. When a PTM clearance is rejected by the flight crew (using CPDLC), this button and a subsequent confirmation button must be pressed to clear Pending PTM information from the PTM avionics.

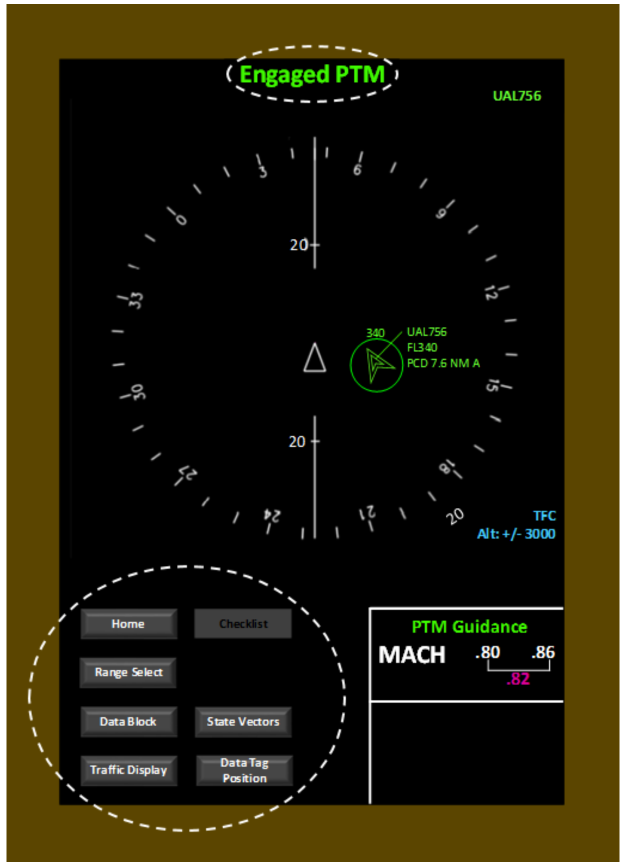


<u>Buttons available for use during Engaged PTM mode</u>:

Engaged Mode – In-Trail



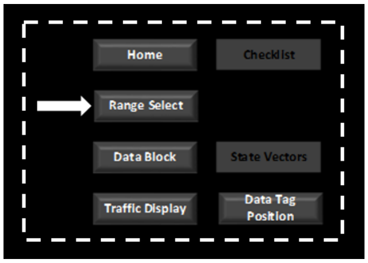
Engaged Mode – Crossing

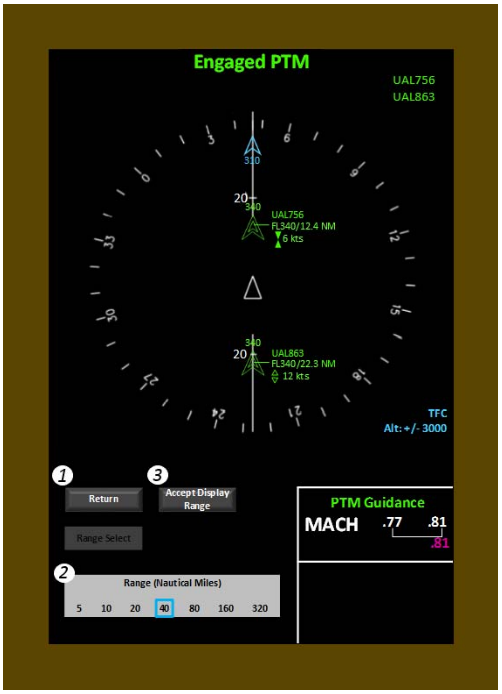


NOTE: All buttons available during Engaged mode (In-Trail) are also available during No PTM mode.

NOTE: Use of the "Checklist" button is described in detail in a subsequent section of this Pilot Guide.

Range Select. Allows CDTI range scale to be changed.





Range values of 5, 10, 20, 40, 80, 160, and 320 NM are available.

1 – ‘Return’ button will exit the Range Select menu to previous screen with the range reverting to the last accepted setting.

2 – ‘Range (Nautical Miles)’ bar is used to select the various CDTI ranges. When a range value is selected, the range will change on the CDTI.

3 – ‘Accept Display Range’ button will accept the current display range and exit the Range Select menu with the current setting becoming the new range for the CDTI.

The range can never be set permanently so that any engaged aircraft is off scale. The range can only be displayed while in the Range Select menu and will revert to the last accepted setting when ‘Return’ is pressed.

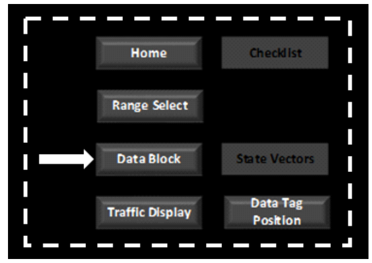
1 – Message indicating that an engaged aircraft is off scale.

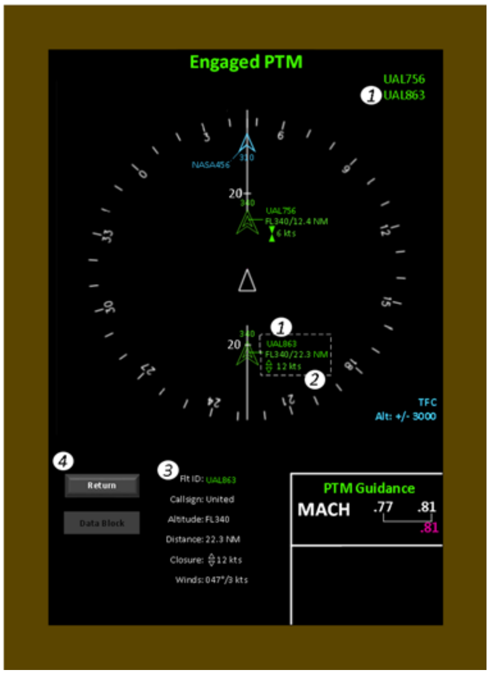
2- ‘Accept Display Range’ button is dimmed and not active. This display range selection is not valid and cannot be accepted.

3 – ‘Return’ button will exit the Range Select menu to previous screen with the range reverting to the last accepted setting.

NOTE: If a range scale has been accepted and an engaged aircraft subsequently goes off scale, an auto range feature will increase the range scale automatically to bring the engaged aircraft into view. The auto range feature will also increase the range scale when a PTM clearance is received and a pending aircraft is not within the displayed range.

Data Block. Allows the display of additional information for a selected aircraft.





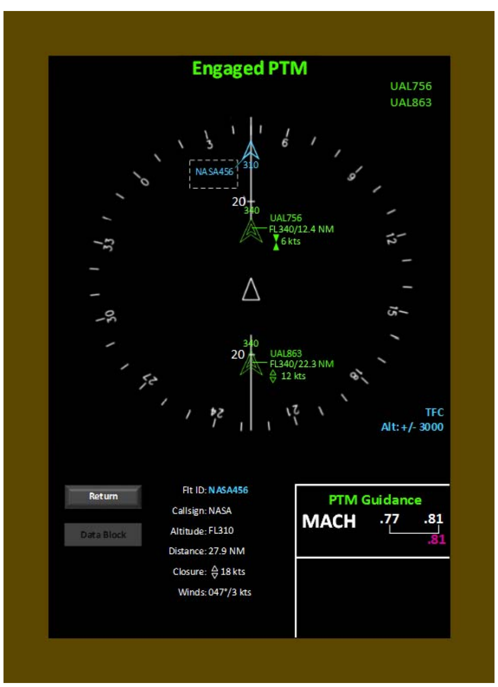
1 – When the ‘Data Block’ button is pressed, additional information for a selected aircraft can be displayed by pressing either an aircraft’s data tag or its flight ID entry in the Flight ID List.

2 – The selected aircraft’s data tag will be surrounded by a dashed white box.

3 – The additional information displayed for a same track aircraft includes flight ID, actual radio callsign, altitude, along-track distance, along-track closure, and aircraft reported winds.

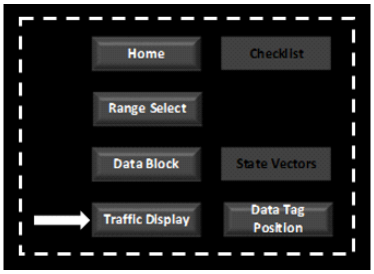
4 – ‘Return’ is used to exit the Data Block menu.

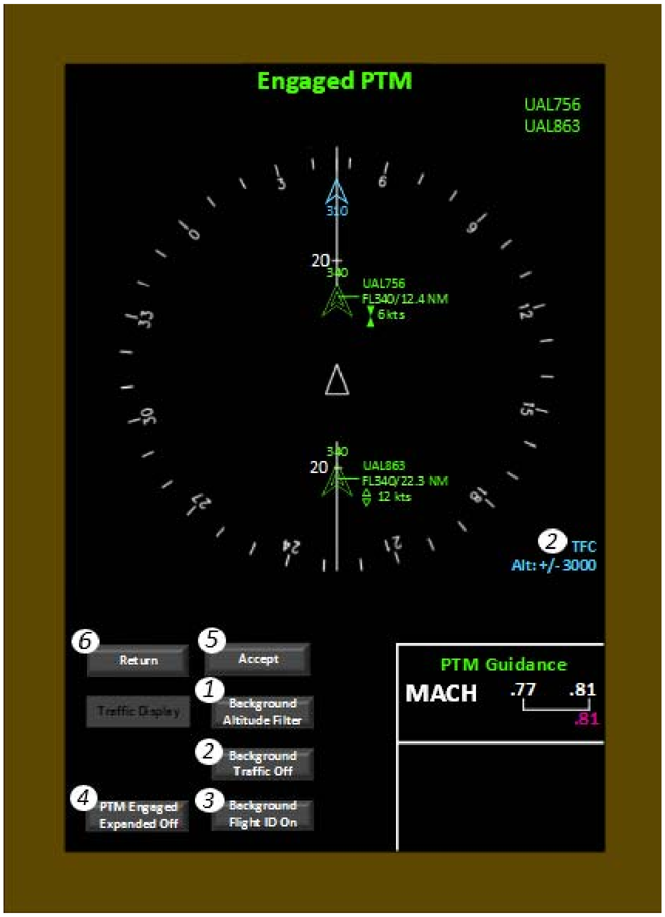
NOTE: The additional information displayed for a crossing aircraft includes flight ID, actual radio callsign, altitude, projected closest distance (in NM) (instead of distance and closure information), and aircraft reported winds.



Additional information may be displayed for a background aircraft. However, aircraft selection can only be made by pressing the aircraft’s data tag since flight IDs for background aircraft are not included in the Flight ID List.

Traffic Display. Allows the configuration of various display features within the CDTI.





1 – ‘Background Altitude Filter’ button. Pressing this button will bring up the altitude filter selection bar (shown below) so that the flight crew can select the setting for altitudes within which background aircraft will be displayed.

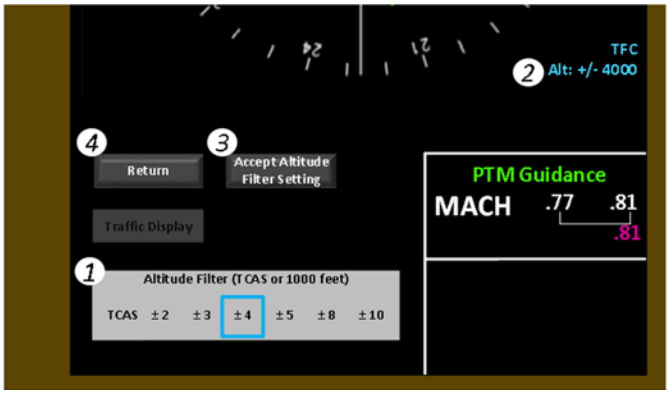
2 – Background Traffic ON/OFF Toggle. Pressing this button or the ‘TFC’ label located on the right side of the display will toggle the display of background aircraft on and off.

3 - Background Flight ID ON/OFF Toggle. Pressing this button will toggle the flight IDs of all background aircraft on and off. (Note: Background aircraft data tags only include flight ID. Altitude is always displayed above/below aircraft symbol.)

4 – PTM Engaged Expanded ON/OFF Toggle. Pressing this button will toggle all engaged aircraft data tags between expanded information and the display of flight ID only. Altitude is always displayed above/below aircraft symbol.

5 – ‘Accept’ button. Exits the Traffic Display menu and retains all display changes.

6 – ‘Return’ button. Exits the Traffic Display menu and discards all changes made since entering the menu.



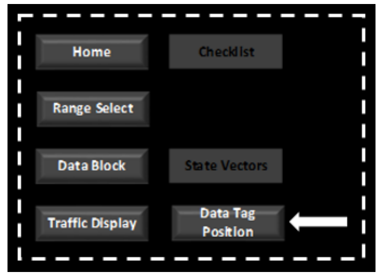
1 – Selectable values for the altitude filter that will display background aircraft. Selection of TCAS will set the altitude filter to match the setting on the TCAS transponder either above, neutral, or below.

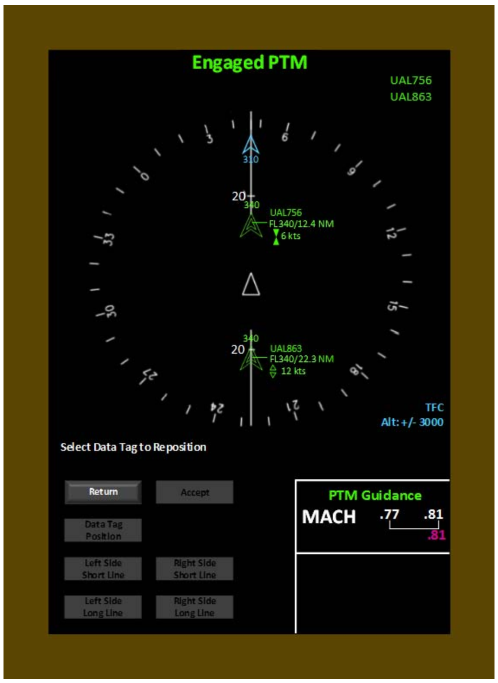
2 – Value will change here to reflect selected filter setting.

3 – ‘Accept Altitude Filter Setting’ button will exit the Background Altitude Filter sub-menu and apply the current filter setting.

4 – ‘Return’ button will exit the Background Altitude Filter sub-menu and revert back to the previously accepted filter setting.

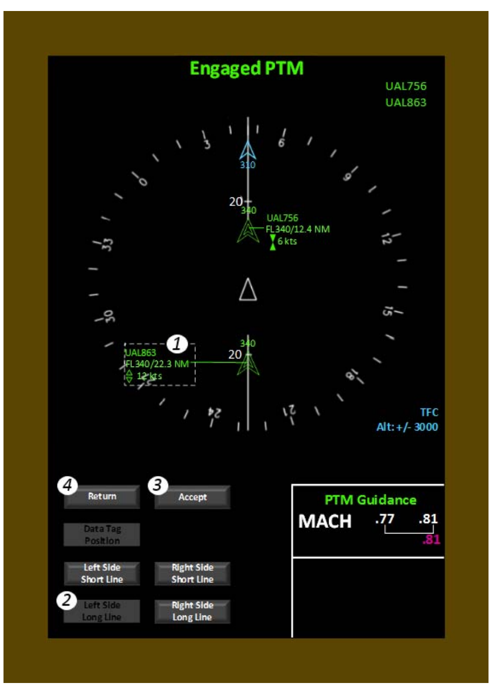
Data Tag Position. Allows the data tag of a selected aircraft to be positioned manually to help the flight crew declutter the CDTI.





A data tag within the CDTI must be selected by the flight crew. Selection from the Flight ID List can also be made for engaged aircraft. Then, the button associated with the position (left or right side of aircraft symbol) and leader line length (short or long) desired for that data tag is pressed.

NOTE: It may be best to declutter the display by using the Traffic Display menu (described above) to turn “off” expanded data tags for engaged aircraft (leaving only flight IDs visible) and to turn “off” flight IDs for background aircraft.



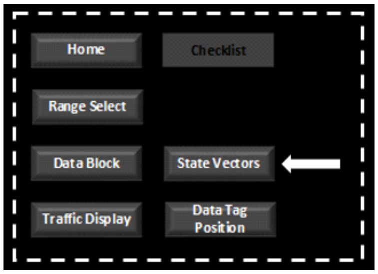
1 – Selected data tag is surrounded by dashed white box.

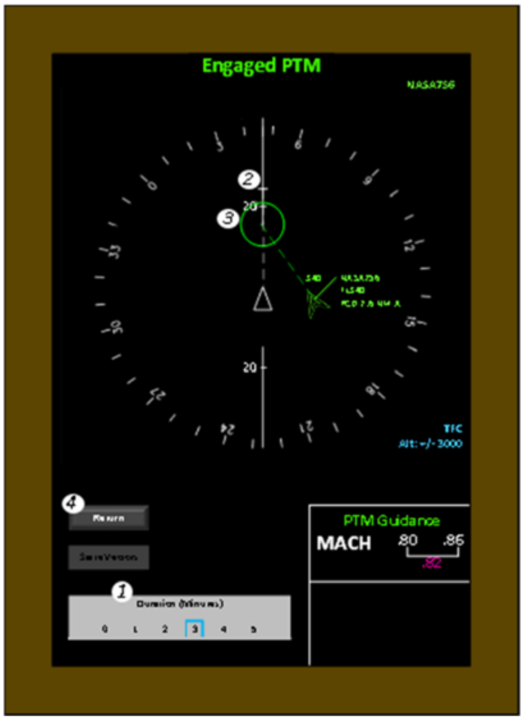
2 – Data tag for UAL863 was moved from right side of aircraft symbol to left side of aircraft symbol, and leader line was lengthened from “short” to “long”.

3 – ‘Accept’ button will make all data tag position selections permanent and exit the Data Tag Position menu.

4 – ‘Return’ button will exit the Data Tag Position menu and revert all data tags to their previous position.

State Vectors. When an engaged aircraft is on a crossing clearance with ownship or a merge clearance prior to ownship crossing the merge point, estimated positions of ownship and the engaged aircraft can be displayed up to 5 minutes into the future.





1 – Flight crew can select duration of state vectors (in minutes). Display shows dashed lines predicting the positions of ownship and engaged aircraft out to the time selected, with each dash representing 30 seconds into the future.

2 – Position of ownship 3 minutes into the future. Predicted position represented by horizontal hash mark located at the end of the sixth dash mark.

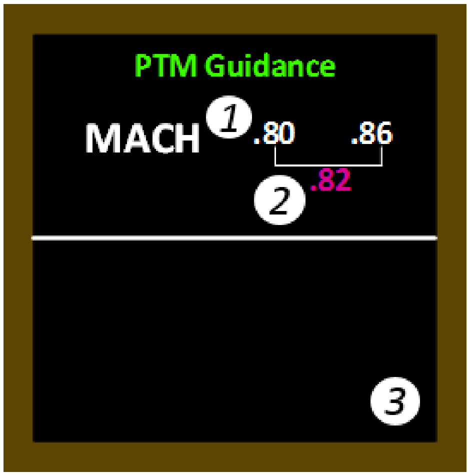
3 – Position of engaged aircraft 3 minutes into the future. Predicted position is surrounded by a 5 NM (radius) circle.

4 – 'Return' button will exit the State Vectors menu.

NOTE: This example shows ownship passing in front of the engaged aircraft, and ownship is located outside of the engaged aircraft's 5 NM separation ring. This can be confirmed by the engaged aircraft's data tag which indicates that ownship will pass 7.6 NM ahead of the engaged aircraft.

NOTE: State vectors may not be permanently displayed on the CDTI, therefore no 'Accept' button is provided.

CONFIGURABLE GRAPHICS DISPLAY (CGD)

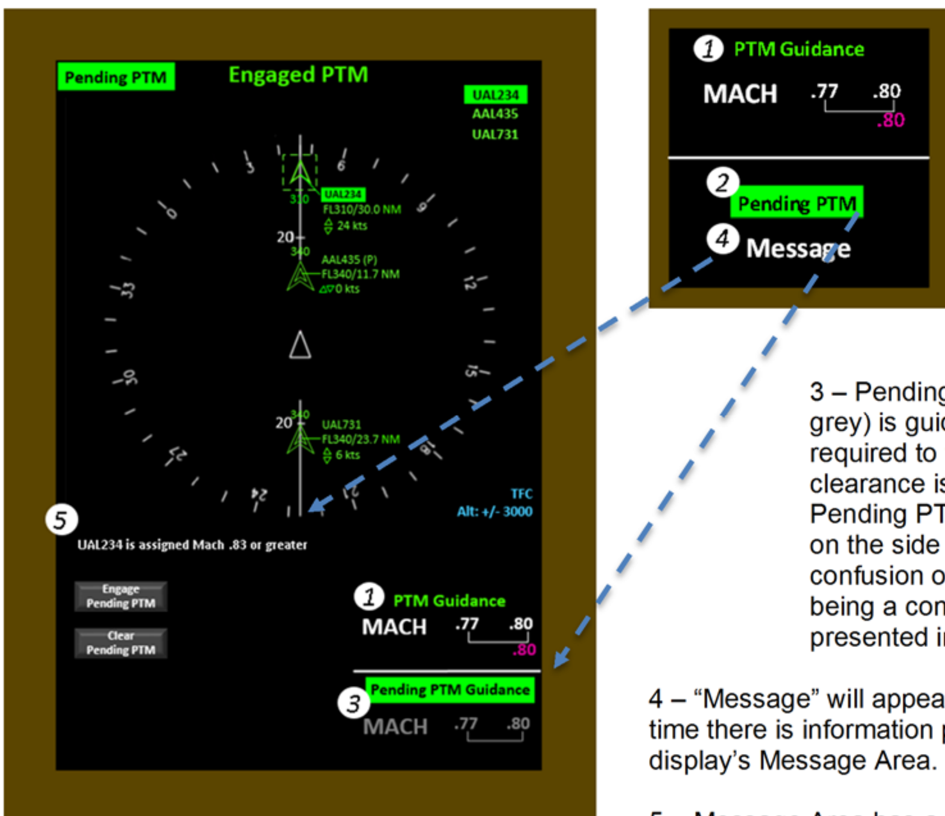


1 – PTM Guidance (shown in white) that ownship must fly during a PTM operation.

2 – Flight crew selected Mach (shown in magenta). This may be from the mode control panel (MCP) or an available mode of the flight management computer (FMC). When the flight crew selected Mach is set at a PTM Guidance range limit, at one end or the other, the flight crew selected Mach will be displayed under that limit. Otherwise, the flight crew selected Mach will be displayed under the center of the range.

3 – Multi-Use Information Area. Displays information pertaining to PTM operations, but is normally blank. "Pending PTM" will be displayed in green reverse video during a Pending PTM mode. "Message" will appear whenever a message is present on the side mounted display in the message area. The color of the "Message" notification will match the color of the message displayed.

The CGD presents PTM Guidance within the flight crew's primary field of view and presents notifications that direct flight crew attention to information located on the side mounted display.



1 – PTM Guidance (shown in white) is presented on the CGD and on the side mounted display.

2 – "Pending PTM" is shown on the CGD to direct attention to the side mounted display's presentation of Pending PTM Guidance.

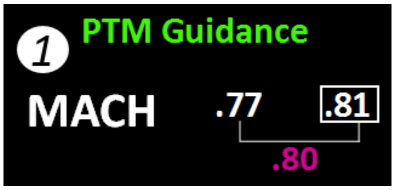
3 – Pending PTM Guidance (shown in grey) is guidance that ownship will be required to fly if the pending PTM clearance is accepted by the flight crew. Pending PTM Guidance is presented only on the side mounted display. To avoid any confusion over the Pending PTM Guidance being a command to follow, it is never presented in the primary field of view.

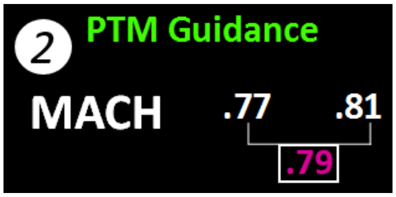
4 – "Message" will appear on the bottom of the CGD any time there is information presented in the side mounted display's Message Area.

5 – Message Area has a larger space available to provide information and indications to the flight crew.

INDICATIONS AND CAUTIONS

Level 1 Indication





Causes:
1 – Change in displayed PTM Guidance
2 – Change in display of flight crew selected Mach

Display Indication:
Changed Mach value boxed in white for 10 seconds

Resolution:
Box around changed Mach value disappears after 10 seconds

Notifications / Messages on CGD and/or side mounted display:
None

Level 2 Indication

Causes:
1 – Flight crew selected Mach is outside of the PTM Guidance (this occurred less than 10 seconds ago)

2 – PTM Guidance requires a specific Mach to be flown for an extended period of time

Display Indication:
PTM Guidance shows a specific Mach to be set, instead of a Mach range

Resolution:
Once correct flight crew selected Mach is set, a Mach range will be shown, if available

Notifications / Messages on CGD and/or side mounted display:
None

Cautions

Causes:
1 – Flight crew selected Mach does not comply with PTM Guidance within 30 seconds of a change in guidance

2 – Flight crew selected Mach is changed to a value outside of the PTM Guidance

3 – PTM Guidance changes by .02 Mach or greater

Display Indication:
Amber highlighting of PTM Guidance and flight crew selected Mach
Double chime presented every 30 seconds

Resolution:
Setting flight crew selected Mach in accordance with PTM Guidance will remove the alert

Notification presented below PTM Guidance on CGD and side mounted display:

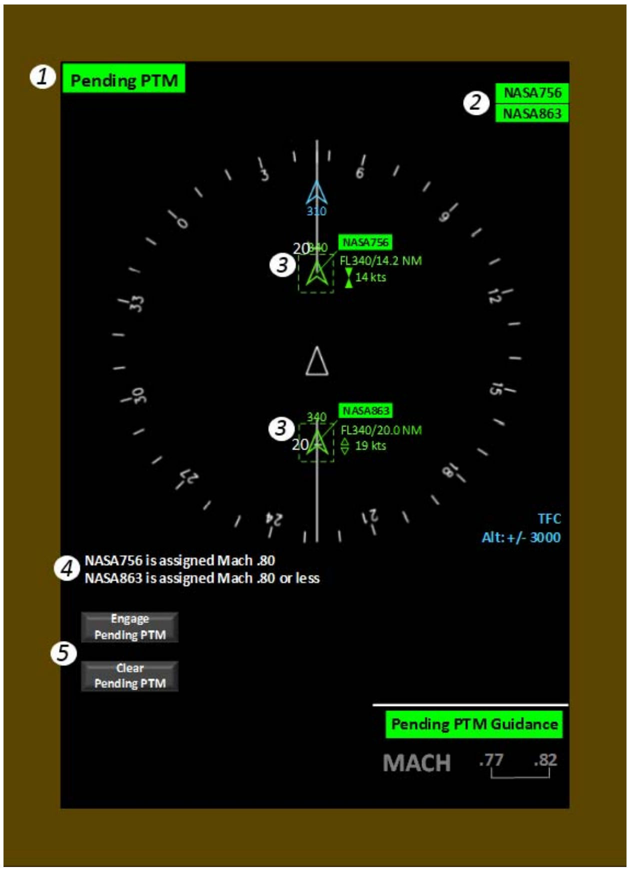
Message

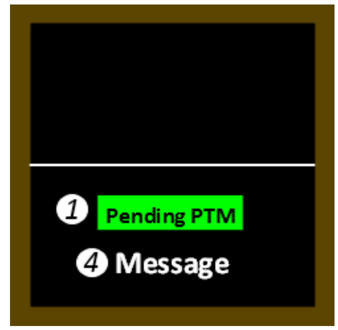
Message presented on the side mounted display's Message Area:

Incorrect Mach speed selected

PTM MODES

PENDING PTM





1 – “Pending PTM” appears in reverse video on the CGD and side mounted display to indicate that a PTM clearance has been received.

2 – Pending aircraft flight IDs are shown in the Flight ID List.

3 – Each pending aircraft symbol is shown as a single green chevron with a dashed rectangular border, and each pending aircraft data tag contains flight ID (in reverse video), altitude, distance, and closure information.

4 – “Message” appears on the CGD to direct flight crew attention to the pending aircraft flight IDs and assigned speeds shown in the side mounted display’s Message Area.

5 – Two buttons are available: ‘Engage Pending PTM’ and ‘Clear Pending PTM’.

When a PTM clearance is received, the flight crew will:

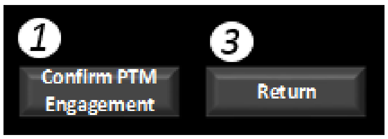
1) Evaluate the Pending PTM Guidance to determine if it is acceptable to fly.

2) Use the CDTI for overall situation awareness of surrounding traffic.

3) Select either the 'Engage Pending PTM' button or the 'Clear Pending PTM' button. (Note: If one of these buttons is not pressed within one minute, a chime will sound at a 30 second interval.)

Engage Pending PTM

If the Pending PTM clearance is acceptable to the flight crew and the 'Engage Pending PTM' button is pressed, 'Confirm PTM Engagement' and 'Return' buttons will become available, replacing the 'Engage Pending PTM' and 'Clear Pending PTM' buttons.

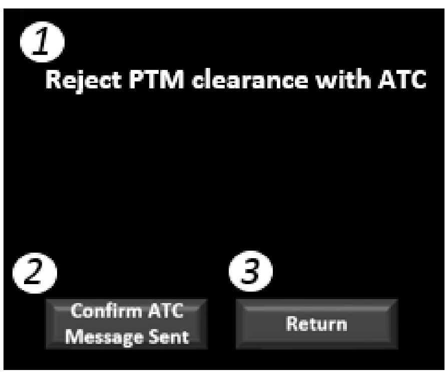


1 – If the flight crew presses the 'Confirm PTM Engagement' button, the PTM avionics enters into Engaged PTM mode. (Note: Engaged mode is covered in the next section of this pilot guide.)

3 – If the flight crew presses the 'Return' button, the display will return to the previous screen where 'Engage Pending PTM' and 'Clear Pending PTM' buttons are available.

Clear Pending PTM

If the PTM clearance is not acceptable to the flight crew, and the 'Clear Pending PTM' button is pressed, 'Confirm ATC Message Sent' and 'Return' buttons will become available, replacing the 'Engage Pending PTM' and 'Clear Pending PTM' buttons.



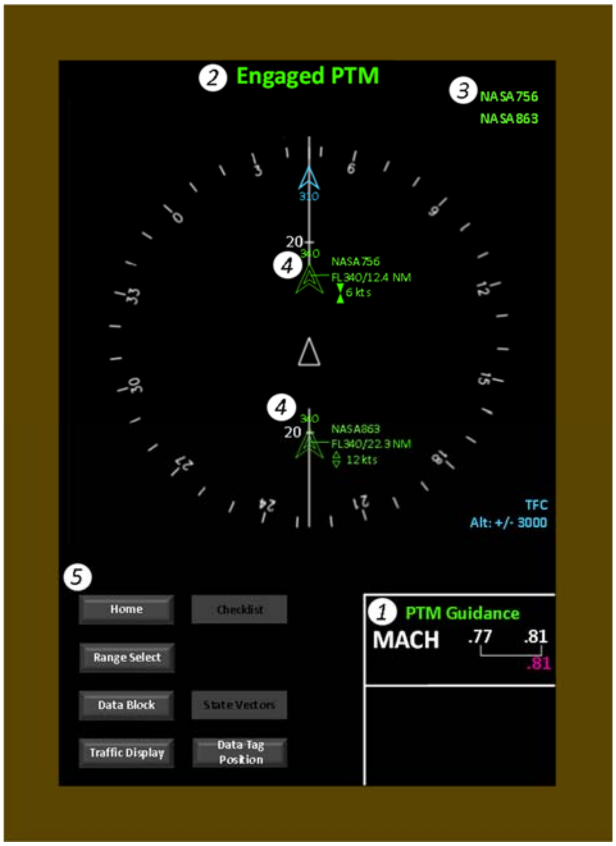
1 – When the flight crew presses the 'Clear Pending PTM' button, a message reminding them of the need to reject the PTM clearance with ATC (via CPDLC) is shown in the side mounted display's Message Area.

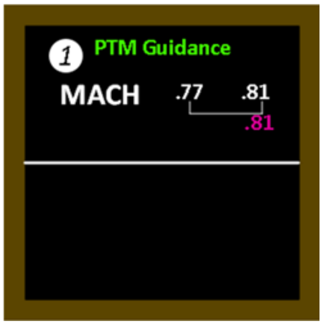
2 – The flight crew will press the 'Confirm ATC Message Sent' button to confirm that their 'Reject' message has been sent to ATC via CPDLC. Pressing the 'Confirm ATC Message Sent' button will clear the Pending PTM information from the PTM avionics, and the PTM avionics will enter a No PTM mode or return to an Engaged PTM mode if that was the previous mode. (Note: No PTM mode is covered in a subsequent section of this pilot guide.)

3 – If the flight crew presses the 'Return' button, the display will return to the previous screen where 'Engage Pending PTM' and 'Clear Pending PTM' buttons are available.

NOTE: If the PTM avionics determines that PTM conditions are not met, the 'Engage Pending PTM' button will be greyed out (inactive). (Detailed information regarding such situations is provided in the "Irregulars and Non-Normals" section of this pilot guide).

ENGAGED PTM





1 – PTM Guidance is shown on the CGD and the side mounted display.

2 – PTM Mode indicator shows 'Engaged PTM'.

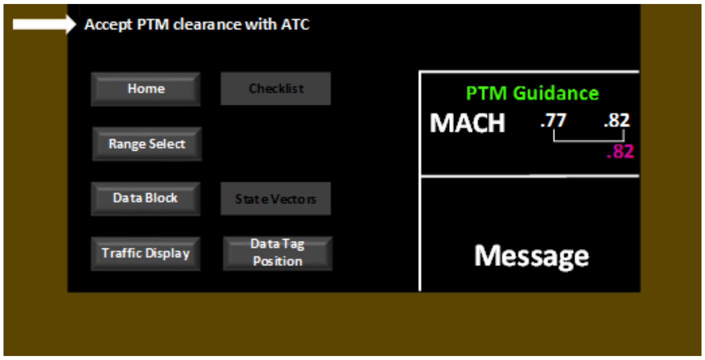
3 – Engaged aircraft flight IDs are listed in the Flight ID List.

4 – Engaged aircraft symbols are shown within the CDTI.

5 – The Engaged PTM mode grouping of buttons is available to adjust the CDTI and to access additional information for engaged and background aircraft.

When a PTM clearance has been accepted and the PTM avionics has been engaged, the flight crew will:

1) Accept the PTM clearance with ATC via CPDLC. (A reminder notification will be shown for 10 seconds in the side mounted display's Message Area, as shown below.)

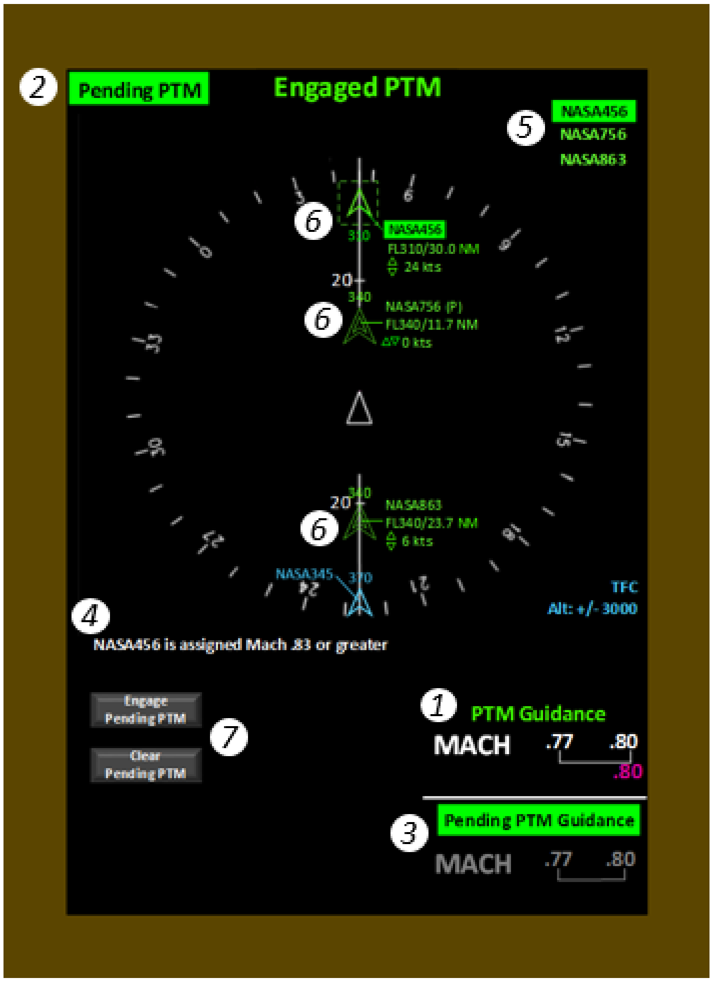


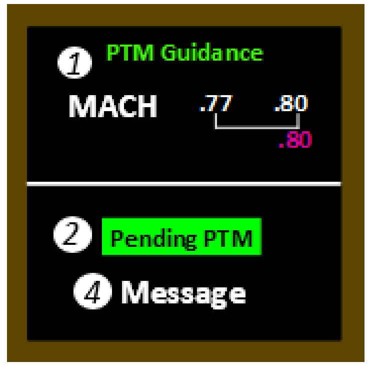
2) Observe the PTM Guidance, and ensure that the flight crew selected Mach remains in compliance with the PTM Guidance.

3) Use the CDTI for overall situation awareness of surrounding traffic.

4) Follow any indications, cautions, or warnings that may be generated by the PTM avionics.

PENDING PTM AND ENGAGED PTM





1 – PTM Guidance is shown on the CGD and the side mounted display. The flight crew must continue to follow this guidance while evaluating the new Pending PTM information.

2 – 'Pending PTM' indicator is shown on the CGD and side mounted display.

3 – Pending PTM Guidance, shown only on the side mounted display, will become the active guidance if the new PTM clearance is accepted and the Pending PTM is engaged. (Note: The Pending PTM Guidance and the PTM Guidance will not always be the same when both are shown on the display.)

4 – 'Message' appears on the CGD to direct the flight crew attention to the pending aircraft flight ID and assigned speed shown in the side mounted display's Message Area.

5 – Pending and engaged aircraft flight IDs are shown in the Flight ID List.

6 – Pending and engaged aircraft symbols are shown on the CDTI.

7 – The Pending PTM mode grouping of buttons is available to either engage or clear the Pending PTM.

When a PTM clearance is received while in a PTM operation, the flight crew will:

1) Observe the PTM Guidance, and ensure that the flight crew selected Mach remains in compliance with the PTM Guidance.

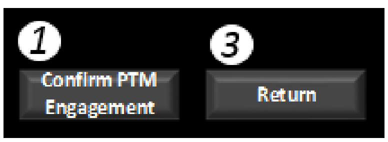
2) Evaluate the Pending PTM Guidance to determine if it is acceptable to fly.

3) Use the CDTI for overall situation awareness of surrounding traffic.

4) Select either the 'Engage Pending PTM' button or the 'Clear Pending PTM' button. (Note: If one of these buttons is not pressed within one minute, a chime will sound at a 30 second interval.)

<u>Engage Pending PTM</u>

If the PTM clearance is acceptable to the flight crew and the 'Engage Pending PTM' button is pressed, 'Confirm PTM Engagement' and 'Return' buttons will become available, replacing the 'Engage Pending PTM' and 'Clear Pending PTM' buttons.

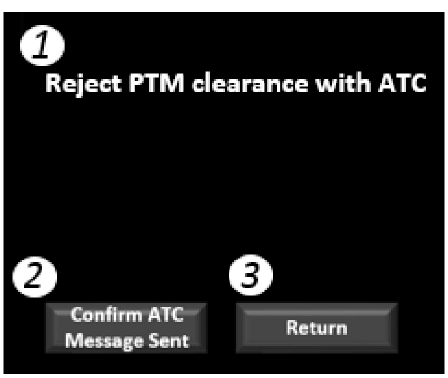


1 – If the flight crew presses the 'Confirm PTM Engagement' button, the PTM avionics returns to Engaged PTM mode with the previous and new engaged aircraft. (Note: Engaged mode is covered in the previous section of this Pilot Guide.)

2 – If the flight crew presses the 'Return' button, the display will return to the previous screen where 'Engage Pending PTM' and 'Clear Pending PTM' buttons are available.

<u>Clear Pending PTM</u>

If the PTM clearance is not acceptable to the flight crew, and the 'Clear Pending PTM' button is pressed, 'Confirm ATC Message Sent' and 'Return' buttons will become available, replacing the 'Engage Pending PTM' and 'Clear Pending PTM' buttons.



1 – When the flight crew presses the 'Clear Pending PTM' button, a message reminding them of the need to reject the PTM clearance with ATC (via CPDLC) is shown in the side mounted display's Message Area.

2 – The flight crew will press the 'Confirm ATC Message Sent' button to confirm that their 'Reject' message has been sent to ATC via CPDLC. Pressing the 'Confirm ATC Message Sent' button will clear the Pending PTM information from the PTM avionics, and the PTM avionics will return to Engaged PTM mode with only the previous engaged aircraft. (Note: Engaged mode is covered in the previous section of this Pilot Guide.)

3 – If the flight crew presses the 'Return' button, the display will return to the previous screen where 'Engage Pending PTM' and 'Clear Pending PTM' buttons are available.

5) After the Pending PTM has been engaged or cleared (and appropriate message sent to ATC), normal activities outlined in the Engaged PTM section of this Pilot Guide will continue.

CANCELLED PTM

1 – Background aircraft is shown (this is the former engaged aircraft).

2 – 'Message' appears on the CGD to direct flight crew attention to the notification shown in the side mounted display's Message Area. Information regarding the aircraft that was cancelled is shown in the notification.

3 – The 'Return' button is the only button available since the cancellation must be acknowledged.

When a Cancel PTM clearance is received, the flight crew will:

1) Acknowledge the cancellation on the side mounted display by pressing the 'Return' button. This action results in the PTM avionics entering a No PTM mode. (Note: No PTM mode is covered in the next section of this pilot guide.) A reminder to 'Accept PTM clearance with ATC' is presented in the side mounted display's Message Area after the 'Return' button is pressed.

2) Flight crew accepts the Cancel PTM clearance with ATC via CPDLC.

NO PTM

1 – 'NO PTM' is shown in the PTM Guidance area on the CGD and in the PTM Guidance area on the side mounted display. The PTM Mode Indicator also displays 'NO PTM'.

2 – 'Message' appears on the CGD to direct flight crew attention to the notification shown in the side mounted display's Message Area. The message to 'Accept PTM clearance with ATC' is displayed for 10 seconds after entering the No PTM mode.

3 – All previously engaged aircraft are shown as background aircraft.

4 – All buttons that are available during an Engaged PTM mode are available to aid the flight crew in their acquisition and maintenance of situation awareness.

When a No PTM Mode is entered, the flight crew will:

1) Receive a reminder message to accept the Cancel PTM clearance with ATC via CPDLC. This message will be shown for 10 seconds.

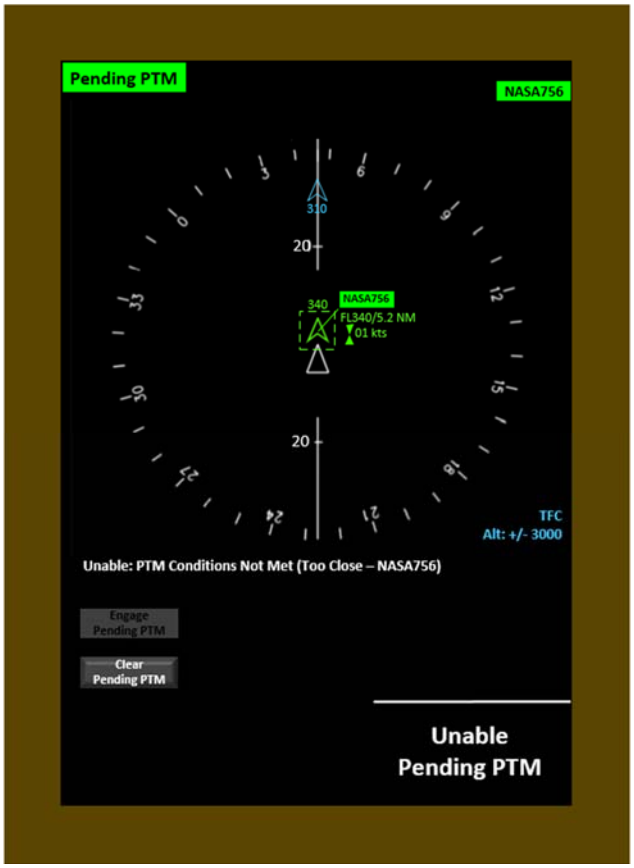
2) Conduct normal operations.

3) Have the ability to use the PTM avionics for situation awareness.

IRREGULARS AND NON-NORMALS

UNABLE TO ACCEPT PTM CLEARANCE

The following conditions result in a PTM clearance not being able to be accepted by the flight crew. In these cases, the 'Engage Pending PTM' button is greyed out and not selectable. The flight crew can only press 'Clear Pending PTM' and then reject the clearance with ATC. The flight crew can provide ATC with a reason for the rejection, if desired. If the 'Clear Pending PTM' button is not pressed within 1 minute, a chime will sound every 30 seconds until the button is pressed.



- Unable: PTM Conditions Not Met [Flight ID]
  - PTM Guidance was not able to be generated.
- Unable: PTM Conditions Not Met ([Flight ID] Not Found)
  - ADS-B signal for the pending aircraft is not being received or was lost prior to the flight crew's acceptance of the PTM clearance.
- Unable: PTM Conditions Not Met (Too Close – [Flight ID])
  - Ownship is closer than PTM spacing to the pending aircraft.

- Unable: PTM Conditions Not Met (Ahead/Behind – [Flight ID])
  - PTM clearance is given as ‘ahead of’ the pending aircraft (ownship in front), but the pending aircraft is actually located in front of ownship, or
  - PTM clearance is given as ‘behind’ the pending aircraft (ownship is behind), but the pending aircraft is actually behind ownship.
  - This condition could be the result of an error regarding the position of the pending or ownship aircraft as determined by the ground equipment, could be associated with the position report accuracy and frequency of the pending aircraft, or could be due to bad data being received over ADS-B.
- Unable: PTM Equipment Failure
  - Internal failure of PTM equipment.

LOSS OF ADS-B SIGNAL DURING ENGAGED PTM

Caution

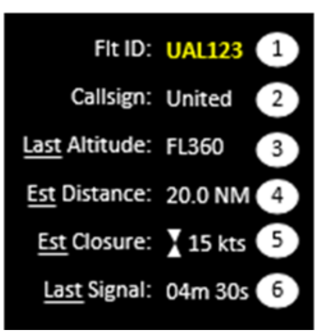
If an engaged aircraft's ADS-B signal is lost for more than 25 seconds, the system will display a caution and present an aural alert. The PTM avionics will then "coast" the aircraft position for 5 minutes from the original signal loss using its last state information. This provides a buffer for a temporary ADS-B signal loss. If the signal is reacquired, operations will proceed as normal with a green 'Event Cleared' message shown for 60 seconds in the side mounted display's Message Area.

1 – Messages (in amber text) notify the flight crew that the ADS-B signal is lost for the engaged aircraft and direct the flight crew to perform the electronic checklist accessed via the 'Checklist' button.

2 – Engaged aircraft symbol, data tag, and flight ID in Flight ID List turn amber. The data tag will have 'CST' displayed (in place of altitude, distance, and closure) to indicate that the aircraft position is being coasted rather than coming from the aircraft's ADS-B signal. Pressing the 'Data Block' button and then either the flight ID in the FLT ID List or the aircraft data tag will allow additional information (shown below) to be displayed for the selected aircraft.

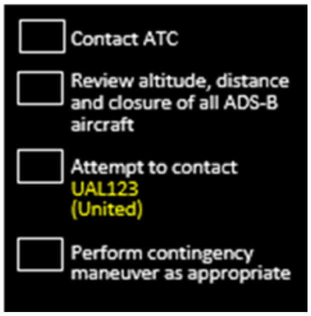
3 – 'Checklist' button becomes active. When pressed, an electronic checklist will appear for the flight crew's use (shown below). Further explanation of checklists is provided in the checklist section of this Pilot Guide.

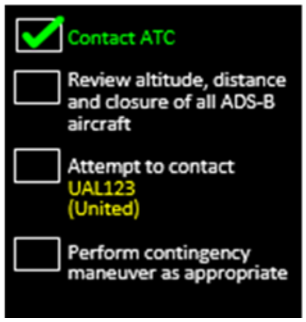
Data Block



1 – Flight ID of engaged aircraft with lost ADS-B signal
2 – Actual callsign to use when calling on the radio
3 – Last altitude reported by ADS-B
4 – Estimated distance (in NM) based on coasted position
5 – Estimated closure rate (in kts) based on coasted position
6 – Last signal shows the time in minutes and seconds since a valid ADS-B signal was received. (The bigger this value, the more unreliable the coasted position becomes).

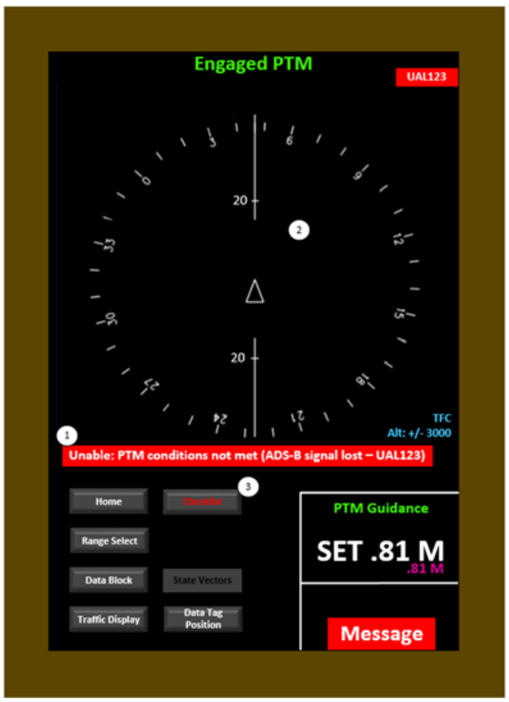
Electronic Checklist





An electronic checklist appears when the 'Checklist' button is pressed. As the flight crew accomplishes checklist items, associated square is pushed to check that item off. Pressing the flight ID of the aircraft in the checklist will cause the Data Block for that aircraft to appear in place of the checklist. However, an incomplete checklist will always reappear, replacing the Data Block, after 60 seconds. If ADS-B signal is reacquired, all checklist items will turn green, then checklist will clear after 60 seconds.

Warning Alert



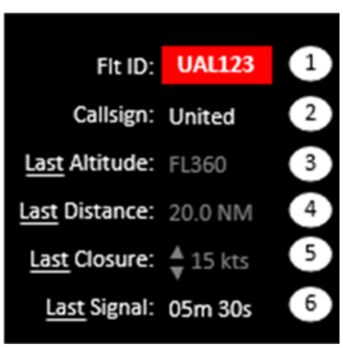
If an engaged aircraft's ADS-B signal loss continues for 5 minutes or longer, the system will display a visual and aural warning. The aircraft is no longer coasted, so its aircraft symbol is removed from the CDTI.

1 – Message alerts the flight crew that the engaged aircraft's ADS-B signal has been lost for 5 minutes or longer.

2 – Engaged aircraft is removed from the CDTI. The flight ID is highlighted in red in the Flight ID List to indicate that no valid data are available. Pressing the 'Data Block' button then the flight ID in the Flight ID List will display additional information (shown below) about that aircraft.

3 – 'Checklist' button is active. Flight ID and callsign will be shown highlighted in red to indicate no valid position data are available. Further explanation of checklists is provided in the checklist section of this Pilot Guide.

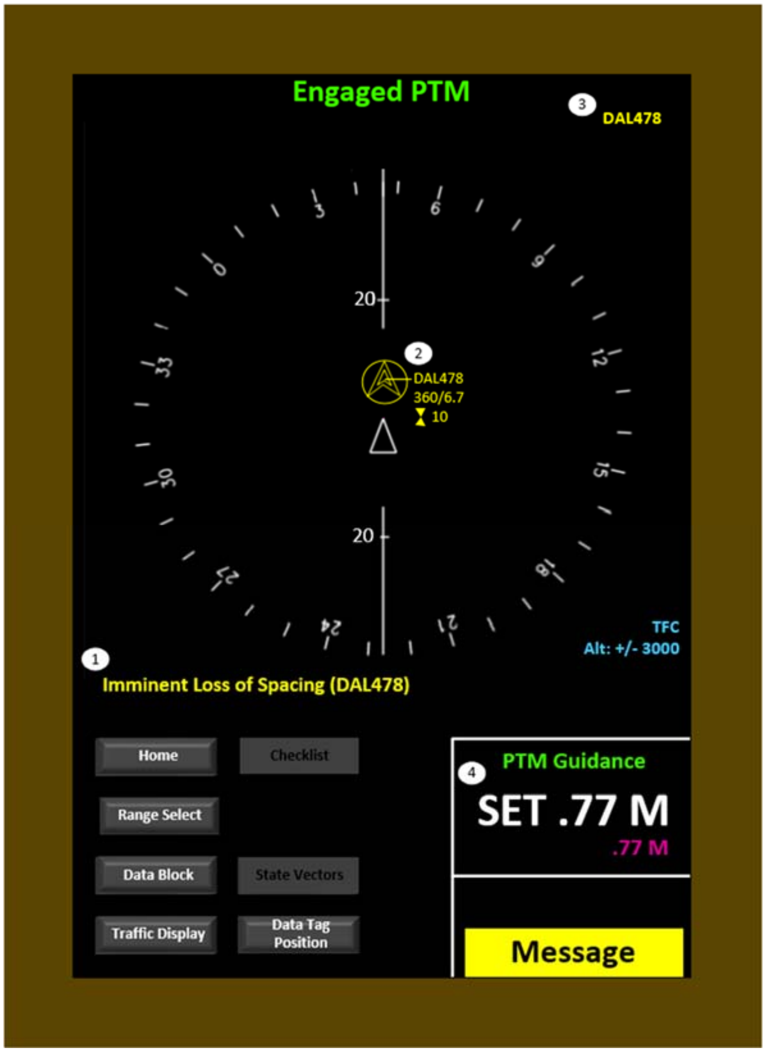
Data Block



The Data Block displays last estimated position data. Information should be considered unreliable but is made available for reference.

1 – Fight ID of engaged aircraft with lost ADS-B signal (highlighted in red to indicate warning)
2 – Actual callsign to use when calling on the radio
3 – Last altitude reported by ADS-B (entry is greyed out to show it is no longer valid)
4 – Last estimated distance (in NM) based on coasted position (entry is greyed out to show it is no longer valid)
5 – Last estimated closure rate (in kts) based on coasted position (entry is greyed out to show it is no longer valid)
6 – Last signal shows the time in minutes and seconds since a valid ADS-B signal was received

IMMINENT LOSS OF SPACING



If the PTM avionics estimates that the ownship will come within 6.5 NM of an engaged aircraft in 60 seconds or less, a caution and aural alert will be presented. This caution may occur at various distances from the engaged aircraft due to closure and other factors.

1 – Message alerts flight crew to an imminent loss of spacing with the engaged aircraft.

2 – Engaged aircraft symbol and data tag are amber. A 5 NM (radius) ring will appear around the engaged aircraft symbol to show the PTM separation distance.

3 – Flight ID in the Flight ID List is amber.

4 – PTM Guidance will try to stabilize ownship outside of or at 6.5 NM. Setting the flight crew selected Mach in accordance with PTM Guidance speed will remove the alert.

LOSS OF SPACING

If the PTM avionics detects that the ownship is within 6.5 NM of an engaged aircraft, a caution will occur and an aural alert will be presented.

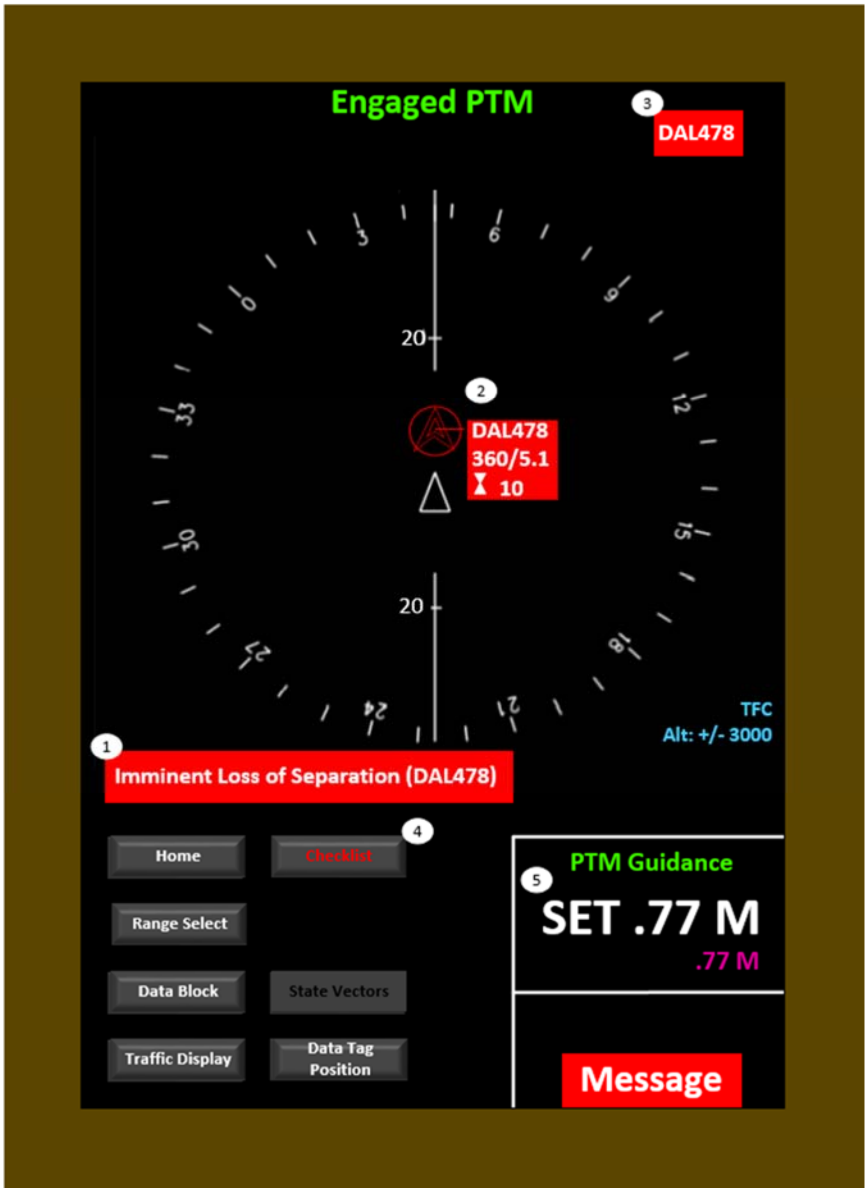
1 – Message alerts flight crew to a loss of spacing with the engaged aircraft.

2 – Engaged aircraft symbol and data tag are amber. A 5 NM (radius) ring will appear around the engaged aircraft symbol to show the PTM separation distance.

3 – Flight ID in the Flight ID List is amber.

4 – PTM Guidance will try to reestablish ownship outside of or at 6.5 NM.

IMMINENT LOSS OF SEPARATION



If the PTM avionics estimates that ownship will come within 5 NM of an engaged aircraft within 60 seconds, a warning and aural alert will be presented. Separation of aircraft becomes the flight crew's primary task.

1 – Message alerts flight crew that a loss of separation is imminent and directs the flight crew to perform the electronic checklist.

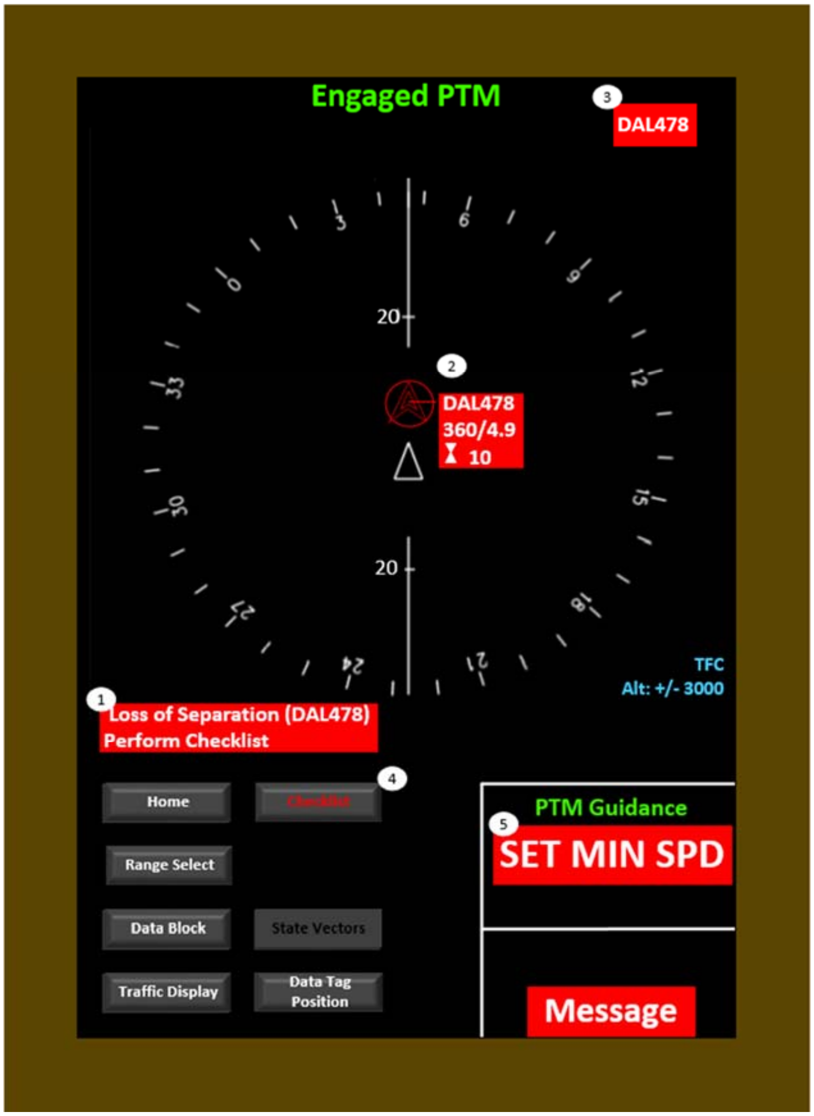
2 – Engaged aircraft symbol is red. A 5NM (radius) ring appears around the engaged aircraft, showing the required distance for the PTM separation standard.

3 – Flight ID for the engaged aircraft is highlighted in red.

4 – Checklist button is active. When pressed, the electronic checklist will appear for the flight crew's use. Further explanation of checklists is provided in the checklist section of this Pilot Guide.

5 – PTM Guidance directs the flight crew to set the slowest speed the avionics can provide.

LOSS OF SEPARATION



If ownship comes within 5 NM of an engaged aircraft, a warning and aura alert will be presented. Separation of aircraft is the flight crew's primary task.

1 – Message alerts flight crew that a loss of separation has occurred and directs the flight crew to perform the electronic checklist.

2 – Engaged aircraft is red. A 5NM (radius) ring appears around the engaged aircraft, showing the required separation for PTM separation standard.

3 – Flight ID for the engaged aircraft is highlighted in red.

4 – Checklist button is active. When pressed, the electronic checklist will appear for the flight crew's use (shown below). Further explanation of checklists is provided in the checklist section of this Pilot Guide.

5 – PTM Guidance directs the flight crew to set the slowest safe speed. Based on the geometry, this could be "SET MAX SPD", or a single Mach value might be provided.

Electronic Checklist

An electronic checklist appears when the checklist button is pressed. As the fight crew accomplishes items, associated square is pushed to check that item off. Pressing the flight ID of the aircraft in the checklist will cause the Data Block for that aircraft to appear. An incomplete Checklist will always reappear after 60 seconds.

CHECKLISTS

LOSS OF ADS-B SIGNAL (CAUTION AND WARNING)

- Contact ATC
  - Inform ATC of the loss of signal on engaged aircraft to see if they can issue a revised clearance that will solve the problem of not receiving the engaged aircraft's ADS-B signal.

- Review altitude, distance, and closure of all aircraft
  - Ensure awareness of all other ADS-B aircraft and the coasted aircraft in case contingency maneuver becomes required.

- Attempt contact with engaged aircraft
  - Attempt to contact aircraft on interplane (123.45) and guard (121.5) to coordinate aircraft maneuvers if necessary. If necessary, use the Data Block to obtain callsign of aircraft.

- Perform contingency maneuver as appropriate
  - If necessary, maneuver aircraft to remain clear of offending aircraft. Use all sources available including TCAS and radio.

LOSS OF SPACING (WARNING)

- Attempt contact with engaged aircraft
  - Contact the offending aircraft and try to coordinate aircraft maneuvers. If the engaged aircraft is having an emergency, it might be attempting a track exit.

- Consider an offset in an appropriate direction to maintain separation
  - Use all information sources available, including TCAS, to determine the best direction to offset to maintain separation.

- Broadcast intent
  - Broadcast on interplane (123.45) and guard (121.5) what you will be doing with your aircraft as far as offsetting or possible altitude change.

- Contact ATC
  - Once aircraft is in a safe stable condition, contact ATC to receive a new clearance.

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14. ABSTRACT

Pairwise Trajectory Management (PTM) is an Interval Management (IM) concept that utilizes airborne and ground-based capabilities to enable the implementation of airborne pairwise spacing capabilities in oceanic regions. The goal of PTM is to use airborne surveillance and tools to manage an "at or greater than" inter-aircraft spacing. Due to the accuracy of Automatic Dependent Surveillance-Broadcast (ADS-B) information and the use of airborne spacing guidance, the minimum PTM spacing distance will be less than distances a controller can support with current automation systems that support oceanic operations. Ground tools assist the controller in evaluating the traffic picture and determining appropriate PTM clearances to be issued. Avionics systems provide guidance information that allows the flight crew to conform to the PTM clearance issued by the controller. The combination of a reduced minimum distance and airborne spacing management will increase the capacity and efficiency of aircraft operations at a given altitude or volume of airspace.

15. SUBJECT TERMS

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