knowledge &
development
centre
Mainport Schiphol

NLR

KLM

Amsterdam
Airport Schiphol

OPERATIONAL PERFORMANCE ASSESSMENT

FOR

ASAS Interval Management
in the Schiphol TMA

KDC/2012/0069 version 1.0
KDC project PRJ-1844

Version Date: 02-11-12

STATUS PAGE

Author(s)

Name	Position	Signature	Date
Frank Bussink	NLR/ATCF		02-11-2012
Nico de Gelder	NLR/ATCF		02-11-2012
Alexander in 't Veld	TU Delft		02-11-2012

Evaluation

Name	Position	Date

Approval (by document owner)

Name	Position	Signature	Date
Ceriel Janssen	Management Team Knowledge & Development Centre (KDC)		27/3/2013

Acceptance (by costumer)

Name	Position	Signature	Date
Evert Westerveld	Chairman Management Team Knowledge & Development Centre (KDC)		27/03/2013

Executive Summary

A Continuous Descent Operation (CDO) is an operation, enabled by airspace design, procedure design and ATC facilitation, in which an arriving aircraft descends continuously, to the greatest possible extent, by employing minimum engine thrust, ideally in a low drag configuration, prior to the final approach fix. An optimum CDO starts from the top of descent and will achieve the maximum reduction in fuel burn, noise and emissions [1].

Providing benefits to both the environment (low emissions) and the operator (fuel cost), CDOs however have been known to diminish capacity due to the greater spacing needed between the aircraft to account for uncertainty in aircraft performance. To ensure optimal system performance, the controller may need to place constraints on the aircraft (speeds, vectors, routes, altitude profiles), which decreases the efficiency of the CDO. These constraints, although made with the individual aircraft in mind, will inevitably move that aircraft away from its "ideal" descent profile and speed. An Airborne Surveillance Applications System (ASAS) - Interval Management (IM) Operation can help the individual aircraft to make the best trade-off between its own (most efficient) descent profile, and maintaining the system flow at critical junctures (e.g., merge points or runway threshold). By shifting the task of precisely spacing behind a lead aircraft to the cockpit, arrival accuracy may be increased, such that achieved capacity during Continuous Descent Operation remains constant or is improved.

With ASAS IM the controller will instruct the flight crew to achieve and/or maintain an Assigned Spacing Goal relative to a Target Aircraft. The key addition within ASAS IM to current operations is the provision of precise speed guidance within the flight deck to enable the flight crew to actively manage the spacing relative to the Target Aircraft. During IM Operations, the controller retains responsible for separation, while the flight crew is responsible for using the IM Equipment to achieve and/or maintain the Assigned Spacing Goal that is set by the controller to meet the operational goals.

This document provides the Operational Performance Assessment (OPA) of the ASAS IM application designed for Schiphol as defined in the Operational Services and Environment Definition (OSED) document [21]. This OPA is based on the joint RTCA/EUROCAE Flight Deck Interval Management Safety and Performance Requirements document and addresses the requirements for operations in the Schiphol TMA. It presents minimum performance requirements on the FIM Equipment that are needed in the Schiphol environment.

Furthermore this document also describes an operational performance evaluation, performed by means of fast-time simulation, incorporating the afore-mentioned performance requirements. A full description of the setup and the results can be found in Section 9. The analysis of the simulation results shows that if the performance requirements are adhered to, it is possible to perform IM-spacing on aircraft flying a RNAV-CDA on merging trajectories. The simulations included strings of 40 aircraft, arriving at 30 and 35 aircraft per hour.

With regard to the FIM Equipment, it is very clear from the simulation results, that a direct control of the autothrottle system of the FIM algorithm yields far more accurate spacing results than when the flight crew is manually setting the speed through the Auto-Pilots' Mode Control Panel. Further analysis of the data shows that the complexity of the arrival routes, especially the number of merge points has an effect on the performance of the FIM. Also the layout, with respect to the wind has a great influence; aircraft arriving from roughly the same direction can handle greater errors in the wind prediction than aircraft pairs on opposite trajectories.
Good results were found for the navigation accuracies and timing errors over the IAF for the traffic mixes and throughput numbers currently observed arriving at Runway 18R at Schiphol.
Although the current levels of navigation accuracy (RNAV 1) and the timing accuracy aim of SARA (±30 seconds over the IAF) show to be adequate to achieve IM-spacing at current traffic loads, the research shows that higher accuracies allow the FIM Equipment to withstand larger disturbances.

Table of contents

Abbreviations

AAS	Amsterdam Airport Schiphol
AC	Aircraft
AC-AV	Aircraft Avionics
AC-FC	Aircraft Flight Crew
ACC	Area Control
ACID	Aircraft Identification
ADS-B ADS-B-RAD ADS-R	Automatic Dependent Surveillance – Broadcast -RAD = Radar -R = Re-broadcast
AGL	Above Ground Level
ALT	Altitude
AMAN	Arrival Manager
AMS	Amsterdam
ANSP	Air Navigation Service Provider
AOC	Airline Operations Control
APP	Approach / Arrival Control
A-RNP	Advanced - Required Navigation Performance
ASA	Aircraft Surveillance Applications
ASAS	Aircraft Surveillance Applications System
ASEP	Airborne Separation
ASPA	Airborne Spacing
ASR	ATM System Requirements
ATC	Air Traffic Control
ATM	Air Traffic Management
ATSA-AIRB	Airborne Traffic Situation Awareness - Airborne
CDM	Collaborative Decision Making
CDO	Continuous Descent Operation
CDTI	Cockpit Display of Traffic Information
CNS	Communication Navigation Surveillance
ConOps	Concept of Operation
CPDLC	Controller Pilot Data Link Communication
CTA	Controlled Time of Arrival
CTA	Control Area
CTR	Control Zone
DCPC	Direct Controller-Pilot Communications
DMAN	Departure Manager
DME	Distance Measurement Equipment
EAT	Expected Approach Time
EFB	Electronic Flight Bag
ETA	Estimated Time of Arrival
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAS	Final Approach Speed
FIM	Flight Deck Interval Management

FIR	Flight Information Region
FMS	Flight Management System
FT	Feet
GIM	Ground Interval Management
GND	Ground
GND-ATC	Ground ATC
GNSS	Global Navigation Satellite System
GSA	Ground Surveillance Applications
HMI	Human Machine Interface
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
IAS	Indicated Airspeed
ID	Identification
IF	Intermediate Approach Fix
ILS	Instrument Landing System
IM	Interval Management
KDC	Knowledge and Development Centre
KPA	Key Performance Area
KTS	Knots
LNAV	Lateral Navigation
LVNL	Luchtverkeersleiding Nederland (Dutch ANSP)
M&S	Merging and Spacing
MET	Meteo
MOPS	Minimum Operational Performance Standards
ND	Navigation Display
NEXTGEN	Next Generation Air Transportation System
NG	Next Generation
NM	Nautical Mile
OC	On-condition
OPA	Operational Performance Assessment
OR	Operational Requirement
OSA	Operational Safety Assessment
OSED	Operational Services and Environment Definition
PBN	Performance Based Navigation
PFD	Primary Flight Display
P-RNAV	Precision Area Navigation
R/T	Radio Telephony
RF	Radius to Fix
RFG	Requirements Focus Group
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
SA	Situational Awareness
SARA	Speed And Route Advisor
SD	Side Display
SESAR	Single European Sky ATM Research

SOFA	Stabilized On Final Approach
SPD	Speed
SPR	Safety and Performance Requirements
SSEP	Airborne Self-Separation
STAR	Standard Instrument Arrival Route
TFM	Traffic Flow Management
TIS-B	Traffic Information Service - Broadcast
TMA	Terminal Manoeuvring Area
TOA	Time of Applicability
ToD	Top Of Descent
TP	Trajectory Predictor
TRACON	Terminal Radar Approach Control
TTG	Time-To-Go
TWR	Tower
UPS	United Parcel Service
UTA	Upper Control Area
VNAV	Vertical Navigation
VSD	Vertical Situation Display
WAM	Wide Area Multi-lateration
WILCO	Will Comply
WTC	Wake Turbulence Categories

Definition of Terms

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

Achieve Stage: The part of the IM Operation, prior to the Achieve-by Point, where the IM Aircraft is driving toward the Assigned Spacing Goal at the Achieve-by Point.

Achieve-by Point: A point on the IM Aircraft's Intended Flight Path, where the Spacing Interval is expected to be within the IM Tolerance of the Assigned Spacing Goal. The Spacing Interval is not expected to be within IM Tolerance of the Assigned Spacing Goal prior to the Achieve-by Point. In distance-based spacing, the Spacing Interval is expected to be within the IM Tolerance when the Target Aircraft reaches the Achieve-by Point. In time-based spacing, the Spacing Interval is expected to be within the IM Tolerance when the IM Aircraft reaches the Achieve-by Point.

Aircraft String: An Aircraft String is formed when each aircraft in a sequence is implementing IM Speeds relative to its assigned Target Aircraft, which is the immediately preceding aircraft in the sequence. The concept of an Aircraft String is used in the analysis and derivation of performance requirements on the IM Speeds provided by the FIM Equipment.

Altitude Constraint: As part of a navigation procedure, a limit or range for the altitude of an aircraft at a given waypoint while climbing or descending.

Assigned Spacing Goal: The time or distance interval between the IM Aircraft and Target Aircraft assigned by the controller as part of the IM Operation. The Assigned Spacing Goal is determined by the controller issuing the IM Clearance and the type and value(s) of the Assigned Spacing Goal are selected to achieve the controller's goal of establishing an efficient flow while maintaining separation from all traffic.

Cleared Flight Path: The navigation route for the IM or Target Aircraft that has been cleared by the controller prior to issuing the IM Clearance to the IM Aircraft.

Coincident Route: Two aircraft are considered to be on Coincident Routes if the Intended Routes coincide no later than the Achieve-by Point and through the Planned Termination Point.

Common Point: A 2D point on the Intended Routes of both the IM and the Target Aircraft that both aircraft have passed or are going to pass based upon their Intended Flight Paths.

Continuous Descent Operation (CDO): An operation, enabled by airspace design, procedure design and ATC facilitation, in which an arriving aircraft descends continuously, to the greatest possible extent, by employing minimum engine thrust, ideally in a low drag configuration, prior to the Final Approach Fix /Final Approach Point.

FIM Equipment: The avionics component that provides the IM capabilities defined. The function of the FIM Equipment is to provide IM Speeds and the IM Turn Point (when applicable) to the flight crew to achieve and/or maintain the Assigned Spacing Goal within the FIM Equipment Tolerance.

FIM Equipment Tolerance: The bounds on the acceptable deviation of the Measured Spacing Interval from the Assigned Spacing Goal at the Achieve-by Point and during the Maintain Stage within which the IM Operation is considered successful.

IM Aircraft: An aircraft that is equipped with FIM Equipment that is instructed to perform an IM Operation. The term IM Aircraft is also used to refer to an aircraft, during pre-initiation activities that the controller is expecting to provide with an IM Clearance.

IM Clearance: The authority given to the flight crew of the IM Aircraft to conduct the IM Operation. This authority is communicated from the controller to the flight crew and includes the information needed to conduct the IM Operation (e.g., Target Aircraft ID, Assigned Spacing Goal, Achieve-by Point).

IM Clearance Type: The basic action that the IM Aircraft is instructed to perform as a part of the IM Operation. There are three basic IM Clearance Types: Achieve-by then Maintain, Maintain Current Spacing, and Turn.

IM Operation: A combination of IM capabilities and procedures used to initiate and execute an IM Clearance. An aircraft following an IM Clearance is an IM Operation, and comprises a specific instance of an Operational Application.

IM Situation Awareness Information: The information or data presented to the flight crew to assist them in developing awareness of how the IM Operation is proceeding

IM Speed: The speed provided by the FIM Equipment to the flight crew during an IM Operation to achieve and/or maintain the Assigned Spacing Goal. The IM Speed may be a precise speed or a speed range, presented in a manner and format consistent with other on-board display of speeds to the flight crew.

IM Special Points: Points that can be used as part of the IM Clearance, i.e., Achieve-by Point, Planned Termination Point, and Intercept Point.

IM System: The overall system that enables IM Operations. This includes the ground domain's ability to provide the controller with the necessary information to determine whether to issue an IM Clearance and the specifics of that clearance, the provision of surveillance data of surrounding aircraft to IM-capable aircraft and the on-board Target Aircraft surveillance (e.g., ADS-B IN), application processing, and the provision of required information to the flight crew of the IM Aircraft used to perform IM Operations.

IM Tolerance: The bounds on the difference between the Spacing Interval and the Assigned Spacing Goal (i.e., the Spacing Error) at the Achieve-by Point or during the Maintain Stage within which the goals of the IM Operation will be met. The IM Tolerance is understood to apply to actual (not measured) aircraft positions.

Intended Flight Path: The flight path the FIM Equipment expects the IM or Target Aircraft to follow.

- The FIM Equipment defines the Intended Flight Path of the Target Aircraft using the Intended Flight Path Information included in the IM Clearance along with other on-board Intended Flight Path Information.
- The FIM Equipment defines the Intended Flight Path of the IM Aircraft using Intended Flight Path Information available on-board the IM Aircraft.

Intended Flight Path Information: Information acquired by the FIM Equipment and used to define the Intended Flight Path. Sources of Intended Flight Path Information may include, for example, the IM Clearance, databases, ADS-B messages, flight crew input, or Flight Management Systems.

Intended Route: The horizontal (2D) projection of the IM or Target Aircraft's Intended Flight Path.

Maintain Stage: The part of the IM Operation where the IM Aircraft adjusts its speed to maintain the Assigned Spacing Goal within the FIM Equipment Tolerance. The Maintain Stage begins after the IM Aircraft has reached the Achieve-by Point, or if the IM Operation is initiated in the Maintain Stage when executing a Maintain Current Spacing Clearance.

Operational Application: An implementation of ASPA-FIM supporting specific IM Operations within a given operational environment and operational objectives. The design of an Operational

Application includes the statement of operational goals, a description of the assumed operating environment, and a specific selection of capabilities and variations defined within the OSED.

Operational Uncertainty: An uncertainty in the ability to predict the future spacing between the IM Aircraft and Target Aircraft. Operational Uncertainties include unknown differences in IM Aircraft and Target Aircraft performance and unknown differences in wind conditions experienced by the IM and Target Aircraft.

Performance Level: The minimum required State Data performance for an IM Operation. The Performance Level includes Horizontal Position Accuracy, Horizontal Position Integrity, Horizontal Velocity Accuracy, as well as vertical position and vertical rate, latency, uncertainty in the time of applicability or of received data, and update rate for which new State Data is received by the FIM Equipment.

Planned Termination Point: A point on the IM Aircraft's Intended Flight Path where the IM Operation is terminated normally.

Predicted Spacing Interval: The predicted horizontal along-path spacing at the Achieve-by Point, in distance or time, between the IM and Target Aircraft as determined by the FIM Equipment.

Route: The horizontal path between two or more points defined as a sequence of waypoints or by latitudes and longitudes. The horizontal path may be part of a defined procedure such as jet routes or standard terminal arrival routes

Spacing Interval: The horizontal along-path spacing between the IM and Target Aircraft.

- For time-based spacing, the Spacing Interval is the difference in time between when the IM Aircraft and the Target Aircraft are measured to cross a reference point. The reference point is a Common Point on Coincident Routes, or an equivalent point on non-Coincident Routes.
- For distance-based spacing, the Spacing Interval is the measured along-path distance between the IM Aircraft and the Target Aircraft at a point in time. The along-path distance may be measured directly if the IM and Target Aircraft are on a common Route, or it may be measured relative to a common or equivalent point if the IM and Target Aircraft are on non-Coincident Routes.

Spacing Error: The difference between the Spacing Interval and the Assigned Spacing Goal.

Speed Constraint: As part of a navigation procedure, a limit or range for the speed of an aircraft at a given point. Modern Flight Management Systems (FMSs) typically interpret a Speed Constraint as an "at or below" limitation.

Speed Restriction: A regulatory limit on the speed of an aircraft in particular airspace. E.g. a maximum indicated airspeed of 250 knots below 10,000 feet.

Target Aircraft: The aircraft against which the IM Aircraft is performing the IM Operation. Note that a Target Aircraft must be ADS-B OUT equipped in this document.

Target Aircraft Identification: A group of letters, figures or a combination thereof that is either identical to, or the coded equivalent of, the Target Aircraft call sign used in air-ground communications, and that is also used to identify the Target Aircraft in ground-ground air traffic services communications.

1 Introduction

1.1 Background

The Aircraft Surveillance Applications System (ASAS) is an umbrella term for a large number of applications using Automatic Dependent Surveillance - Broadcast (ADS-B), see [4]. This data link system transmits information from the aircraft (including identification, position, altitude, speed, course) to the ground and other aircraft. Based on this digital information from (other) nearby aircraft, airborne applications have been developed that support Air Traffic Management (ATM) operations. For applications in [4] the following categories are defined:

- Airborne Traffic Situational Awareness (ATSA)
  - Improving the flight crews' knowledge of surrounding traffic, both in the air and on ground
- Airborne Spacing (ASPA)
  - Establishing and maintaining a given distance or time with another aircraft, as instructed by a (new) Air Traffic Control (ATC) instruction.
- Airborne Separation (ASEP)
  - Delegating the responsibility for the separation of traffic and associated tasks to the flight crew. This delegation of responsibility is limited to traffic by the designated aircraft.
- Airborne Self-Separation (SSEP)
  - The separation of the aircraft relative to all surrounding traffic in accordance with applicable airborne separation standards and air traffic rules.

Several ASAS applications have been developed and examined over the past 10-15 years. For a number of these applications standards have been developed and harmonized in the ADS-B Requirements Focus Group (RFG), a partnership between EUROCAE / Eurocontrol and RTCA / FAA, with input from various parties from the U.S. and Europe (including aircraft manufacturers, avionic manufacturers, air traffic control organizations and research), see [5]. ASAS applications are also an integral part of the new separation methods in the SESAR Concept of Operations (ConOps). It is one of the cornerstones on which the SESAR ATM Target Concept is built, see [6].

In 2009, the KDC ASAS project [7] performed research into applications based on ADS-B that may be of benefit to Schiphol (SPL). An important conclusion was that the Airborne Spacing (ASPA) – Flight Deck Interval Management (FIM) application, which is the airborne part of the ASAS – Interval Management (IM) suit, needs to be further developed. ASPA-FIM is an "Airborne Spacing" application, with the important feature that it may overcome the potential capacity reductions, resulting from the introduction of Continuous Descent Operations (CDO) during daytime operations and in particular during peak hours.

Capacity problems associated with Continuous Descent Operations were identified early on and a note of this was made to the KDC Research Agenda:

The government and neighbouring communities have an urgent call for Continuous Descent Operations at Schiphol to be implemented in the coming years. These CDO procedures are based on fixed routes, routes which will be introduced as a result of consultation among various parties at the Alders table. CDOs will yield improvements with regard to fuel use and a number of environmentally aspects such as emissions and noise, when compared to the current so-called step-down approaches. However, the introduction of CDO's also has a downside in that, unless additional measures are taken, CDOs that are based on fixed routes have a negative effect on the landing capacity. Reducing the peak hour capacity will damage the network of KLM/AF and will jeopardize the future of Schiphol. For the Dutch aviation sector, the introduction of CDO with no mitigation procedures or technologies to overcome the shortcomings is unacceptable.

In view of the introduction of CDOs with a high peak hour capacity (> 30 landings per hour per runway) additional steps are required. ASAS-IM (within SESAR also known as ASAS

Sequencing and Merging) is internationally regarded as one of the most appropriate concepts to address this deficiency. With ASAS-IM, aircraft (via ADS-B) exchange flight information and use this information to control an ATC assigned distance or time interval with a preceding aircraft. This close loop control may provide the accuracy and predictability that is required to maintain peak hour capacity. Initial operational trials have been conducted by United Parcel Services (UPS), in cooperation with the FAA, at Louisville International Airport in the United States and have shown positive results.

The project, for which this document is written, is aimed at the further development of ASAS-IM and to demonstrate its feasibility within the specific operating and environmental conditions of Schiphol airport. Global research on CDOs with ASAS-IM up till now has only been conducted in Terminal Manoeuvring Areas (TMA) which are much larger than the Schiphol TMA. In principle each local situation must be validated individually, because of the airspace structure, the approach and departure routes and associated procedures and, importantly the supply and composition of air traffic. In order to support a strategic deployment decision, it is very important that testing and evaluations be performed with a fairly high degree of fidelity.

1.2 Document Objective

This document provides the Operational Performance Assessment (OPA) for the ASPA-FIM application as defined in the Operational Services and Environment Definition (OSED) document [21]. The OSED describes the services, intended functions and associated procedures of the application and the assumptions about the environment in which the application is specified to operate. The OPA provides the analyses of the performance of the specific Operational Application of ASPA-FIM and the environment for which it is designed.

The OPA focuses on those aspects of the system that impact the usability of ASPA-FIM under normal operation. The aim of this analysis is to fully characterize the minimum performance requirements of the system that are required to meet the operational objectives. The primary operational objective, as defined in the OSED, is to achieve precise inter-aircraft spacing using the FIM Equipment. The second operational objective, which is derived in the OPA, is to ensure good overall system behavior in IM Operations with multiple aircraft participating. In addition, the minimum functional and performance requirements ensure consistent operation and interoperability for a range of IM Operations.

The objectives of the OPA for ASPA-FIM include:

- Deriving the data items needed to support the IM Operation;
- Deriving information requirements and functional requirements on those data items;
- Deriving the Operationally-Required Tolerances needed by the controller to ensure proper management of the flow and to establish trust in the system;
- Deriving the minimum surveillance requirements for the Target Aircraft and the minimum requirements on the IM Aircraft's State Data;
- Deriving the minimum performance of the IM Speed determined by the FIM Equipment in order to meet the operational objectives established in the OSED; and
- Deriving the minimum performance of the IM Speed determined by the FIM Equipment in order to provide good overall system behavior in the assumed operating environment.

1.3 Analysis Approach

The OPA analysis approach is based on the ASPA-FIM Operational objectives, Operational Requirements (ORs) and assumptions defined in the OSED. More specifically, the ASPA-FIM OPA for Schiphol:

- Identifies operationally-required information based upon ORs in the OSED [21].
- Translates the ORs into Performance Requirements (PRs) on the exchange of information across the data interfaces of the FIM Equipment.
- Analyzes the defined Scenarios and Operational Requirements in the OSED to set performance requirements on the FIM Equipment.

- Analyzes the Operationally-Required Tolerances for the SPL IM Operational Application, to determine the IM Tolerances.
- Sets PRs and Assumptions that baseline Target Aircraft surveillance and IM Aircraft State Data performance to support the SPL IM Operational Application.
- Derives the required performance of the IM Speeds calculated by the FIM Equipment to ensure that the allocation of the IM Tolerance is met in the presence of the Operational Uncertainties identified for the SPL Scenario.
- Identifies relevant design considerations for the IM System that did not result in minimum requirements for the SPL IM Operational Application but are considered beneficial, and as such serves as guidance to implementers.

1.4 Document Source

The material in this document has been derived from the "Safety, Performance and Interoperability Requirements document for Airborne Spacing – Flight Deck Interval Management (ASPA-FIM)" developed by the "ADS-B Requirements Focus Group" (RFG) [2,3]. It has been adapted to the meet the Schiphol operational and environmental requirements.

1.5 Document Structure

The document is structured in the following manner:

- Section 1 (this section) provides a brief introduction to the document, i.e. the background, objectives and analysis approach of the KDC IM OPA study for Schiphol;
- Section 2 describes the operational context of Interval Management in the Schiphol environment;
- Section 3 presents a high-level description of the CNS/ATM System relevant to IM operations;
- Sections 4 to 7 are the main sections in this document and present all the results of the IM performance assessment for the assumed SPL TMA operations;
- Section 8 summarises the performance requirements;
- Section 9 presents the set-up, design and results of the fast-time simulation to evaluate the IM performance, addressing main operational uncertainties and FIM implementation options.
- Appendix A derives the IM Tolerance and FIM Equipment Tolerance for the SPL arrival operations.
- Appendix B presents the relevant Measured Spacing Interval uncertainties as specified by the joint EUROCAE/RTCA FIM SPR (ED-195, DO-328).

2 Schiphol ASAS-IM Operational Application

2.1 Interval Management

In the context of fixed arrival routes and Continuous Descent Operations (CDO), ASAS Interval Management (IM) is regarded, according to current internationally accepted view (SESAR, NextGen), to be the most appropriate application to fulfill the operational requirements. ASAS-IM is defined in [2,3] as the overall system that enables improved means for managing traffic flows and precise inter-aircraft spacing, including the use of ground tools that assist the controller in evaluating the traffic picture and determining appropriate instructions to merge and space aircraft safely and efficiently [8-15]. Interval Management includes both the ground capabilities needed for the controller to issue an IM Clearance and the airborne capabilities needed for the flight crew to follow the IM Clearance. Ground capabilities used for determining IM Clearances issued to aircraft can be simply the provision of the complete traffic picture and the experience of the controller for basic operations or automated tools to assist the controller in more complex traffic patterns or environments. Airborne (i.e. flight deck) capabilities designed to support IM Operations are called Airborne Spacing – Flight Deck Interval Management (ASPA-FIM).

The controller using IM will instruct the flight crew to achieve and/or maintain an Assigned Spacing Goal relative to a Target Aircraft. The key addition within IM operations to current operations is the provision of precise speed guidance onboard the aircraft to enable the flight crew to actively manage the spacing relative to the Target Aircraft. During IM Operations, the controller retains responsible for separation, while the flight crew is responsible for using the FIM Equipment to achieve and/or maintain the Assigned Spacing Goal that is set by the controller to meet the operational goals. Ground capabilities are foreseen to support controllers in the separation provision, this relates to the controller tasks of monitoring progress (complying with the IM Clearance) and making decisions to intervene or not to intervene.

2.2 Schiphol Concept of Operation

For Schiphol, IM operations start with Amsterdam Area Control (ACC) using an Arrival Manager (AMAN) or other means to build up a properly spaced sequence of aircraft to the designated runway. From this planned sequence, aircraft pairs can be determined. Each pair consists of an IM aircraft and a Target aircraft. The Target aircraft may initially be on a different route. ATC furthermore needs to assure that both aircraft arrive at their IAFs in time in order to be able to adhere to the fixed arrival routes and to start IM operations. For that ATC uses the Speed And Route Advisor (SARA) tool. This tool helps ACC to deliver the aircraft on their designated Initial Approach Fixes (IAF) at the appointed time with a tolerance of +/-30 sec around the planned schedule time.

Prior to entering the TMA, the IM aircraft will receive an IM Clearance. For that ATC determines the IM Clearance parameters and assesses these to ensure that applicability parameters are met. The IM Clearance which will be communicated over radio, includes among other which aircraft to follow (Target ID), the spacing requirement (Assigned Spacing Goal) and the Intended Flight Path Information of the Target aircraft. The Achieve-by point, Planned Termination Point and IM tolerance are all part of the IM procedure for which the aircraft will be cleared.

Upon reception of the IM Clearance, the flight crew acknowledges reception and enters the instruction into the FIM equipment. The equipment is subsequently used to determine the likelihood of success for completing the IM operation. The FIM equipment also checks the input to see if the data of both the Target and IM aircraft is of sufficient quantity and quality for IM Operation. When it determines that all execution requirements are met, an initial IM speed is calculated and displayed in the cockpit. The crew now determines if this speed is feasible and stays within any applicable regulatory and/or performance limits. When this assessment is successful the crew notifies ATC that the IM clearance is accepted and IM operations have been initiated.

The crew now opens the speed window on the Mode Control Panel (MCP) and dials-in the IM speed. The Auto Throttle System activates and adjusts the throttles to adhere to the commanded speed. During the IM operation both the crew and the FIM equipment will monitor the conformance with the IM Clearance. The flight crew may terminate the IM operation at any time if out of conformance or unfeasible IM speeds are observed. If this occurs the IM application is stopped and ATC is notified. ATC in the meantime monitors the progression of both flights. When separation and/or spacing issues are identified ATC determines whether to intervene. In some instances tactical adjustments to the lead aircraft may resolve the problem without impacting the IM aircraft. In other instances ATC will suspend the IM Clearance so that it can be amended or ATC terminates it altogether.

Upon reaching the Planned Termination Point, the FIM equipment will notify the crew of termination and removes the IM speed from the cockpit displays. The crew is now instructed to fly speeds in accordance will normal operational procedures, resulting in stabilized approach conditions at 1000 ft AGL.

A full description of the ConOps is provided in the Operational Service and Environment Definition (OSED) document [21] which among others describes the services, intended functions and associated procedures of the Schiphol ASAS-IM application, along with the assumptions about the environment in which the application is specified to operate. In this document argumentation is provided for the choices made with respect to the IM concept elements for Schiphol. A summary of these choices is provided in the table below.

Table 1: Selected IM concept elements

Concept element	**Selected option**
Target aircraft	Single target operations
First IM execution moment	Near Initial Approach Fix (IAF)
Target aircraft route prior to merge point	Segmented route to merge point
IM Clearance type	IM Achieve-by (then Maintain)
Assigned spacing goal type	Time-based
Assigned spacing goal value	Pair-wise assigned spacing goal Determined on the ground
Achieve-by point	Final merge point / Intermediate Approach Fix (IF)
Planned Termination Point	Final Approach Fix (FAF)
Passing the IM instruction to the flight crew	Radio-Telephony (R/T)
IM Speed implementation	Flight crew manually inputs IM Speeds
IM algorithm	Trajectory-based algorithm
Start of CDO	At IAF
CDO altitude profile	At or above constraints and/or altitude window constraints at waypoints
CDO speed profile	Nominal speed profile with +/-10% control margins
Horizontal separation minima	Current distance-based criteria (3/4/5 NM)

CTA accuracy of delivering aircraft (at the IAF)	30 seconds (99%) – SARA
PBN regime in Schiphol TMA	P-RNAV (i.e., RNAV 1) Fly-by turns, no RF legs
Surveillance regime in Schiphol TMA	Radar
Ground IM automation	Tools to support the controllers in initiating, monitoring and, if necessary, terminating IM operations

2.3 General ATM System requirements

While the main driver to introduce IM at Schiphol is to retain capacity during CDO, compliance with other high level requirements will also be needed. For IM Operations these major ATM System Requirements (ASR) are related to a number of Key Performance Areas, such as capacity, predictability, safety and environmental impact and are summarized below.

High level capacity requirement
ASR.1 The introduction of IM Operations shall retain daytime capacity while performing Continuous Descent Operations along fixed routes.

High level safety requirements
ASR.2 IM Operations shall not increase the workload of controllers beyond a manageable level.

ASR.3 IM Operations shall not increase the workload of flight crews beyond a manageable level.

ASR.4 The introduction of IM Operations shall not lead to a reduction in safety.

High level predictability requirements
ASR.5 IM Operations shall support the controllers in creating a more predictable and stable traffic flow.

High level environmental requirement
ASR.6 The introduction of IM Operations shall enable increased CDO, which shall decrease the noise and emission impact of flight operations.

High level efficiency requirement
ASR.7 The introduction of IM Operations shall enable increased CDO, which shall increase the fuel efficiency of flight operations.

High level flexibility requirement
ASR.8 The introduction of IM Operations shall retain the flexibility in changing runway configurations.

2.4 Operational assumptions

Assumptions have been made about the environment in which the application is specified to operate. These assumptions form an important basis for all future assessments and analyses. All requirements must be considered within the context of these assumptions, as well as the operations and environments defined. Any deviation from the assumptions noted in this document could impact the corresponding requirements and therefore must be accounted for in supporting analysis or introduction of other assumptions and/or mitigations. The Operational Assumptions for the defined concept are summarized below.

Table 2: OSED Assumptions

Reference	Assumption
ASSUMP-OSED.1	Intentional misuse or abuse of the FIM Equipment or procedures is outside the scope of this document.
ASSUMP-OSED.2	The controller only issues an IM Clearance that is feasible including appropriate Target Aircraft, the Assigned Spacing Goal, and any included IM Special Points.
ASSUMP-OSED.3	The controller has the necessary information to determine the IM Aircraft, Target Aircraft and Assigned Spacing Goal.
ASSUMP-OSED.4	The airspace is under surveillance (e.g., radar and/or ADS-B-RAD) so that the controller has positive control over all involved aircraft.
ASSUMP-OSED.5	The controller has selected an IM Aircraft and Target Aircraft which have the appropriate equipment, compatible speed profiles, compatible positions and compatible routes.
ASSUMP-OSED.6	There is appropriate coordination between all controllers involved in the IM Operation to enable the IM Operation to proceed without undo interruption.
ASSUMP-OSED.7	The IM Aircraft has already received, and is following, a navigation clearance which defines their Intended Flight Path.
ASSUMP-OSED.8	The Target Aircraft Identification used in the IM Instruction matches what the Target Aircraft is broadcasting as its identification.
ASSUMP-OSED.9	Direct Controller-Pilot Communications (DCPC), such as voice, is available throughout the IM Operation.
ASSUMP-OSED.10	The controller and flight crew are provided with a new set of voice messages to conduct IM, but the guidelines for these are out of scope for this document.
ASSUMP-OSED.11	The flight crew manually inputs the IM Speed into the speed guidance system, which is active during the IM manoeuvre.
ASSUMP-OSED.12	The IM Clearance has the equivalent effect to a controller's speed instruction and supersedes Speed Constraints on the IM Aircraft's Intended Flight Path; however, appropriate regulatory Speed Restrictions are still to be respected.
ASSUMP-OSED.13	During aircraft handoffs between controllers, the receiving controller has sufficient information to continue the IM Operation.
ASSUMP-OSED.14	IM Operation are defined for the arrival process within the Schiphol TMA only.
ASSUMP-OSED.15	IM Operations can be performed in airspace of any traffic density.
ASSUMP-OSED.16	IM Operations can be conducted under both Instrument Meteorological Conditions (IMC) and Visual Meteorological Conditions (VMC).
ASSUMP-OSED.17	The airborne surveillance level within the deployment environment is mixed.
ASSUMP-OSED.18	The flight crew has a traffic situation awareness tool, such as ATSA-AIRB, available to them.

2.5 Operational Requirements

The Operational Requirements specify the performance elements of the application associated with the operators and define the necessary procedural steps, tasks and actions that must be performed by these operators for proper execution of the IM Operations. Within the OSED, these Operational Requirements are defined and listed below.

Table 3: OSED Operational Requirements

Ref.	Operational Requirement
OR.1	The controller shall be trained to perform IM Operations.
OR.2	The controller shall determine when to use an IM Operation.
OR.3	The controller shall assign a precise Assigned Spacing Goal.
OR.4	The Achieve-by Point, which is a point on the IM Aircraft's Intended Flight Path, shall be an intrinsic part of the cleared navigation procedure.
OR.5	The Planned Termination Point, which is a point on the IM Aircraft's Intended Flight Path, shall be an intrinsic part of the cleared navigation procedure.
OR.6	As part of the IM Instruction, the controller shall identify the Intended Flight Path of the Target Aircraft.
OR.7	Deleted.
OR.8	When the controller issues a new clearance to the IM and/or Target Aircraft that results in a modification to their Intended Flight Paths, the controller shall terminate the IM Operation.
OR.9	During the Execution Phase, the flight crew shall terminate the IM Operation and notify the

	controller if the IM and/or Target Aircraft have deviated by more than operational limits from their Intended Flight Paths.
OR.10	The controller shall identify the following information when issuing the IM clearance: - Target Aircraft Identification; - Assigned Spacing Goal; - IM Clearance Type (procedural); - Achieve-by Point (procedural); - Planned Termination Point (procedural) - IM Tolerance (procedural); and - Target Aircraft Intended Flight Path Information.
OR.11	Upon receipt of the IM Clearance, the flight crew shall make the data identified in the IM Clearance available to the FIM Equipment.
OR.12	If one or more of the following conditions are not met, the flight crew shall reject the IM Clearance: - The Target Aircraft has been positively identified; - Target Aircraft data quality is sufficient for the IM Operation; - IM Aircraft data quality is sufficient for the IM Operation; - the flight crew is trained for IM Operations; - the FIM Equipment is able to present IM Speed; and - there is a reasonable likelihood of successfully completing the IM Operation.
OR.13	The flight crew shall be trained how to use the FIM Equipment and to perform the IM Operations.
OR.14	The flight crew shall implement changes from the IM Speed guidance in a timely manner consistent with other cockpit duties, unless safety-of-flight considerations, operational acceptability, or regulatory limitations preclude it.
OR.15	Deleted.
OR.16	Deleted.
OR.17	During the Execution Phase, the following information shall be available for display to the flight crew: - the IM Speed; - FIM Equipment status; and - IM Situation Awareness Information.
OR.18	The flight crew shall be notified when the IM Speed guidance changes.
OR.19	If the flight crew is unable to continue conforming to the IM Clearance, they shall notify the controller.
OR.20	The flight crew shall terminate the IM Operation if: - they are unable to continue conforming with the IM Instruction; - the data quality for the IM Aircraft is no longer sufficient to support the IM Operation; - the data quality for the Target Aircraft is no longer sufficient to support the IM Operation; or - if the FIM Equipment is no longer able to provide IM Speed.
OR.21	As with other instructions or clearances, the controller shall monitor the IM Aircraft to ensure that IM Aircraft is behaving in an acceptable manner and is in conformance with the IM Clearance.
OR.22	The controller shall terminate the IM Operation if it is no longer desirable.
OR.23	The flight crew shall terminate the IM Operation upon reaching the Planned Termination Point.
OR.24	Upon reaching the Planned Termination Point, the FIM Equipment shall terminate the FIM application by removing the IM Speed.
OR.25	If the flight crew initiates the termination of the IM Operation, other than at the Planned Termination Point, the flight crew shall notify the controller and maintain an operationally appropriate speed until otherwise instructed.
OR.26	If the controller terminates the IM Operation prior to the Planned Termination Point, the controller shall include a speed instruction in the termination instruction.
OR.27	Once the IM Operation is terminated the controller shall resume conventional control of the IM Aircraft.
OR.28	The flight crew shall only receive IM Speed after successful initiation and up to the Planned Termination Point.
OR.29	The flight crew shall have the ability to remove or suppress all IM-related displays and information.
OR.30	The controller shall issue a When Able Instruction when they are unsure if the IM Aircraft has airborne surveillance information on the Target Aircraft and they want the IM Aircraft flight crew to begin the IM Operation once the IM Aircraft has airborne surveillance information on the Target Aircraft.

OR.31	Following a When Able Instruction, the flight crew shall inform the controller when they commence IM Operations.
OR.32	When the controller wants the flight crew to initiate an IM Operation at some later time, the trigger event shall be communicated with the IM Instruction.
OR.33	After an expect Instruction, the flight crew shall notify the controller when they are able to begin the IM Clearance.
OR.34	The controller shall terminate the current IM Operation and issue a new IM Instruction if the Target Aircraft Identification is to be modified.
OR.35	During the Execution Phase, the controller shall be able to amend an existing IM Clearance to change the following data: - Assigned Spacing Goal(s); - Achieve-by Point; - Planned Termination Point; - IM Tolerance; - IM Aircraft Intended Flight Path Information; and - Target Aircraft Intended Flight Path Information.
OR.36	The flight crew shall assess the feasibility of the modified IM Clearance before accepting the new instruction
OR.37	The flight crew shall suspend the IM Operation when instructed by the controller.
OR.38	The flight crew shall only resume the IM Operation when instructed by the controller.
OR.39	The flight crew shall reassess feasibility of conforming to the IM Clearance before resuming a suspended IM Operations.
OR.40	The controller shall only issue the IM Clearance to an aircraft operating under Instrument Flight Rules (IFR).
OR.41	Controllers shall have all necessary information at hand required to initiate an IM Clearance, even when the target aircraft is not in the area of responsibility of the controller at the time of the IM Clearance.
OR.42	Controllers shall be able to compare the current spacing interval, with the assigned spacing interval. Threshold values shall be used to alert the controller when large discrepancies occur.
OR.43	Controllers shall to be able to return to and operate under normal operations.

3 The CNS/ATM system

Figure 1 presents the generic surveillance functional architecture considered by RTCA and EUROCAE to support the ASAS-IM application. The figure identifies the airborne domains and the ground domain associated with IM Applications enabled by ADS-B. The aircraft performing ASPA-FIM (i.e., the IM Aircraft) is represented by the IM Aircraft Receive Domain. Surrounding aircraft, including the Target Aircraft (i.e., the intended traffic to use for the IM Operation) are represented by the Target Aircraft Transmit domain. The Transmit Aircraft Domain represents the functions associated with providing the ADS-B OUT capability needed to support the IM application. The Receive Aircraft Domain provides the ADS-B IN capability and the functions needed to support IM operations. The Ground Domain represents the capability to host ground-based surveillance applications in support of Air Traffic Services.

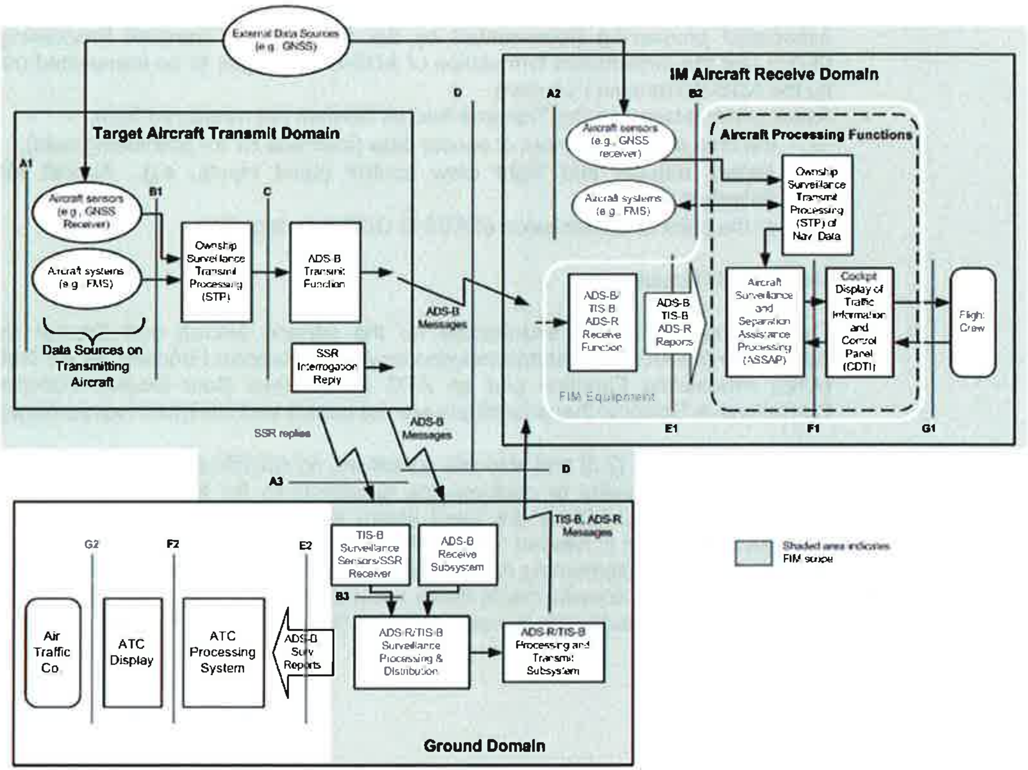


Figure 1: Surveillance Functional Architecture

Figure 1 also identifies the system functions and functional interfaces (small lines with associated letters and numbers, e.g., B1) associated with the aircraft domains and the ground domain. The figure identifies the functional interfaces (e.g., D, G1) to which the Performance (and Safety) Requirements are allocated. These interfaces are referenced throughout the document where requirements are provided.

General functional capabilities and key aspects of the architecture are specified below.

For the Receive Aircraft Domain:

- The minimum surveillance functional architecture includes:
  - reception of ADS-B messages (represented by the ADS-B Receive Function);
  - ownship sensor data processing;
  - surveillance data processing and applications-specific processing (represented by the Airborne Surveillance and Separation Assurance Processing Function [ASSAP]); and

  - the provision of necessary information to the flight crew by the Traffic Display Function and its associated control interface.
- Requirements allocated to the Receive Aircraft Domain are measured from the point of reception (interface D) for ADS-B information, or the output of the aircraft sensors and systems (interface B2) for ownship information, through the conveyance of needed information to the flight crew (interface G1).

Note: TIS-B (Traffic Information Service - Broadcast) and ADS-R (Automatic Dependent Surveillance – Rebroadcast) data are shown in Figure 1 as potential other sources of surveillance data, however they are deemed not suitable to support the ASPA-FIM application at SPL.

For the Transmit Aircraft Domain:

- The minimum surveillance functional architecture includes onboard aircraft sensors and associated processing (represented by the Surveillance Transmit Processing Function [STP]) and the subsequent formulation of ADS-B messages to be transmitted (represented by the ADS-B Transmit Function).
- Assumptions placed on the Transmit Aircraft Domain are measured from:
  - the time of measurement of sensor data (interface A1 for positioning data);
  - sensor outputs and flight crew control panel inputs, e.g., Aircraft Identification (interface B1); and
  - at the point of transmission of ADS-B OUT (interface D).

For the Ground Domain:

- The minimum functional architecture for the generic Aircraft and Ground Surveillance Application (ASA/GSA) systems includes an ADS-B Receive Function, an Air Traffic Control (ATC) Processing Function and an ATC Surveillance Data Display Function. For IM Operations at Schiphol these functions are not considered minimum requirements.

For the ASPA-FIM SPR [2,3] and also this document, no specific analysis is performed to derive specific ground functionality or performance requirements for the ground component of the larger IM System. Assumptions are used where appropriate on ground capabilities so that analysis can derive what is needed from ASPA-FIM to support the provided IM Clearances from the ground. ANSP's implementing ASPA-FIM will need to perform appropriate assessments to ensure that the ground domain meets these assumptions or appropriate changes are made to the requirements allocated to the Receive Airborne Domain (i.e., IM Aircraft).

4 Information Requirements

The information needed to conduct the ASPA-FIM application at Schiphol is defined by the SPL IM OSED [21] and is broken down by entry method to the FIM Equipment. This section summarizes the information needs by interface.

4.1 Information made available to the FIM Equipment by the Flight Crew

The OSED identifies the information available from the communicated IM Clearance (OR.10):

- Target Aircraft Identification;
- Assigned Spacing Goal;
- IM Clearance Type;
- Achieve-by Point;
- Planned Termination Point;
- IM Tolerance; and
- Target Aircraft Intended Flight Path Information.

Some of this information will be conveyed in the controller instruction, other will be an intrinsic part of the procedure or be derived from other information. Information that will be communicated over R/T:

- Target Aircraft Identification: *<acid>*
- Assigned Spacing Goal: *< interval>*
- Target Aircraft Intended Flight Path Information: *<procedure name>*

PR.1 Information conveyed to the FIM equipment by means of R/T communication shall include Target Aircraft Identification, Assigned Spacing Goal and Target Aircraft Intended Flight Path Information.

Examples:

- Target Selection
  <call sign> for interval spacing, select traffic <acid> on <procedure name>

- IM Clearance
  <call sign> for interval spacing, space <interval> seconds behind <acid>

- Route Clearance combined with IM Clearance
  <call sign> descend via the <procedure name>. for interval spacing, space <interval> seconds behind <acid>

Information that will be an integral part of the IM procedure and as such defined in the navigation charts regarding the cleared transition:

- IM Clearance Type;
- Achieve-by Point;
- Planned Termination Point; and
- IM Tolerance.

The IM Clearance type will be Achieve then Maintain. The Achieve-by Point for all aircraft will be the Intermediate Approach Fix (IF) being the final merge point. The Planned Termination Point will be the Final Approach Fix (FAF). And the required IM tolerance is also pre-determined and part of the procedure.

PR.2 Information conveyed to the FIM equipment as part of the charted IM procedure shall include IM Clearance Type, Achieve-by Point, Termination Point and IM Tolerance.

All of the information from OR.10, with the exception of the IM Clearance Type, must ultimately be made available to the FIM Equipment through the Interface G1 (OR.11).

4.2 Information provided to the Flight Crew by the FIM Equipment

The flight crew must have available for display the information related to the IM Clearance.

PR.3 The FIM Equipment shall make the following information available for display to the flight crew:
- Target Aircraft Identification;
- Assigned Spacing Goal;
- Achieve-by Point;
- Planned Termination Point;
- IM Tolerance; and
- Target Aircraft Intended Flight Path Information.

The OSED has identified conditions for accepting the IM Clearance (OR.12), flight crew tasks for successful execution of the IM Clearance, including timely implementation of the IM Speed (OR.14), and flight crew tasks for monitoring the IM Operation to determine if they are able to conform to the IM Clearance (OR.21). To support these flight crew tasks, there are two types of information that the FIM Equipment needs to display to the flight crew before the IM Clearance is accepted and during the Execution Phase of the IM Operation:
- IM Situation Awareness Information[1]; and
- the IM Speed.

PR.4 Before the IM Clearance is accepted and during the Execution Phase of an IM Operation, the FIM Equipment shall provide the following information for display to the Flight Crew (Interface G1):
- IM Situation Awareness Information; and
- the IM Speed;

4.3 IM Aircraft Data made available to the FIM Equipment

In order to support the provision of information to the flight crew required by PR.3, information needed to calculate the IM Speed, derive the IM Situation Awareness Information, etc., is required from the IM Aircraft. The OPA analyses the information required by PR.3 and derives the lower-level information required to be available to the FIM Equipment via Interface B2.

PR.5 The following IM Aircraft data items shall be provided to the FIM Equipment by on-board sensors or other aircraft systems through Interface B2 or determined by the FIM Equipment in the IM Aircraft Receive Domain:
- Horizontal Position;
- Pressure Altitude;
- Horizontal Velocity;
- Horizontal Position Accuracy;
- Horizontal Velocity Accuracy;
- Horizontal Position Integrity; and
- IM Aircraft Intended Flight Path Information.

4.4 Target Aircraft Data made available to the FIM Equipment

In order to support the provision of information to the flight crew required by PR.3, information pertaining to the Target Aircraft is needed to calculate the IM Speed, derive the IM Situation

---

[1] For the purposes of this requirement, the term "IM Situation Awareness Information" describes the information that the flight crew needs in order to assess whether the IM Operation is progressing safely, as anticipated, and towards success.

Awareness Information, etc. The OPA analyses the information required by PR.3 and derives the lower-level information assumed to be available to the FIM Equipment at Interface D.

PR.6 The following data items pertaining to the Target Aircraft shall be provided to the FIM Equipment through Interface D:
- Horizontal Position;
- Pressure Altitude;
- Horizontal Velocity;
- Horizontal Position Accuracy;
- Horizontal Velocity Accuracy;
- Horizontal Position Integrity; and
- Aircraft Identification.

5 Functional Requirements

The functional requirements on the FIM Equipment which result from the Operational Requirements (ORs) and description from the OSED are analysed in the section below. The analysis is focused on the interaction between the flight crew and the FIM Equipment in support of conducting the IM Operation.

5.1 Functional Requirements Supporting Data Availability to the FIM Equipment

Throughout the IM Operation, the flight crew interacts with the FIM Equipment by way of Interface G1 (Figure 1).

5.1.1 IM Clearance Information

Upon receipt of the IM Clearance, the flight crew makes the IM Clearance information available to the FIM Equipment (OR.11). The FIM Equipment displays the IM Speed and IM Situation Awareness Information only after all IM Clearance information has been made available to the FIM Equipment.

PR.7 The FIM Equipment shall display the IM Speeds and IM Situation Awareness Information only after all IM Clearance information has been made available to the FIM Equipment.

5.1.1.1 Target Aircraft Identification

The FIM Equipment must provide the flight crew with the means to select the Target Aircraft by use of the Target Aircraft Identification.

PR.8 The FIM Equipment shall provide the flight crew with the means to select the Target Aircraft by use of the Target Aircraft Identification.

Requirements to facilitate modification of the IM Clearance during the IM Operation are described in section 5.1.2.1. However, whenever a new Target Aircraft is selected by its identification, all FIM data associated with a previous IM Clearance that may currently be stored in memory must be cleared (OR.34).

PR.9 The FIM Equipment shall clear any stored IM Clearance information when a new Target Aircraft is selected by its Target Aircraft Identification.

5.1.1.2 Assigned Spacing Goal

In the Achieve-by then Maintain Clearance, the Assigned Spacing Goal has two aspects: a type and associated numerical value(s). The OSED for SPL has defined that the Assigned Spacing Goal is of type "Precise" (OR.3). The FIM Equipment is required to accept and process this Assigned Spacing Goal Type.

PR.10 The FIM Equipment shall be capable of accepting a Precise Assigned Spacing Goal.

5.1.1.3 Achieve-by Point

The Achieve-by Point is specified in the IM Clearance, and is in the SPL concept defined as the final merge point being the intermediate approach fix of the assigned runway, and should be common to both IM and Target aircraft (OR.4). The FIM Equipment should only accept Achieve-by Points that comply with OR.4, in other words both IM and Target aircraft should be planned to the same final approach and runway. The Achieve-by Point is provided as a fixed, geographical point on the IM Aircraft's Intended Flight Path in the form of a named waypoint (e.g., EH608) and is part of the published IM procedure.

PR.11 The FIM Equipment shall only accept an Achieve-by Point that is on the IM Aircraft's Intended Flight Path and common to Target Aircraft's Intended Flight Path.

PR.12 The FIM Equipment shall accept an Achieve-by Point that is a fixed, geographical point in the form of a named waypoint.

5.1.1.4 Planned Termination Point

The Planned Termination Point is specified as position on the IM Aircraft's Intended Flight Path as part of the IM Clearance, and is in the SPL concept defined as the Final Approach Fix. The OSED places further restrictions on the location of the Planned Termination Point that may be established by the controller (OR.5). The FIM Equipment should accept only Planned Termination Points that comply with OR.5.

PR.13 The FIM Equipment shall accept only a Planned Termination Point that:

- is on the IM Aircraft's Intended Flight Path and common to Target Aircraft's Intended Flight Path;
- is coincident with of after the Achieve-by Point; and
- is no closer to the runway threshold than 5 NM.

The OSED defines that the Planned Termination Point is an intrinsic part of the cleared procedure and as such not communicated over R/T (OR.4). The Planned Termination Point is provided as a fixed, geographical point on the IM Aircraft's Intended Flight Path in the form of a named waypoint (e.g., EH621) and is part of the published IM procedure.

PR.14 The FIM Equipment shall accept a Planned Termination Point that is a fixed, geographical point in the form of a named waypoint.

The FIM Equipment is required to terminate the IM Operation upon reaching the Planned Termination Point (OR.24). Certification experts have recommended the automatic removal of IM-related information from displays when the IM Aircraft reaches the Planned Termination Point.

PR.15 The FIM Equipment shall remove the IM Speeds and IM Situation Awareness[2] Information from the display when the IM Aircraft reaches the Planned Termination Point.

5.1.1.5 IM Tolerance

The IM tolerance defines the bounds on the difference between the Spacing Interval and the Assigned Spacing Goal (i.e., the Spacing Error) at the Achieve-by Point or during the Maintain Stage within which the operational goals of the IM Operation will be met. The IM Tolerance is therefore an operational quantity and applies to actual (not measured) aircraft positions. For the SPL arrival operations, it is expected that a single IM Tolerance is specified by the ANSP and that it is part of the published IM procedure.

5.1.1.6 IM and Target Aircraft Intended Flight Path Information

During the IM Operation, the FIM Equipment uses the Intended Flight Paths as representations of the Cleared Flight Paths of the IM and Target Aircraft. The Intended Flight Paths will include speed and altitude constraints, which define the nominal path and are used by the FIM Equipment to calculate the Spacing Interval and the IM Speeds.

The information needed by the FIM Equipment to define the IM Aircraft's Intended Flight Path is assumed to be available to the FIM Equipment over interface B2.

PR.16 The FIM Equipment shall be capable of retrieving the IM Aircraft's Intended Flight Path from sources on-board the IM Aircraft.

The FIM Equipment defines the Target Aircraft's Intended Flight Path using the Intended Flight Path Information included in the IM Clearance and from sources on-board the IM Aircraft when needed. Other sources of Target Intended Flight Path Information outside of the IM Aircraft domain (e.g., Target Aircraft ETA via ADS-B or trajectory information over data link) are not considered at this stage.

---

[2] IM Situation Awareness Information refers only to that information that is pertinent to initiating and executing the IM Operation. Other situation awareness information provided by a traffic situation awareness tool, such as ATSA-AIRB, does not need to be removed upon termination.

PR.17 The FIM Equipment shall define the Intended Flight Path of the Target Aircraft from Intended Flight Path Information included in the IM Clearance and sources on-board the IM Aircraft.

At initiation, the controller provides Intended Flight Path Information for the Target Aircraft, which is used to create the Intended Flight Path. The FIM Equipment uses the Intended Flight Path Information, possibly with other sources of information available on-board the IM Aircraft, to defined the Target Aircraft's Intended Flight Path. In the SPL concept the Target Aircraft Intended Flight Path Information is provided as either the same procedure as the IM Aircraft or a named procedure (e.g., RIVER 3B TRANSITION) that merges with the IM Aircraft's Intended Flight Path.

PR.18 The FIM Equipment shall accept the Target Aircraft's Intended Flight Path Information that is either the same procedure as the IM Aircraft or a named procedure that merges with the IM Aircraft's Intended Flight Path.

In the case of same procedure the Intended Flight Paths of the IM aircraft and Target aircraft are the same. In this case, Intended Flight Path Information for the Target Aircraft acquired through interface G1 indicates to the FIM Equipment that the IM and Target Aircraft are on the same procedure. In order to calculate IM Speeds, the additional information needed to calculate the Spacing Interval and the IM Speeds could be derived from just the State Data of the IM Aircraft (Interface B2) and the Target Aircraft (Interface D).

In the case of a named procedure, the Target Aircraft's Intended Flight Path Information includes a procedure name. This information is made available to the FIM Equipment, which accesses an on-board database for the rest of the information needed to define the Intended Flight Path.

PR.19 The FIM Equipment shall accept a named procedure in the Target Aircraft's Intended Flight Path Information in the format of one of the following options:

- standard arrival route (STAR) designator;
- transition designator; or
- instrument approach procedure (IAP) designator.

Any of the formats above can be combined in a way that makes navigational sense.

To ensure that the calculations of the Spacing Interval and the IM Speeds are valid, the FIM Equipment must check that the reported positions and altitudes of the IM and Target aircraft are consistent with their Intended Flight Path that is defined by the FIM Equipment. Different implementations may allow for greater or lesser variation between the Intended Flight Path and the actual flight path.

The FIM Equipment notifies the flight crew if the IM and/or Target Aircraft are not in conformance with their Intended Flight Paths. The criteria for conformance to the Intended flight Path is determined as part of the definition of the Operational Application and may vary from application to application. A notification to the flight crew is required when either the IM Aircraft and/or Target Aircraft are not in conformance with their Intended Flight Path. The conformance check mitigates the likelihood of providing IM Speeds that are potentially hazardous or misleading.

PR.20 The FIM Equipment shall notify the flight crew when the IM Aircraft and/or Target Aircraft are not in conformance with their Intended Flight Paths.

5.1.2 IM Clearance modification/termination/suspension

5.1.2.1 Modification of the IM Clearance information

During the Execution Phase, the controller may amend the IM Clearance with a new Assigned Spacing Goal, Achieve-by Point, Planned Termination Point, IM Tolerance, and Target Aircraft Intended Flight Path Information (OR.35). In such situations, the flight crew needs to be able to modify these IM Clearance parameters within the FIM Equipment without having to enter the IM Clearance information again in its entirety.

PR.21 The FIM Equipment shall provide the means to modify the following information while retaining all other IM Clearance information:
- Assigned Spacing Goal;
- Achieve-by Point;
- Planned Termination Point;
- IM Tolerance; and
- Target Aircraft Intended Flight Path Information.

The operational behaviour that follows the modification of an IM Clearance is assumed to be similar to terminating an IM Clearance and issuing a new IM Clearance. The flight crew must also have the ability to clear all information from a previous IM Clearance from the FIM Equipment.

PR.22 The FIM Equipment shall provide to the flight crew a means of clearing all information from a previous IM Clearance.

5.1.2.2 Termination prior to the Planned Termination Point

The controller or the flight crew may terminate the IM Operation for reasons other than reaching the Planned Termination Point. At a minimum, the FIM Equipment must provide the means to the flight crew to remove the IM Speeds and IM Situation Awareness Information from displays when the controller or flight crew terminates the IM Operation (OR.29).

PR.23 The FIM Equipment shall provide the means for the flight crew to remove the IM Speeds and IM Situation Awareness Information from displays.

5.1.2.3 Suspending and Resuming the IM Operation

The IM Speeds and IM Situation Awareness Information may be misleading during a suspended operation, where the IM and/or Target Aircraft may be manoeuvred away from their Intended Flight Paths. PR.23 allows the flight crew to remove the IM Speeds and IM Situation Awareness Information from displays when the controller suspends the IM Operation with the expectation to resume.

The FIM Equipment must also provide the means to the flight crew to restore the IM Speeds and IM Situation Awareness Information to the displays when the controller resumes the IM Operation.

PR.24 The FIM Equipment shall provide the means for the flight crew to restore the IM Speeds and IM Situation Awareness Information to the displays if that information was previously removed by flight crew action.

5.1.2.4 Conditional IM Clearance

When the controller issues a conditional IM Clearance, the flight crew makes the IM Clearance information available to the FIM Equipment and determines whether they can accept the clearance after the starting event has occurred. The FIM Equipment may display IM Speeds and IM Situation Awareness once all of the IM Clearance information has been made available to the FIM Equipment. However, the IM Speeds and IM Situation Awareness provided prior to the starting event may be misleading. PR.23 supports the flight crew's ability to remove misleading information prior to the starting event, and PR.24 supports the flight crew's ability to restore the information after the starting event has occurred in order to assess the acceptability of the clearance.

5.1.2.5 Expected IM Clearance

When the controller issues an expected IM Clearance, the flight crew makes the IM Clearance information available to the FIM Equipment and waits until the controller issues the IM Clearance. As in the case of the conditional IM Clearance, PR.23 and PR.24 support removing and restoring the IM Speeds and IM Situation Awareness Information as necessary.

5.2 Functional Requirements Supporting Display Items

The FIM Equipment will provide information to the flight crew through the Human Machine Interface (G1) throughout the IM Operation. There are two requirements identified in Section 4.2 (PR.3 and PR.4) related to the display of information to the flight crew. This section focuses on functional requirements related to the list of displayed information in PR.4.

5.2.1 IM Speed

The presentation of the IM Speed at interface G1 is required both in the Initiation Phase (OR.12) and during Execution (OR.20). Before going from Initiation to Execution, the flight crew checks and accepts the IM Speed as being operationally acceptable.

The difference in the Spacing Interval that is achieved or maintained and the Assigned Spacing Goal is ultimately dependent upon the Operational Uncertainties and the Spacing Interval uncertainty. The IM Speeds provided to the flight crew are designed to achieve or maintain the Spacing Interval within the IM Tolerance of the Assigned Spacing Goal specified for the IM Operation.

Requirements are set within this section to ensure the correct expected behaviour of the IM Aircraft following the IM Speeds.

5.2.1.1 Operational Objective for the IM Speeds

Figure 2 depicts the relationships between the Assigned Spacing Goal, the IM Tolerance, and the Spacing Interval to illustrate the operational objective of driving the Spacing Interval to within the IM Tolerance of the Assigned Spacing Goal at the Achieve-by Point and during the Maintain Stage. Whereas the figure shows a Precise Assigned Spacing Goal given in time, similar relationships exist for a Precise Assigned Spacing Goal given in distance.

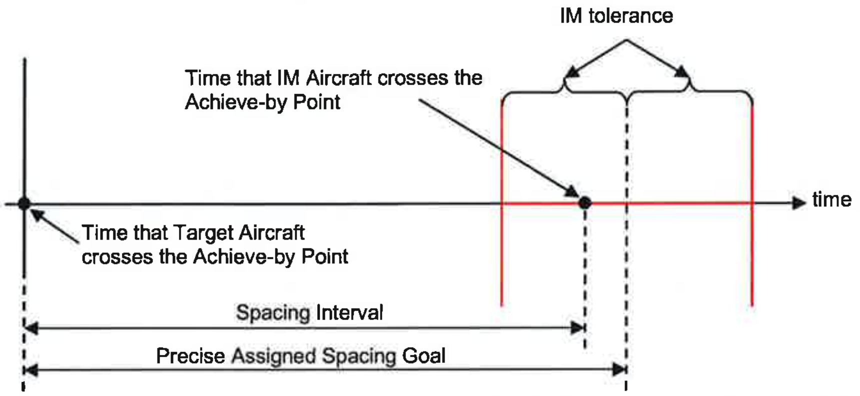


Figure 2: Operational objective to drive the Spacing Interval with the IM Tolerance of the Assigned Spacing Goal

As errors in the Spacing Interval are not known to the FIM Equipment, the FIM Equipment accomplishes the operational objective by driving to a smaller allocated FIM Equipment Tolerance, as shown in Figure 3. In this figure, the error in the Spacing Interval is assumed to be zero, which results in the FIM Equipment Tolerance being centred within the IM Tolerance.

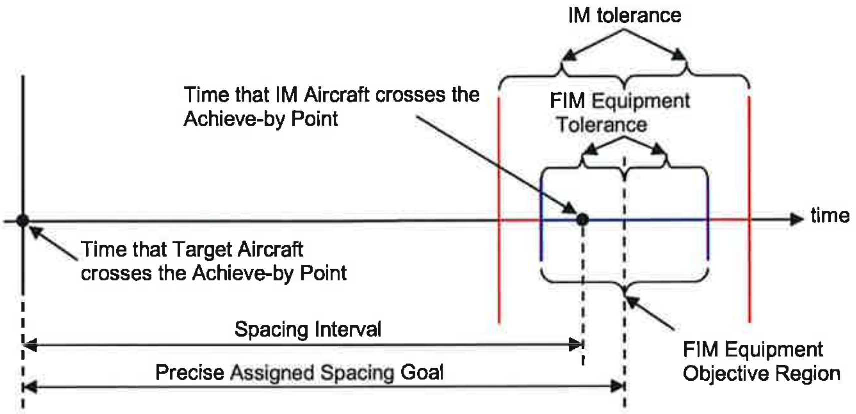


Figure 3: Depiction of the FIM Equipment Tolerance, which is centred within the IM Tolerance when the Measured Spacing Interval Error is zero

There is a defined region, in time or distance, where the IM Operation from an equipment's point of view is considered successful. This region, called the FIM Equipment Objective Region, shown in Figure 3, is related to the Precise Assigned Spacing Goal and the FIM Equipment Tolerance. The FIM Equipment provides IM Speeds to achieve and maintain a Spacing Interval within the FIM Equipment Objective Region at the Achieve-by Point and during the Maintain Stage, respectively.

The effect of errors in the Spacing Interval on the FIM Equipment Objective Region and how the Spacing Interval gets controlled as a consequence is explored further in Section 9 and reference [19].

5.2.1.2 Definition of the FIM Equipment Objective Region

In the Achieve-by Then Maintain Clearance with a precise Assigned Spacing Goal given in time, the Spacing Interval should be within the FIM Equipment Tolerance of the precise value, when the IM Aircraft is measured to cross the Achieve-by Point and for the duration of the IM Operation until the Planned Termination Point is reached (Figure 4).

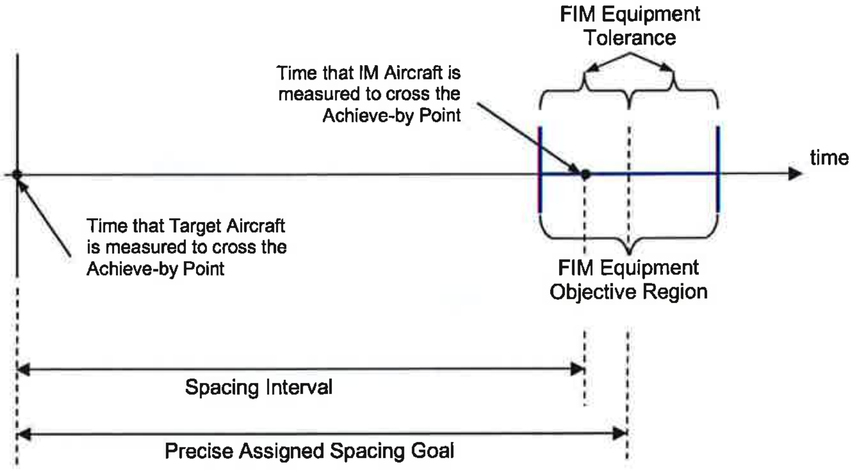


Figure 4: FIM Equipment Objective Region for the Spacing Interval given a precise Assigned Spacing Goal in Time

5.2.1.3 Determination of FIM Equipment Tolerance

The FIM Equipment determines an appropriate FIM Equipment Tolerance relative to the Assigned Spacing Goal within which the Measured Spacing Interval is controlled. This ensures that the true Spacing Interval which does not include measurement errors is within the IM Tolerance.

To accommodate for the uncertainties in the Measured Spacing Interval, the FIM Equipment determines IM Speeds to drive the Measured Spacing Interval within the FIM Equipment Tolerance. The FIM Equipment Tolerance is smaller than the IM Tolerance to accommodate an allocation for the uncertainty in the Measured Spacing Interval.

PR.25 The FIM Equipment shall determine the FIM Equipment Tolerance based on the following Equation: FIM Equipment Tolerance ≤ SQRT[$(\text{IM Tolerance})^2$ – $(\text{Measured Spacing Interval Uncertainty})^2$].

The IM Tolerance is provided as part of the IM Clearance. The remaining unknown in order to be able to compute the FIM Equipment Tolerance is the Measured Spacing Interval Uncertainty. One acceptable means to establish an appropriate Measured Spacing Uncertainty for the purposes of determining an acceptable FIM Equipment Tolerance is to use the spacing uncertainty analysis results presented in Table 33 and Table 34 in APPENDIX B.

5.2.1.4 Requirements on the IM Speed

Prior to reaching the Achieve-by Point, the Spacing Interval may be outside of the FIM Equipment Tolerance; however, the IM Speeds must be working to drive the Spacing Interval within the FIM Equipment Tolerance by the Achieve-by Point.

PR.26 During the Achieve Stage, the FIM Equipment shall provide IM Speeds such that, if followed, the Spacing Interval is within the FIM Equipment Tolerance at the Achieve-by Point.

In order to provide IM Speeds that drive the Spacing Interval back to within the FIM Equipment Tolerance, the FIM equipment needs to determine what the Predicted Spacing Interval is at the Achieve-by Point. For that the FIM equipment must calculate the Time To Go (TTG) or Estimated Time of Arrival (ETA) for both IM and Target Aircraft. The difference in predicted time or distance at the Achieve-by Point provides the Predicted Spacing Interval. Figure 5 gives an example of how the predicted spacing interval and spacing error may be computed.

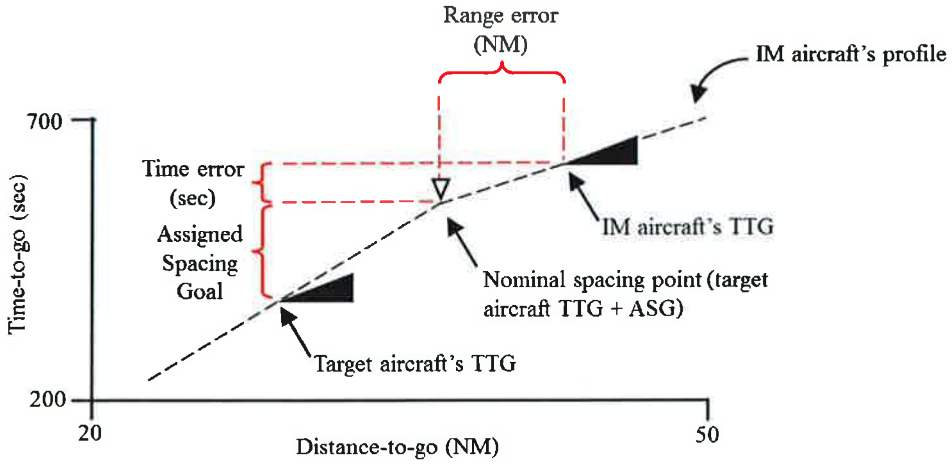


Figure 5: Determination of Predicted Spacing Interval

PR.27 During the Achieve Stage, the FIM Equipment shall determine the Predicted Spacing Interval at the Achieve-by Point.

When the Predicted Spacing Interval is outside the FIM Equipment Tolerance, the FIM Equipment shall provide IM Speeds such that the Predicted Spacing Interval returns to within the FIM Equipment Tolerance. However there is no requirement that the FIM Equipment Tolerance needs to be met prior to the Achieve-by Point as longs as the IM Speeds drive the Spacing Interval back to within the FIM Equipment Tolerance. This means that Gain-Scheduling may be used to vary the points at which the spacing error needs to be closed more aggressively.

When reaching the Achieve-by Point and towards the Planned Termination Point, the Measured Spacing Interval is expected to be within the appropriate FIM Equipment Objective Region. During the Maintain Stage, the FIM Equipment will provide IM Speeds that are designed to keep the Measured Spacing Interval within the FIM Equipment Objective Region. If the Measured Spacing Interval is outside of the FIM Equipment Objective Region, the IM Speed will be designed to drive the Measured Spacing Interval back within the FIM Equipment Tolerance.

PR.28 During the phase of operation at and after reaching the Achieve-by Point and until the Planned Termination Point, the FIM Equipment shall issue IM Speeds such that:

- when the Measured Spacing Interval is within the FIM Equipment Tolerance, the IM Speeds, if followed, keep the Measured Spacing Interval within the FIM Equipment Tolerance; and
- when the Measured Spacing Interval is outside the FIM Equipment Tolerance, the IM Speeds drive the Measured Spacing Interval within the FIM Equipment Tolerance.

Throughout the IM Operation, the flight crew checks that the IM Speed is safe and appropriate to implement. Whereas requirements PR.26 and PR.28 ensures that the IM Speeds presented to the flight crew is designed to achieve the goal of the IM Clearance, IM Situation Awareness and other information in the cockpit, will give the flight crew additional assurance that implementing the IM Speeds will bring them into conformance with their clearance.

The flight crew is expected to implement the IM Speed unless the IM Speed is outside of acceptable limits (OR.14). Avionics certification experts have indicated that the FIM Equipment should be aware of aircraft speed performance limits in order to appropriately limit the IM Speeds that are displayed to the flight crew. The minimum requirement is to limit the displayed IM Speeds based upon simple static values related to the aircraft installation.

PR.29 The FIM Equipment shall limit the IM Speeds displayed to the flight crew to within minimum and maximum speeds.

In order for the flight crew to assess whether the IM Speeds being provided will achieve conformance with the clearance, they must be made aware when IM Speeds are being limited.

PR.30 The FIM Equipment shall provide an indication to the flight crew when the displayed IM Speed is being limited.

In order for the IM Speeds to provide effective performance, timely implementation of the IM Speeds is required. There are various implementations for notifying the flight crew that a new IM Speed has been presented: an annunciation of a new IM Speed at some frequency, an annunciation of an IM Speed based on some speed-change threshold, or continuous display of an IM Speed with annunciation at the time to implement. In all cases, some annunciation to the flight crew is required to aid the flight crew in their task of timely implementation of the IM Speed (OR.14).

PR.31 The FIM Equipment shall provide notification to the flight crew of changes to the IM Speed.[3]

---

[3] PR.31 supports manual entry of the IM Speed. This PR is not intended to preclude other implementations that do not require manual entry of the IM Speeds.

5.2.2 IM Situation Awareness

As described in references [2,3,21], the flight crew monitors the progress of the IM Operation, and notifies the controller if they are unable to conform to the IM Clearance. The flight crew of the IM Aircraft is provided with information to support the safe and appropriate initiation and execution of the IM Clearance, as well as to monitor the progress of the IM Operation. There are three main components to the IM Situation Awareness Information:

- Information needed to support flight crew tasks;
- FIM Equipment Tolerance notification; and
- IM and Target Aircraft data qualification.

This information is studied in the following subsections.

5.2.2.1 Information Needed to support Flight Crew Tasks

The flight crew of the IM Aircraft ensures that a number of conditions are met before accepting the IM Clearance (OR.12). After accepting the IM Clearance, the flight crew of the IM Aircraft continues to monitor the state of and progression of the IM Operation until termination (OR.19, OR.20).

The flight crew performs multiple tasks starting with initiation through execution of the IM Clearance. In order to understand the flight crew tasks and the associated information needed to support the flight crew in performing each task, a flight-crew task analysis for the SPL implementation has to be conducted. This task analysis should cover the Initiation, Execution, and Termination and include the information required to be available for display per PR.3.

In the Initiation Phase, the flight crew should be able to verify that the IM Clearance information made available to the FIM Equipment is consistent with the IM Clearance. The provision of the IM Speed is considered sufficient for the flight crew to know that the FIM Equipment is operational. The flight crew should be able to evaluate the initial IM Speed to determine its acceptability for the IM Aircraft (e.g., IM Speed is within the IM Aircraft's speed envelope).

During the Execution Phase, a number of flight crew tasks are related to monitoring the progression of the IM Operation (e.g., Spacing Interval is trending towards the Assigned Spacing Interval at the Achieve-by Point). Information on the flight deck, as well as required information provided by the FIM Equipment (e.g., PR.3 and PR.4), will also support these tasks. However other IM Situation Awareness Information is required to help the flight crew determining whether the IM Speed is appropriate to meet the operational objectives defined by the IM Clearance.

The determination of additional information presented to the flight crew as a part of the IM Situation Awareness Information is dependent upon the specific implementation and airframe manufacturer's flight-deck design philosophy.

5.2.2.2 FIM Equipment Tolerance Indication

Prior to reaching the Achieve-by Point, the Spacing Interval may be outside of the IM Tolerance as it is working towards the Assigned Spacing Goal by the Achieve-by Point. Due to nominal effects, such as the Operational Uncertainties related to the environment, spacing conditions at initiation and Target Aircraft behaviour (see Section 9 and reference [19]), there will be times when the Predicted Spacing Interval differs from the Assigned Spacing Goal by more than the FIM Equipment Tolerance. As a result the Predicted Spacing Interval remains outside the IM Tolerance until it reaches the Achieve-by Point. There is no requirement to achieve the IM Tolerance prior to this point.

Because the principal goal of the IM Speeds is to bring the Spacing Interval to within the IM Tolerance, or to keep it there, an indication of when the Spacing Interval is sufficiently outside the FIM Equipment Tolerance is required. The flight crew's awareness of the Spacing Interval outside the FIM Equipment Tolerance aids in their determination of whether they are able to conform to the IM Clearance (OR.19).

Based on the FIM Equipment Tolerance representing the assumed 95% bound on nominal performance in the assumed operating environment, an indication when the Spacing Interval during the Maintain Stage is equal to or greater than 1.3 times the FIM Equipment Tolerance is reasonable. The 1.3 factor is related to the 99% bound on the nominal spacing performance, resulting in an indication prior to the IM Aircraft reaching the Controller Intervention Threshold (Section 6.1).

PR.32 At the Achieve-by Point and during the Maintain Stage of the IM Operations, the FIM Equipment shall indicate to the flight crew when the magnitude of the difference between the Assigned Spacing Goal and the Spacing Interval exceeds 1.3 times the FIM Equipment Tolerance.

5.2.2.3 IM and Target Aircraft Data Qualification Information

The FIM Equipment determines whether the IM Aircraft and the Target Aircraft are providing data that is of sufficient quality for the IM Operation. To prevent misleading information from being shown to the flight crew, the FIM Equipment can only provide IM Speeds and IM Situation Awareness information if the IM and Target Aircraft are qualified for the IM Operation. The criteria for determining whether the IM Aircraft is providing data that are qualified for the IM Operation is given by PR.35 and PR.37, and the criteria for determining whether the Target Aircraft is providing data that are qualified for the IM Operation is given by PR.36, PR.38, and PR.39.

PR.33 The FIM Equipment shall provide IM Speeds and IM Situation Awareness information only if the IM Aircraft and Target Aircraft are qualified for the IM Operation.

If the IM Aircraft or Target Aircraft is not qualified for the IM Operation, the flight crew is required to inform the controller of this fact. The FIM Equipment must provide an indication to the flight crew when the IM Aircraft or Target Aircraft is not qualified for the IM Operation (OR.12).

PR.34 The FIM Equipment shall indicate to the flight crew if the IM Aircraft or Target Aircraft is not qualified for the IM Operation

6 Performance Requirements

The intended function of the FIM Equipment is to provide IM Speeds to achieve and maintain the Spacing Interval to within the IM Tolerance needed for the IM Operation. In this section, the framework to determine the IM Tolerance needed for the SPL IM Operation is developed, allocations of that IM Tolerance are made to the Measured Spacing Interval Uncertainty and to the FIM Equipment Tolerance which specifies the required performance in the assumed operating environment, and performance requirements are set to meet the allocations determined for the SPL IM Operations.

To begin the analysis, the operational goals and controller needs for the IM Operation are translated into spacing metrics. These metrics, called the Operationally-Required Tolerances (ORTs), are described using two quantities:

- the Nominal Spacing Bounds, which provides the performance that meets the operational goals, and
- the Controller Intervention Threshold, which describes theoretical bounds around the Assigned Spacing Goal, where the controller will not intervene in the IM Operation.

Based on these allocations, minimum requirements on the IM Tolerance, FIM Equipment Tolerance and Aircraft State Data are derived. Minimum requirements on the accuracy of surveillance data for the Target Aircraft, the accuracy of the IM Aircraft's State Data, and data latencies are set to ensure that the Spacing Interval may be determined with sufficient accuracy (section 6.3.1).

6.1 Operationally-Required Tolerances

In this section, a methodology is presented to determine the IM Tolerance from the ORT metrics. This methodology is applied to the SPL IM Operations (presented in APPENDIX A) to determine the IM Tolerances.

The ORTs are used to model the operational goals and to represent controller needs for an IM Operation. The quantities that comprise the ORTs are the Nominal Spacing Bounds and the Controller Intervention Thresholds:

- The Nominal Spacing Bounds relate the operational goals for a specific IM Operation to a nominal spacing performance so that the operational goals are met. The Nominal Spacing Bounds are assumed to be related to a Gaussian distribution of the Spacing Interval at the Achieve-by Point or during the Maintain Stage. The Nominal Spacing Bounds are chosen such that the Spacing Intervals of at least 95% of IM Aircraft meet the operational goals.

- The Controller Intervention Threshold is a threshold which, if crossed, will cause controllers to intervene in the IM Operation because they do not trust that the IM Aircraft is able to conform to the IM Clearance. The Controller Intervention Threshold is modelled as a threshold beyond which the controller will not allow the Spacing Interval to exceed. The nominal spacing performance should be such that the Spacing Intervals of at least 99% to 99.9% of IM Aircraft respect the Controller Intervention Threshold.

Figure 6 illustrate the ORTs in the context of an IM Operation.

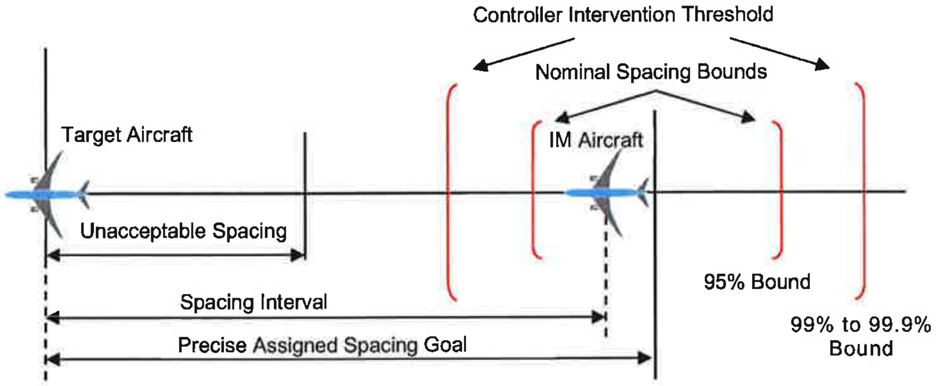


Figure 6: Illustration depicting the Operationally-Required Tolerances, which are comprised of the Nominal Spacing Bounds (NSB) and the Controller Intervention Threshold (CIT)

Figure 6 is applicable at the Achieve-by Point and during the Maintain Stage. In Figure 6, the term "unacceptable spacing" is notionally used to represent any Spacing Interval that is unacceptable to the controller for the given IM Operation and the assumed operating environment. Unacceptable spacing is related to (distance) separation.

When specifying the Controller Intervention Threshold, a percentage of the Assigned Spacing Goal or a maximum deviation, in time or distance, from the Assigned Spacing Goal should be provided. For IM Operations at Schiphol, the Controller Intervention Threshold is set with an allowable frequency in the range of 0.1% to 1.0%.

The IM Tolerance is the 95% bound on nominal spacing performance, which is assumed to be modelled by a Gaussian distribution, that satisfies the constraints set by both the Nominal Spacing Bounds and Controller Intervention Thresholds. The Nominal Spacing Bounds and the Controller Intervention Thresholds are set independently. The Nominal Spacing Bounds represent the performance related to the operational goals, and this performance must be reconciled with the Controller Intervention Thresholds to verify that the nominal spacing performance in the assumed operating environment will not lead to controller intervention too frequently. The IM Tolerance is then defined by the most-stringent ORT.

6.2 Allocation

In order to set requirements that support the Spacing Interval being within the IM Tolerance of the Assigned Spacing Goal at the Achieve-by Point, an allocation of the IM Tolerance is made to:

- the FIM Equipment Tolerance, which is related to the performance of the IM Speeds in the assumed operating environment; and
- the Measured Spacing Interval Uncertainty, which is bounded by the performance of IM Aircraft and Target Aircraft State Data.

The first allocation constrains the performance of the IM Speeds that are provided to work against the Operational Uncertainties in the assumed operating environment. The initial Spacing Interval, winds, turns, and Target Aircraft accelerations are all factors which lead to an increased uncertainty in the Predicted Spacing Interval being within the FIM Equipment Tolerance of the Assigned Spacing Goal. The actual operating environment is the most uncertain and stressing factor in meeting the FIM Equipment Tolerance; therefore, a conservative approach is taken to ensure sufficient allocation is provided to the performance of the IM Speeds in the actual operating environment.

The second allocation constrains the performance of the Horizontal Position Accuracy, Horizontal Velocity Accuracy, total and Uncompensated Latency, and other performance parameters related to the quality of the airborne surveillance from the Target Aircraft and the quality of the IM Aircraft's State Data. The analysis of State Data errors takes into consideration the availability of certain performance in the envisioned airspace, as well as respecting the allocation of the IM Tolerance to the Measured Spacing Interval Uncertainty. From the analysis, two sets of assumptions and requirements on the IM and Target Aircraft State Data performance parameters are determined. The two sets of requirements are expected to meet the budgeted IM Tolerance allocation for the IM Operation.

The IM Tolerance is allocated to these two error sources. Minimum performance requirements on the IM Speeds in the assumed operating environment and minimum performance requirements to the State Data are specified to respect the allocations of the IM Tolerance made to each error source.

6.2.1 Allocation Process

The allocation process contained within the OPA proceeds as follows:

- determine IM Tolerances for the IM Operation and associated operational goals (APPENDIX A);
- allocate an appropriate amount of spacing uncertainty (e.g., 10 seconds, 95%), to the FIM Equipment Tolerance;
- determine the minimum requirements on the IM and Target Aircraft State Data that satisfy the remaining allocation;
- conclude that one of two sets of State Data performance requirements (i.e., Performance Level 1 or 2, see APPENDIX B) meets the allocation without sacrificing availability; and
- update the allocations according to the State Data performance applied to the IM Operation.

6.2.1.1 Initial Allocation of Spacing Uncertainty

The IM Tolerances for the SPL IM Operations are determined in 0. The Tolerances differ depending on the time of day. The minimum IM Tolerance is required during the morning inbound peak when the throughput demand is 35 ac/hr/rwy. The results from the IM Tolerance derivations are shown in Table 4 and Table 5.

Table 4: IM Tolerance for SPL IM Operations (method 1)

Time of day	IM Tolerance (seconds)
7:00-8:00	12.3
8:00-9:00	11.0
9:00-19:00	17.7
19:00-20:00	15.2
20:00-22:00	26.3
22:00-7:00	23.1

Table 5: IM Tolerance for SPL IM Operations (method 2)

Time of day	IM Tolerance (seconds)
7:00-8:00	13.6
8:00-9:00	10.4
9:00-19:00	21.5
19:00-20:00	15.9
20:00-22:00	35.6
22:00-7:00	36.0

A budget for the performance of the IM Speeds in the assumed operating environment is based on analysis of prior simulations and field tests of trajectory based spacing algorithms, the results of which are presented in Table 6.

Table 6: Analysis of precision from prior research and field testing

Implementation	Reference	Type of sim	Precision
AMSTAR	AIRBORNE PRECISION SPACING IN MERGING TERMINAL ARRIVAL ROUTES: A FAST-TIME SIMULATION STUDY	Fast Time	<4s, 95%
ASTAR	Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations	HITL	2.5s, 66% and 7.5s, 95%
ATAAS	EVALUATION OF OPERATIONAL PROCEDURES FOR USING A TIME-BASED AIRBORNE INTER-ARRIVAL SPACING TOOL	HITL	6s, 95%
ASTAR	AIRBORNE PRECISION SPACING: A TRAJECTORY-BASED APRROACH TO IMPROVE TERMINAL AREA OPERATIONS	Fast-time and HITL	9-10s, 95%
ASTAR /Follow the Leader	FLIGHT EVALUATION OF A TIME-BASED AIRBORNE INTER-ARRIVAL SPACING TOOL	Field Test	10s, 95% (15s, 95%)

In simulated environments without Target Aircraft surveillance errors and IM Aircraft State Data errors, observed performance ranges from 2.5 to 10 seconds, 95%. The wide range in results arises from the differences in scenarios and modelled uncertainty factors. In field testing, the observed precision is in the range of 10 to 15 seconds, 95%.

The difference between field testing and a simulated environment, combined with the observation that the actual operating environment will include a number of additional variables that add to uncertainty, leads to the conclusion that the budget for the assumed operating environment should be set conservatively. A budget of 10 seconds, 95%, for time-based spacing has been applied as the initial FIM Equipment Tolerance. Using the Root-Sum-Squared method, the budget for the Measured Spacing Interval uncertainty is computed.

The results of the initial allocation are provided in Table 7 and Table 8.

Table 7: Initial Allocations of the IM Tolerances for SPL IM Operations (method 1)

IM Tolerance	Initial FIM Equipment Tolerance	Budgeted Measured Spacing Interval Uncertainty
11.0 seconds	10.0 seconds	4.58 seconds

Table 8: Initial Allocations of the IM Tolerances for SPL IM Operations (method 2)

IM Tolerance	Initial FIM Equipment Tolerance	Budgeted Measured Spacing Interval Uncertainty
10.4 seconds	10.0 seconds	2.86 seconds

The final allocation will be based on the State Data errors that results from the choice in State Data Performance Level and applicable along path speeds (APPENDIX B).

6.3 Aircraft State Data

6.3.1 Performance Requirements on Aircraft State Data

The performance requirements and assumptions provided in this section define the minimum State Data Quality that is necessary from the IM and Target Aircraft, in order to determine the final allocation budget.

The allocation and subsequent process of identifying minimum performance requirements and assumptions yields two identified Performance Levels for the State Data from the IM and Target Aircraft.

Performance Level 1 refers to the use of minimum State Data Quality, with a horizontal position accuracy of 0.3 NM. State Data with improved horizontal position accuracy, 0.1 NM instead of 0.3 NM, is referred to as Performance Level 2. When State Data Quality is better for horizontal position accuracy this enables smaller Measured Spacing Interval uncertainties and hence supports tighter IM Tolerance values.

The requirements and assumptions defining Performance Level 1 and Performance Level 2 have been developed to the greatest extent practical to be able to be supported with minimum ADS-B OUT Rule-compliant equipment State Data performance.[4]

FIM Equipment uses information about the states of the IM Aircraft and Target Aircraft to calculate the Predicted Spacing Interval, the Measured Spacing Interval, and the IM Speed. State Data generically includes the aircraft's position, velocity, and the time (or times) of applicability (TOA) for the position and velocity. The IM Aircraft's State Data is known from ownship sensors. The Target Aircraft's State Data is received from ADS-B.

State Data Quality is specified herein using measures of performance that include the following:

- Horizontal Position Accuracy
- Horizontal Velocity Accuracy
- State Data Latency
- State Data Update Interval
- Vertical Position Accuracy
- Vertical Rate Accuracy (optional)

The effect that each of these State Data Quality factors has on the uncertainty in the Measured Spacing Interval has been analyzed and is presented in [2,3]. A conservative modeling approach is taken to bound this uncertainty, and conservative assumptions are identified where appropriate. Using error analysis models, the Measured Spacing Interval uncertainty (95%) attributed to surveillance and IM State Data Quality has been determined. The results that are relevant for IM Operations at Schiphol have been reproduced in APPENDIX B.

To meet the budget for State Data errors provided in Table 7 and Table 8 for IM Operations in the SPL concept, Performance Level 2 is required. Note that Performance Level 2 is compatible with the European Implementing Rule that specifies ADS-B OUT. This results in the following requirements on IM and Target aircraft state data and the update rate of Target aircraft state data.

PR.35 The IM Aircraft shall have a horizontal position accuracy of at least 0.1 NM (95%).

PR.36 In order to be considered qualified for an IM Operation, the Target Aircraft's State Data shall have a horizontal position accuracy of at least 0.1 NM (95%).

PR.37 The IM Aircraft's State Data shall have a horizontal velocity accuracy of at least 10 m/s (95%) at interface B2

PR.38 In order to be considered qualified for an IM Operation, the Target Aircraft's State Data shall have a horizontal velocity accuracy of at least 10 m/s (95%) at interface B2

---

[4] Note 1: Minimum ADS-B OUT rules include: 1) FAA Rule (reference §91.227), and 2) draft EASA Rule (SPI IR– V2.0) for the draft EASA Rule.

PR.39 FIM Equipment shall only consider Target Aircraft qualified for IM Operations when a surveillance update of position and velocity at interface D has occurred within the last 25 seconds.

6.3.2 Final Allocation of Spacing Uncertainty

For IM arrival operations at SPL, an assumed conservative along path groundspeed of 150 knots at the FAP (method 1) and 170 knots at the IF (method 2) results in a measured spacing interval uncertainty of 3.33 and 3.04 seconds respectively, see APPENDIX B. Given the IM Tolerance and measured spacing interval uncertainty, the FIM Equipment Tolerance is computed using the Root Sum Squared method:

FIM Equipment Tolerance = SQRT[(IM Tolerance)^2 – (Measured Spacing Interval Uncertainty)^2].

The results of the final allocation are provided in Table 9 and Table 10 below.

Table 9: Final Allocations of the IM Tolerances for SPL IM Operations (method 1)

IM Tolerance	Measured Spacing Interval Uncertainty	FIM Equipment Tolerance
11.0 seconds	3.33 seconds	10.5 seconds

Table 10: Final Allocations of the IM Tolerances for SPL IM Operations (method 2)

IM Tolerance	Measured Spacing Interval Uncertainty	FIM Equipment Tolerance
10.4 seconds	3.04 seconds	9.9 seconds

PR.40 For IM Operations at SPL, the IM Tolerance shall be at most 11.0 seconds (method 1).

PR.41 For IM Operations at SPL, the IM Tolerance shall be at most 10.4 seconds (method 2).

PR.42 For IM Operations at SPL, the FIM Equipment Tolerance shall be at most 10.5 seconds (method 1).

PR.43 For IM Operations at SPL, the FIM Equipment Tolerance shall be at most 9.9 seconds (method 2).

6.4 Relating the Assumed Operating Environment to the Operational Uncertainties and the FIM Equipment Tolerance

In IM Operations, the spacing goal is to be realised by using the limited freedom in the horizontal speed domain. This implies that the spacing goal might need to be rejected at the request when it is probable infeasible. The IM operation might also be cancelled after acceptance if the goal turns out to be infeasible during the execution phase. The objective to avoid such events, leads to a set of Performance Requirements on the IM operation. The deduction of these requirements is rather technical, combining modeling assumptions, simple geometries, approximations and generic assumptions.

The main reasoning behind the deduction of the requirements is however based on the following straightforward idea that randomness and inaccuracy are to be counterbalanced by freedom and flexibility:

- There is a variation of times of arrival at the Initiation Points with respect to the planning from which the spacing goal is derived. The times of arrival of two aircraft are assumed to be independent and normally distributed, with standard deviation σ_{arr}.
- There are errors in the initial estimates of the times to fly to the Achieve-by Point, both for the IM aircraft and the Target aircraft. These errors are assumed to be independent and normally distributed, with standard deviation σ_{time}^{IM}.
- The main freedom is in the IM aircraft's ability to adapt the speed in order to realise the spacing goal. The control domain is assumed to be 10 %; that is: the IM aircraft can fly 10

% slower or faster than its (preferred or prescribed) nominal speed. The amount of spacing that can be adjusted then depends on the time to fly to the point where the spacing goal is to be realized, denoted as $\overline{t_{nom}^{IM}}$.

- There is an acceptable deviation of the spacing interval according to the estimates in the IM aircraft, also referred to as the FIM Equipment Tolerance, denoted by σ_{tol}.

Reference [19] has deduced, based on an assumed success rate of the IM Operation, the following main performance.

PR.44 The IM Operation shall use the following inequality to give sufficiently acceptable IM Clearance acceptance/rejection rates during FIM initiation and sufficiently acceptable continuation/cancellation rates during the Achieve Stage.

$$\sqrt{\sigma_{arr}^2 + \left(\sigma_{time}^{IM}\right)^2} \leq 0.026 \cdot \overline{t_{nom}^{IM}} + 0.3 \cdot \sigma_{tol}$$

(where σ_{arr} denotes the standard deviation of the time of arrival of aircraft at the Initiation Point, σ_{time}^{IM} denotes the standard deviation in the estimates by the IM aircraft of the time to fly between Initiation Point and Achieve-by Point for the IM aircraft itself and the Target Aircraft, and where $\overline{t_{nom}^{IM}}$ denotes the time from the Initiation Point to the Achieve-by Point averaged over all situations).

Example

Assume that it is known that approximately 95 % of the aircraft arrive within a window of 20 s around their Controlled Time of Arrive at the Initiation Point (derived from the SARA design goal of 30 seconds, 99%). Assume further that the time from the Initiation Point to the Achieve-by Point is 595 seconds (derived from the Fast Time Simulations for the SUGOL transition to runway 18R) and that the FIM Equipment Tolerance is set to 9.9 seconds (PR.43). It then follows that:

$$\sigma_{tol} = 4.95\ \text{s} \qquad \sigma_{arr} = 10.0\ \text{s} \quad ; \quad \overline{t_{nom}^{IM}} = 595\ s \xRightarrow{(PR.45)} \sigma_{time}^{IM} \leq 13.7\ s$$

This in turn implies that at least 95 % of the estimated times to the Achieve-by Point –for both the ownship and target aircraft– have an accuracy of 27 s, this equals approximately 5% of the remaining flight time.

PR.45 The FIM Equipment shall estimate the nominal time from the IM Aircraft's present position to the Achieve-by Point with an accuracy of 5% (95%).

PR.46 The FIM Equipment shall estimate the nominal time from the Target Aircraft's present position to the Achieve-by Point with an accuracy of 5% (95%).

Performance requirement PR.44 is broken down further by considering contributions to the estimation error, related to σ_{time}^{IM}. This includes: along track tolerance, cross track tolerance, path definition error, temperature estimation error, altitude and CAS control errors, deceleration imprecision and wind speed prediction. Some basic models for these contributions are considered, relating them to operationally used parameters.

Reference [19] has derived the individual contributions and PR.44 then leads to:

$$\sigma_{arr}^2 + \overline{t_{nom}}^2 \cdot \{1 \cdot 10^{-8} \cdot \sigma_{ATT}^2 + 3.1 \cdot 10^{-5} \cdot \sigma_{bank}^2 + 1 \cdot 10^{-8} \cdot \sigma_{XTT}^2 + 2.9 \cdot 10^{-6} \cdot \sigma_{temp}^2$$
$$+1.4 \cdot 10^{-8} \cdot \sigma_{alt}^2 + 1.4 \cdot 10^{-4} \cdot \sigma_{speed}^2 + C^2 \cdot \sigma_{decelaration}^2 + 5.8 \cdot 10^{-5} \cdot \sigma_{wind}^2 \}$$

$$\leq \left(0.026 \cdot \overline{t^{IM}_{nom}} + 0.3 \cdot \sigma_{tol}\right)^2$$

For a specific operational environment, this equation allows to allocate the total error budget of the estimated times to the various error contributions.

Example 1
Assume, as in the previous examples, that the average time from initiation point to achieve-by point is 595 seconds and that the FIM Equipment Tolerance is set to 9.9 seconds. Substitution of the following values:

$$\sigma_{ATT} = 100\,m \qquad \sigma_{bank} = 2^0 \qquad \sigma_{XTT} = 100\,m \qquad \sigma_{temp} = 3^0\mathrm{C}$$

$$\sigma_{alt} = 50\,m \qquad \sigma_{speed} = 0.8\ m/s \qquad \sigma_{decelaration} = 0\ m/s^2 \quad \sigma_{wind} = 1\,m/s$$

would imply that PR.44 is just met.

Example 2
Assume, as in the previous example, an average time from initiation point to achieve-by point of 595 seconds and assume a wind prediction accuracy of 5 m/s (10 knots) (95%) then its contribution is (square root of $\overline{t_{nom}}^2 \cdot 5.8 \cdot 10^{-5} \cdot \sigma^2_{wind}$) is 11.3 seconds. This indicates that the wind prediction error is likely to be the main error contribution, and it only leaves 7.7 seconds for the remaining operational uncertainties. For comparison, a temperature prediction accuracy of 5 degrees Celsius (95%) results in an error contribution of 2.5 seconds.

In the process of deriving PR.44, reference [19] has also deduced an IM Clearance acceptance criterion. This criterion is extended to the Achieve Stage of the IM Operation.

PR.47 During both the Initiation and Achieve Stage of the IM Operations, the FIM Equipment shall indicate to the flight crew when the estimate of the Target Aircraft's ETA/TTG to the Achieve-by Point plus the Assigned Spacing Goal is not within the IM Aircraft's acceptance/continuation interval.
This acceptance/continuation interval is defined as 80% of the difference between the IM Aircraft's earliest and latest ETA/TTG to the Achieve-by Point plus two times the FIM Equipment Tolerance, and it is centred on the IM Aircraft's nominal ETA/TTG. The earliest/latest ETA/TTG is estimated based on the nominal speed profile plus/minus 10%.

6.5 IM Speed Performance in the Assumed Operating Environment

The IM Speeds provided by the FIM Equipment should be such that the IM Aircraft's response to the IM Speed meets two simultaneous objectives.

- The IM Speeds should yield good string behavior for an Aircraft String performing an IM Operation; and
- The IM Speeds should provide sufficient performance in the assumed operating environment such that the Measured Spacing Interval is within the FIM Equipment Tolerance at the Achieve-by Point and during the Maintain Stage.

A sequence of IM and Target Aircraft pairs performing IM Operations forms an Aircraft String when each IM Aircraft is also acting as a Target Aircraft for the next trailing IM Aircraft in the -+sequence. Figure 7 illustrates an Aircraft String along a common route; it should be noted that Aircraft Strings in the SPL concept will also be comprised of aircraft on merging or non-coincident routes.

Figure 7: Depiction of an Aircraft String

Good string behavior refers to the mitigation of spacing-error[5] growth along the Aircraft String in response to an Operational Uncertainty. The growth of spacing errors along the string means that the maximum magnitude of the spacing error experienced by each aircraft increases along the string in response to a Target Aircraft accelerating or decelerating. This growth in spacing error along the string can also lead to a growth in the magnitude of IM Speed changes needed to correct the spacing errors.[6] Spacing-error and IM-Speed growth along an Aircraft String can lead to operational inefficiencies as a result of the FIM Equipment providing IM Speeds to increase and decrease speeds when managing the Spacing Interval.

The analysis in the FIM SPR [2,3] shows that undesired string behavior results from the FIM Equipment providing IM Speeds that too aggressively correct the IM Aircraft's spacing error relative to the Target Aircraft. Good string behavior may be achieved by limiting the aggressiveness of the IM Speeds, and therefore, limiting the responsiveness of the IM Aircraft to changes in the spacing error.

Whereas limiting the aggressiveness of the IM Aircraft's response to spacing errors yields good string behavior, the aggressiveness of the IM Speeds should not be so limited that they do not provide sufficient correction of spacing errors. The IM Speeds need to provide enough correction to bring and keep the Spacing Interval within the FIM Equipment Tolerance, in the presence, for example, of Operational Uncertainties (Section 9).

A general performance requirement on the IM Speeds provided by the FIM Equipment is derived from the analysis in the FIM SPR. To yield good overall performance of an Aircraft String performing IM Operations, the IM Speeds provided by the FIM Equipment in response to an instantaneous change in the Spacing Interval or a gradual change in the Spacing Interval may only change trend once. For example, in response to an instantaneous or gradual increase in the Spacing Interval, the IM Speeds may increase and decrease, but the IM Speeds may not increase, decrease, and increase again.

PR.48 At the Achieve-by Point and during the Maintain stage when the Measured Spacing Interval is outside of the FIM Equipment Tolerance, the FIM Equipment shall provide IM Speeds that only change trend once (e.g., speeds increase then decrease only and vice versa) in response to the following:

- a step input (i.e., an instantaneous increase or instantaneous decrease) in the Measured Spacing Interval; and
- a ramp input (i.e., a gradual increase or a gradual decrease) in the Measured Spacing Interval.

Reference [20] gives evidence that trajectory-based IM algorithms based on Estimated Times of Arrival at the Achieve-by Point or Times-To-Go (TTG) to the Achieve-by Point are string stable.

---

[5] Spacing error is defined as the difference in the Spacing Interval between an IM and Target Aircraft and the Assigned Spacing Goal.

[6] Undesired string behavior is evident on busy highways when drivers speed up and slow down to maintain a desired spacing relative to the preceding vehicle; i.e., the vehicles have a sinusoidal speed profile. The sinusoidal speeds have a greater impact on vehicles further along the string.

7 Design Requirements

In addition to the FIM Performance Requirements summarized in Section 8, the following sections provide guidance to implementers on additional design requirements deemed to be necessary in implementations of ASAS IM application for SPL.

7.1 Availability

Availability is an indication of the ability of the FIM Equipment to provide usable service. Availability is expressed in terms of the probability of the system being available at the beginning of the intended operation.

While defined here for completeness, there are no availability requirements specified for IM Operations at SPL as they are viewed to be driven more by business case considerations rather than technical considerations.

7.2 Continuity

Continuity is the probability that the FIM Equipment performs its required function without unscheduled interruption, assuming that the system is available when the procedure is initiated. Continuity is expressed per unit time, e.g., per flight hour or per operation.

While defined here for completeness, there are no continuity requirements specified for IM Operations at SPL as they are viewed to be more driven by business case considerations rather than technical considerations.

7.3 Coverage Volume

The ASPA-FIM coverage volume represents the region for which adequate surveillance coverage is provided to support reception and tracking of qualified Target Aircraft. Before issuing the IM Clearance, the controller is assumed to have an expectation of the ADS-B coverage volume for the IM Aircraft. The timing of the IM Clearance as well as the use of the Expected IM Clearance is based on the expected coverage volume.

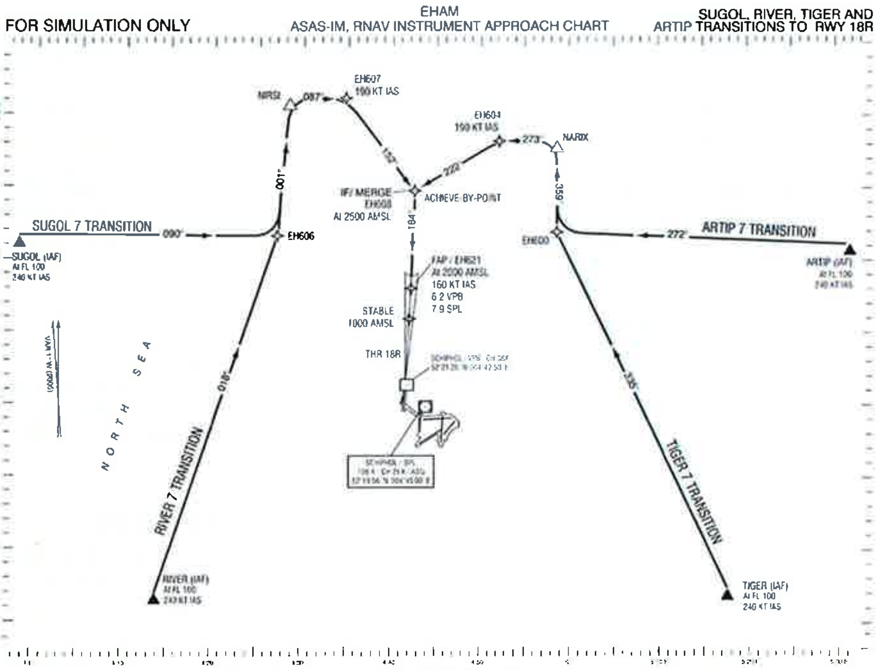


Figure 8: Example SPL RNAV transitions runway 18R

Table 11: Distances between IAFs [Nm]

	RIVER	SUGOL	ARTIP	TIGER
RIVER	-	37.4	63.9	48.7
SUGOL	37.4	-	58.6	64.4
ARTIP	63.9	58.6	-	34.0
TIGER	48.7	64.4	34.0	-

For IM Operations at SPL the desired coverage volume is equal to or greater than the maximum distance between the IM initiation points (IAF). Analysis of this distance (Table 11) indicates that a coverage volume of 65 Nm is desired. However, as IM and/or Target aircraft can be outside the TMA when the IM Aircraft is cleared for spacing the desired distance should be even larger, therefore a coverage volume of 70-80 Nm is desired. When the IM aircraft cannot initiate spacing, as qualified ADS-B data is not yet received, it needs to continue adhering to the constraints associated with the transition.

7.4 IM Situation Awareness Elements

As described in Section 5.2.2.1, the determination of additional information presented to the flight crew as a part of the IM Situation Awareness Information is dependent upon the implementation and flight-deck design philosophy. Based on operational input during the development of the OSED and OPA, a certain level of situational awareness specific to the IM Clearance and showing progress towards achieving the Assigned Spacing Goal before the IM Aircraft reaches the Achieve-by Point was deemed important and potentially required.

The following elements are recommended for display to the flight crew to support IM Situation Awareness:

- Measured Spacing Interval (in Maintain Stage) and Predicted Spacing Interval (in Achieve Stage);
- Indication that the IM Speed is limited;
- Status of compliance with minimum (and possibly also maximum) spacing error closing rate during Achieve Stage (i.e., compliance with PR.44).
- Status of IM and Target Aircraft states relative to their respective Intended Flight Paths; and
- FIM Equipment Status (i.e., equipment is operating as expected and no annunciated failures have been detected).

It should be noted that the minimum IM Situational Awareness requirements will be defined in the FIM Minimum Operational Performance Standards (MOPS), as currently in development by RTCA and EUROCAE.

7.5 IM Speed Frequency

The frequency of new IM Speeds displayed to the flight crew needs to be made at a rate that is sufficient to meet the performance requirements (e.g., drive the Spacing Interval within the FIM Equipment Tolerance of the Assigned Spacing Goal at the Achieve-by Point or during the Maintain Stage) while not being excessive from a pilot workload perspective.

7.6 Limiting IM Speeds that are Displayed to the Flight Crew

As described in Section 2.5 (OR.14), the flight crew is expected to implement the IM Speed unless the IM Speed is outside of acceptable limits, and there is a minimum requirement to limit the IM Speeds to within aircraft static operating limits (PR.29).

Avionics certification experts have indicated a desire for the FIM Equipment to also limit the IM Speeds to regulatory limits. Although it is not required, it is recommended that the FIM

Equipment be aware of regulatory limits and to limit the IM Speeds displayed to the flight crew to the regulatory limits.

8 Summary of Performance Requirements

The Performance Requirements specify the performance elements of the FIM Equipment associated with the IM Operation. The SPL FIM OPA, as described in the previous chapters, has derived these requirements. The FIM Performance Requirements for the Schiphol IM Operations are listed in Table 12 below.

Table 12: Summary of OPA Performance Requirements

Ref.	Performance Requirement
PR.1	Information conveyed to the FIM equipment by means of R/T communication shall include Target Aircraft Identification, Assigned Spacing Goal and Target Aircraft Intended Flight Path Information.
PR.2	Information conveyed to the FIM equipment as part of the charted IM procedure shall include IM Clearance Type, Achieve-by Point, Termination Point and IM Tolerance.
PR.3	The FIM Equipment shall make the following information available for display to the flight crew: – Target Aircraft Identification; – Assigned Spacing Goal; – Achieve-by Point; – Planned Termination Point; – IM Tolerance; and – Target Aircraft Intended Flight Path Information.
PR.4	Before the IM Clearance is accepted and during the Execution Phase of an IM Operation, the FIM Equipment shall provide the following information for display to the Flight Crew (Interface G1): – IM Situation Awareness Information; and – the IM Speed;
PR.5	The following IM Aircraft data items shall be provided to the FIM Equipment by on-board sensors or other aircraft systems through Interface B2 or determined by the FIM Equipment in the IM Aircraft Receive Domain: – Horizontal Position; – Pressure Altitude; – Horizontal Velocity; – Horizontal Position Accuracy; – Horizontal Velocity Accuracy; – Horizontal Position Integrity; and – IM Aircraft Intended Flight Path Information.
PR.6	The following data items pertaining to the Target Aircraft shall be provided to the FIM Equipment through Interface D: – Horizontal Position; – Pressure Altitude; – Horizontal Velocity; – Horizontal Position Accuracy; – Horizontal Velocity Accuracy; – Horizontal Position Integrity; and – Aircraft Identification.
PR.7	The FIM Equipment shall display the IM Speeds and IM Situation Awareness Information only after all IM Clearance information has been made available to the FIM Equipment.
PR.8	The FIM Equipment shall provide the flight crew with the means to select the Target Aircraft by use of the Target Aircraft Identification.

PR.9	The FIM Equipment shall clear any stored IM Clearance information when a new Target Aircraft is selected by its Target Aircraft Identification.
PR.10	The FIM Equipment shall be capable of accepting a Precise Assigned Spacing Goal.
PR.11	The FIM Equipment shall only accept an Achieve-by Point that is on the IM Aircraft's Intended Flight Path and common to Target Aircraft's Intended Flight Path.
PR.12	The FIM Equipment shall accept an Achieve-by Point that is a fixed, geographical point in the form of a named waypoint.
PR.13	The FIM Equipment shall accept only a Planned Termination Point that: – is on the IM Aircraft's Intended Flight Path and is common to the Target Aircraft's Intended Flight Path; – is coincident with of after the Achieve-by Point; and. – is no closer to the runway threshold than 5 NM.
PR.14	The FIM Equipment shall accept a Planned Termination Point that is a fixed, geographical point in the form of a named waypoint.
PR.15	The FIM Equipment shall remove the IM Speeds and IM Situation Awareness Information from the display when the IM Aircraft reaches the Planned Termination Point.
PR.16	The FIM Equipment shall be capable of retrieving the IM Aircraft's Intended Flight Path from sources on-board the IM Aircraft.
PR.17	The FIM Equipment shall define the Intended Flight Path of the Target Aircraft from Intended Flight Path Information included in the IM Clearance and sources on-board the IM Aircraft.
PR.18	The FIM Equipment shall accept the Target Aircraft's Intended Flight Path Information that is either the same procedure as the IM Aircraft or a named procedure that merges with the IM Aircraft's Intended Flight Path.
PR.19	The FIM Equipment shall accept a named procedure in the Target Aircraft's Intended Flight Path Information in the format of one of the following options: – standard arrival route (STAR) designator; – transition (TRANS) designator; or – instrument approach procedure (IAP) designator. Any of the formats above can be combined in a way that makes navigational sense.
PR.20	The FIM Equipment shall notify the flight crew when the IM Aircraft and/or Target Aircraft are not in conformance with their Intended Flight Paths.
PR.21	The FIM Equipment shall provide the means to modify the following information while retaining all other IM Clearance information: – Assigned Spacing Goal; – Achieve-by Point; – Planned Termination Point; – IM Tolerance; and – Target Aircraft Intended Flight Path Information.
PR.22	The FIM Equipment shall provide to the flight crew a means of clearing all information from a previous IM Clearance.
PR.23	The FIM Equipment shall provide the means for the flight crew to remove the IM Speeds and IM Situation Awareness Information from displays.
PR.24	The FIM Equipment shall provide the means for the flight crew to restore the IM Speeds and IM Situation Awareness Information to the displays if that information was previously removed by flight crew action.
PR.25	The FIM Equipment shall determine the FIM Equipment Tolerance based on the following Equation: FIM Equipment Tolerance $\leq$ SQRT[(IM Tolerance)^2 – (Measured Spacing Interval Uncertainty)^2].
PR.26	During the Achieve Stage, the FIM Equipment shall provide IM Speeds such that, if followed, the Spacing Interval is within the FIM Equipment Tolerance at the Achieve-by Point.
PR.27	During the Achieve Stage, the FIM Equipment shall determine the Predicted

	Spacing Interval at the Achieve-by Point.
PR.28	During the phase of operation at and after reaching the Achieve-by Point and until the Planned Termination Point, the FIM Equipment shall issue IM Speeds such that: – when the Measured Spacing Interval is within the FIM Equipment Tolerance, the IM Speeds, if followed, keep the Measured Spacing Interval within the FIM Equipment Tolerance; and – when the Measured Spacing Interval is outside the FIM Equipment Tolerance, the IM Speeds drive the Measured Spacing Interval within the FIM Equipment Tolerance.
PR.29	The FIM Equipment shall limit the IM Speeds displayed to the flight crew to within minimum and maximum speeds.
PR.30	The FIM Equipment shall provide an indication to the flight crew when the displayed IM Speed is being limited.
PR.31	The FIM Equipment shall provide notification to the flight crew of changes to the IM Speed.
PR.32	At the Achieve-by Point and during the Maintain Stage of the IM Operations, the FIM Equipment shall indicate to the flight crew when the magnitude of the difference between the Assigned Spacing Goal and the Spacing Interval exceeds 1.3 times the FIM Equipment Tolerance.
PR.33	The FIM Equipment shall provide IM Speeds and IM Situation Awareness information only if the IM Aircraft and Target Aircraft are qualified for the IM Operation.
PR.34	The FIM Equipment shall indicate to the flight crew if the IM Aircraft or Target Aircraft is not qualified for the IM Operation
PR.35	The IM Aircraft shall have a horizontal position accuracy of at least 0.1 NM (95%).
PR.36	In order to be considered qualified for an IM Operation, the Target Aircraft's State Data shall have a horizontal position accuracy of at least 0.1 NM (95%).
PR.37	The IM Aircraft's State Data shall have a horizontal velocity accuracy of at least 10 m/s (95%) at interface B2
PR.38	In order to be considered qualified for an IM Operation, the Target Aircraft's State Data shall have a horizontal velocity accuracy of at least 10 m/s (95%) at interface B2
PR.39	FIM Equipment shall only consider Target Aircraft qualified for IM Operations when a surveillance update of position and velocity at interface D has occurred within the last 25 seconds.
PR.40	For IM Operations at SPL, the IM Tolerance shall be at most 11.0 seconds (method 1).
PR.41	For IM Operations at SPL, the IM Tolerance shall be at most 10.4 seconds (method 2).
PR.42	For IM Operations at SPL, the FIM Equipment Tolerance shall be at most 10.5 seconds (method 1).
PR.43	For IM Operations at SPL, the FIM Equipment Tolerance shall be at most 9.9 seconds (method 2).
PR.44	The IM Operation shall use the following inequality to give sufficiently acceptable IM Clearance acceptance/rejection rates during FIM initiation and sufficiently acceptable continuation/cancellation rates during the Achieve Stage. $$\sqrt{\sigma_{arr}^{2} + (\sigma_{time}^{IM})^{2}} \leq 0.026 \cdot \overline{t_{nom}^{IM}} + 0.3 \cdot \sigma_{tol}$$ (where σ_{arr} denotes the standard variation of the time of arrival of aircraft at the Initiation Point, σ_{time}^{IM} denotes the standard deviation in the estimates by the IM aircraft of the time to fly between Initiation Point and Achieve-by Point for the IM aircraft itself and the Target Aircraft, and where $\overline{t_{nom}^{IM}}$ denotes the time from the Initiation Point to the Achieve-by Point averaged over all situations).

PR.45	The FIM Equipment shall estimate the nominal time from the IM Aircraft's present position to the Achieve-by Point with an accuracy of 5% (95%).
PR.46	The FIM Equipment shall estimate the nominal time from the Target Aircraft's present position to the Achieve-by Point with an accuracy of 5% (95%).
PR.47	During both the Initiation and Achieve Stage of the IM Operations, the FIM Equipment shall indicate to the flight crew when the estimate of the Target Aircraft's ETA/TTG to the Achieve-by Point plus the Assigned Spacing Goal is not within the IM Aircraft's acceptance/continuation interval.
PR.48	At the Achieve-by Point and during the Maintain stage when the Measured Spacing Interval is outside of the FIM Equipment Tolerance, the FIM Equipment shall provide IM Speeds that only change trend once (e.g., speeds increase then decrease only and vice versa) in response to the following: – a step input (i.e., an instantaneous increase or instantaneous decrease) in the Measured Spacing Interval; and – a ramp input (i.e., a gradual increase or a gradual decrease) in the Measured Spacing Interval.

9 Operational Performance Evaluation of the SPL IM Operations

9.1 Overview

In order to evaluate the performance of the ASAS-IM concept and investigate the robustness of the concept against operational uncertainties an off-line simulator batch study was performed. Performing a batch study allows the random variations of various parameters during a large number of fast-time simulations from which statistical conclusions can be drawn.

9.2 Experiment Design

9.2.1 Scenario design

For the batch study the arriving traffic for Schiphol's runway 18R was simulated under various wind and traffic density conditions. The aircraft are arriving from either two or four IAFs to Runway 18R, merging at three possible merge points, EH600, EH606 and EH 608, see Figure 9. The aircraft are simulated to follow a procedure, which defines a nominal route as well as the nominal speed profile, while managing the distance to their lead aircraft using the spacing algorithm. Final merge point EH608 (IF/MERGE) was selected as the Achieve-by Point (ABP), while the Final Approach Point was selected to be the Planned Termination Point.

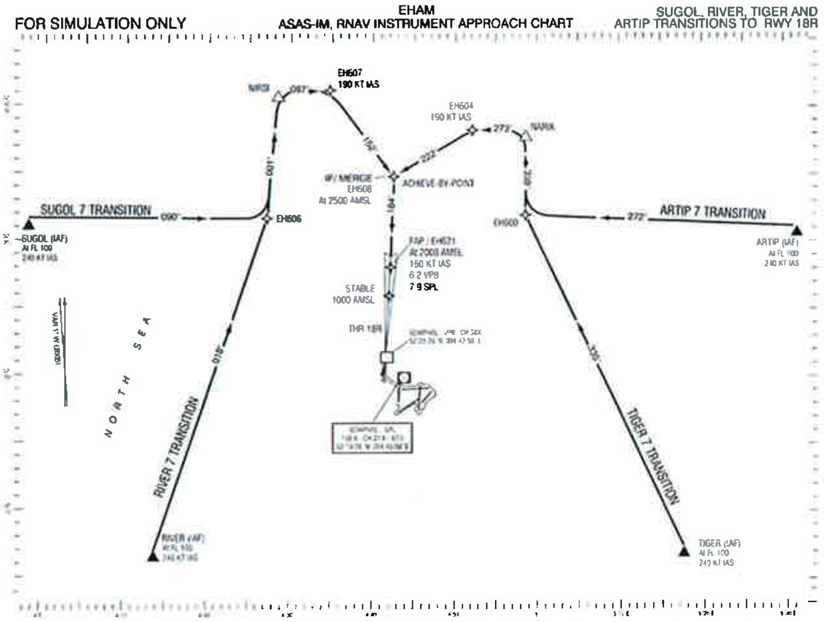


Figure 9: Batch study approach scenario

Spacing Algorithm

The spacing algorithm used in this simulation is a trajectory based algorithm, developed by NASA Langley Research Center (LaRC), called ASTAR (Airborne Spacing for Terminal Arrivals). ASTAR is the latest iteration in a series of Trajectory Based spacing algorithm developments and has become the current state-of-the-art [12,15].

The workings of ASTAR are illustrated in Figure 10 where two aircraft are engaged in FIM (called a spacing pair). The Lead aircraft is flying its assigned approach while continuously broadcasting state vector information. The Ownship is coupled to the Lead and required to achieve an assigned spacing interval, which is illustrated on the y-axis in the Figure. It is emphasized that the Lead and Ownship do not need to be on the same trajectory.

$$t_{spacing} = \Delta t + TTG_{lead} \tag{1}$$

$$\varepsilon_{spacing} = TTG_{ownship} - t_{spacing} \tag{2}$$

The position of the Lead aircraft broadcast over ADS-B, together with knowledge of the named procedure, allows the Ownship to calculate a Time To Go for the Lead (TTGlead) to the achieve-by-point. With the Lead TTG and the Ownship TTG, the spacing error ($\varepsilon_{spacing}$) can readily be calculated. The TTG calculations are based on groundspeed / distance. Hence, if wind is non-zero, a wind forecast is required.

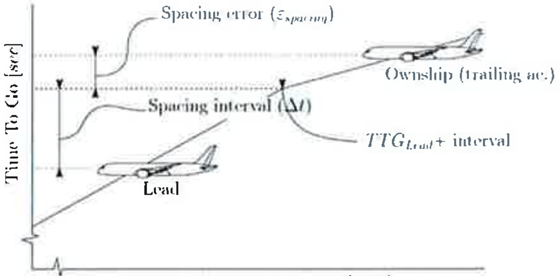


Figure 10: Trajectory based spacing algorithm

The algorithm aims to achieve the spacing goal, i.e., reduce spacing error ($\varepsilon_{spacing}$), to zero at the achieve-by-point. The error is minimized by commanding speed deviations from he nominal speed profile to either gain or lose time on the current TTG. This deviation is limited to ±10% of the nominal speed ($V_{nom}^{\pm 10\%}$) to maintain system stability [12,15]. A temporary deviation of the spacing interval while en-route towards the runway is allowed, as long as it does not reduce spacing precision at the achieve-by-point.

Traffic Manager

The simulation environment use in this study is called Traffic Manager (TMX) [22]. TMX is a medium fidelity desktop simulation application designed for interaction studies of aircraft in present or future Air Traffic Management (ATM) environments. The tool was developed by the National Aerospace Laboratory (NLR) and furthermore extended and used by NASA Langley Research Center (LaRC). TMX can simulate up to 2000 aircraft simultaneously. The fidelity allows the assessment of system wide effects in fast time over longer periods and with large traffic flows. The tool is not designed to assess individual aircraft performance.

Figure 11. Screenshot of the Traffic Manager (TMX) interface

Aircraft dynamic model
The aircraft dynamic model is a NLR in-house developed six-degrees-of-freedom model, augmented with aircraft performance data from Eurocontrol's Base of Aircraft Data (BADA). The aircraft state is updated every cycle and limited by the BADA performance envelope.
Simulated aircraft in TMX have a Flight Management System (FMS), which incorporates all the main functions found in an actual FMS. It allows for coupled flying with LNAV (Lateral Navigation), VNAV (Vertical Navigation) and auto-throttle auto pilot functions. Input for the FMS comes from route files which usually include waypoints and constraints, as found in real-world SID (Standard Instrument Departure) / STAR (Standard Arrival) and airway procedures. The FMS incorporates a Trajectory Predictor, which is used to predict times of arrival at waypoints and to fly Required Time of Arrivals (RTA) to these waypoints.

ADS-B
TMX incorporates an ADS-B model with all the main reports and functionalities as currently laid down in the ADS-B framework documents [2,3,5]. Reception and broadcast range can be varied with a decay in reception probability close to the maximum range. The broadcast rates for the different reports can be varied as well.

Wind and Weather Model
TMX furthermore includes 3D wind fields that can differentiate between "truth" and predicted wind. The weather model includes polygon based weather cells that move with the wind.

9.2.2 Independent variables

In order to introduce realistic disturbances into the simulations, a number of independent variables were introduced. By varying the independent variables in all possible combinations, it is possible to investigate the sensitivity of the IM-spacing to different combinations of these parameters and to assess the operational viability of the IM-concept.

Navigation accuracy
To research the effect of the navigation accuracy of the participating aircraft, three levels of navigation accuracy were used: ANP0.0/RNP0.0, ANP0.15/RNP0.3, and ANP0.3/RNAV1. These levels were chosen to cover the range from perfect navigation with zero error to current day operation at Schiphol at RNAV1. This way the effect of RNP-levels on the operational performance can be evaluated which can be used for a future RNP mandate. As per the RNP/RNAV requirements, the RNP scenarios include RF-legs, where the RNAV scenario does not.

To incorporate the effect of the ANP-level, the aircraft were simulated to follow not a straight line but a sinusoidal wave, see Figure 12. It is clear that the distance flown is always greater for a higher ANP-value. Two important parameters have to be considered: the amplitude of the wave, which is related to the ANP value and the period of the wave, which is related to the angular velocity of the aircraft. The amplitude is equal to the ANP-value. The period of the wave is determined by the maximum turn speed during flight, which is estimated at 0.02 rad/s. This implicates that the duration of one period is 100π seconds, assuming a speed of 100 m/s (straight forward) a distance of $10{,}000\pi$ meters. This turns out to be between 18-21 NM for the groundspeeds involved in the simulated scenarios.

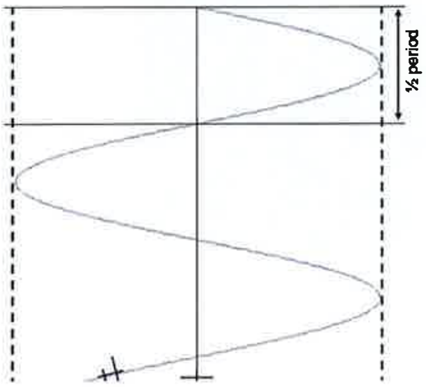
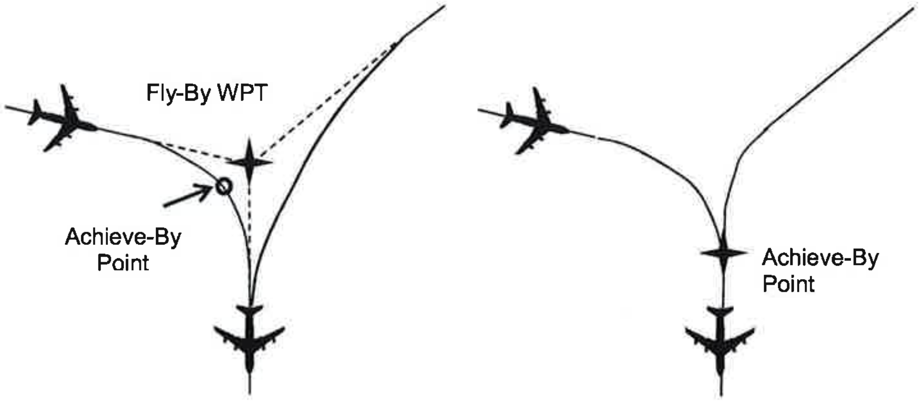


Figure 12: Sinusoidal ground track.

During curved sections of the approach path, there is a difference between the RNAV scenario and the RNP scenarios. The RNP-scenarios include RF-legs, thus prescribing an exact ground track during the turn, while the RNAV-scenario, uses fly-past waypoints, where the flown ground track is dependent on ground speed, bank angle and track change. As the Achieve-By Point (ABP) for the FIM-algorithm is defined as the merge-point as indicated in Figure 9. This has consequences for the RNAV scenario, as the actual merge point of the lead and own-ship trajectories varies, which makes it unsuitable to act as the ABP for the FIM algorithm. To cope with this, the merge point for the RNAV scenario is defined as the point where the aircraft are passing abeam the merge waypoint, half way along the turning segment, see Figure 13.



RNAV Fly-By Waypoint

RNP RF-legs

Figure 13. RNAV and RNP merge point definition.

Level of automation

Two FIM implementations were included. In the first scenario the pilot is making all speed selections through the Mode Control Panel (MCP). This is modeled by incorporating random variations on the average pilot time delay on executing the commands displayed on the FIM-display. The second scenario assumes all the participating aircraft have an direct coupling to the autothrottle (AT) to automatically follow the FIM-commands, hence providing a more accurate speed profile following.

Pilot model

The MCP scenario utilizes a pilot model to include the varying time delays that occur when a human operator manually changes the IAS selections. Based on research by NASA [24], pilot reaction time for MCP runs: mean = 8 sec, +/- 4 sec (3 sigma normally distributed). The autothrottle scenarios did not incorporate a pilot reaction time, as the autothrottle system would be directly connected to the aircraft guidance system.

Wind field

To incorporate the effect of wind on the FIM performance, three wind scenarios were included.
A wind profile that matches average southwesterly wind conditions at Schiphol Airport was chosen from the OPTIMAL experiment [23] and adapted to have a 15 kts headwind at 3,000ft on final for runway 18R (inbound course 183), see Table 13. Two more wind profiles were constructed from this profile so that the headwind at 3,000ft on final is 20 kts and 25 kts, respectively.

Table 13. Wind profiles used in the batch study.

WindField	*0 ft*	*1,000 ft*	*3,000 ft*	*7,000 ft*	*10,000 ft*
0, SW wind profile	210/12	220/17	230/22	240/32	240/42
1 (+5 kts HW on final)	195/16	205/20	215/24	225/34	225/44
2 (+10 kts HW on final)	195/21	205/25	215/29	225/39	225/49

Traffic density and traffic mix

Based on the analysis of the Schiphol traffic throughput levels as presented in APPENDIX A, two traffic scenarios were included in the batch study. One including the largest inbound peak between 8.00-9.00AM in the morning when the throughput level is 35 aircraft per hour per runway, and one just before the inbound peak between 7.00-8.00AM where the traffic density is 30 aircraft per hour.

Based on the SPL data analysis, the 7-8AM scenario has a 45% Heavy, 55% Medium traffic mix, while the 8-9AM scenario has a 14% Heavy, 86% Medium traffic mix. Furthermore, during the inbound peak only two IAFs are in use for RWY 18R, as the airport will switch to two landing runways. Outside the inbound peak aircraft coming from all four IAFs are directed to RWY 18R.

Table 14 Traffic Mix and Approach configuration.

Time of Day	*Configuration*	*Throughput*	*Heavy*	*Medium*
7-8AM	4 IAFS (ARTIP, RIVER, SUGOL, TIGER)	30 ac/h	45%	55%
8-9AM	2 IAFS (RIVER, SUGOL)	35 ac/h	14%	86%

CTA levels
The last parameter that is varied is the accuracy with which the aircraft meet the Controlled Time of Arrival (CTA) over the IAF. Based on the operational experience gained with the Speed And Route Advisor (SARA, [18]). SARA can deliver aircraft over the IAF at a CTA with an accuracy of ±30 seconds (99%).

Three levels of accuracy were chosen to investigate if a higher precision level is required; 30 seconds, to indicate current day SARA performance, 15 seconds to incorporate future requirements as laid down by SESAR and 0 seconds, to be able to exclude the effect altogether and run with zero CTA error.

Test matrix

Table 15: Batch study independent measures summary.

Time of Day	*ANP Level*	*WindField*	*CTA Error*	*FIM*
7-8AM	ANP0	0	30	MCP
8-9AM	ANP0.15	1	15	AT
	ANP0.3	2	0	

Two baseline scenarios are considered. For each traffic density (7-8AM and 8-9AM) a batch is run with zero CTA error. These will be compared against the other scenarios.

As every combination of independent measures is evaluated, this brings the total number of experiment conditions to 108 (2*3*3*3*2=108).

- 1500 measurement points per combination of experiment conditions are needed, to be able to reach a conclusion at the 95th percentile. 95th percentile is 75 out of 1500. (sensitivity of one equals 1/1500 = 6.7E-04, the aim is to keep this figure below E-03, 0.1%)
- 41 aircraft per scenario:.40 IM Operations (i.e., measurement points) per scenario.
- In total 1500 / 40 ≈ 40 scenarios are needed.
- 40 scenarios with 41 aircraft each per combination of experiment conditions

Total number of scenarios:

- This means two baseline traffic scenarios (2x TimeOfDay, CTA accuracy 0) and four derived traffic scenarios (2x TimeOfDay, 2x CTA accuracy).
- All other scenarios only change the following codes (ANP at 3 levels, WindField at 3 levels, and FIM at 2 levels). 18 combinations.
- 6 x 18 = 108 combinations of experiment conditions
- 108 x 40 = 4320 scenarios (is 4320 x 40 ≈ 173k IM Operations)

9.3 Performance Metrics

In order to assess the effect of the independent measures on the IM performance, a number of performance metrics are defined. The chosen metrics aim not only to provide insight in the accuracy of the IM operation during each simulation run, but also to check whether any separation minima were violated and to see how close the IM algorithm is operating to its operational limits.

9.3.1 Spacing Error

The first parameter to look at is the accuracy with which the ASTAR algorithm is able to achieve the required spacing at the ABP, which is the EH608 end-of-turn for the RNP-scenarios and abeam the Fly-By waypoint for the RNAV scenarios, as explained in Section 9.2.

The spacing error is defined as follows:

$$\epsilon_{spacing} = \left(t_{(ABP)_{Ownship}} - t_{(ABP)_{Lead}}\right) - spacing\ goal$$

where $t_{(ABP)_{Ownship}}$ and $t_{(ABP)_{Lead}}$ are the crossing times overhead the ABP of the Ownship and the Lead aircraft, respectively, and the spacing goal is the time interval in seconds that the Ownship should be spaced behind the Lead aircraft.

9.3.2 Range Error

To investigate the actual distance between the aircraft when the IM aircraft reaches the ABP, the distance between the two aircraft was logged overhead the ABP.

9.3.3 Minimum Range

The experiment is setup in such a way that the aircraft stop actively spacing once they pass the Planned Termination Point (PTP). From the PTP to the runway threshold, all aircraft maintain 160 KIAS until reducing to the final approach speed at 4 NM from the runway. The minimum range between all simulated aircraft pairs was recorded to check if any separation minima were violated.

9.3.4 Relative IAS error

The relative IAS error is a measurement to indicate how much the aircraft deviated from the nominal profile speed on that leg, i.e. how much of the control space is used. The ASTAR algorithm has a control space of +/- 10% of the nominal speed for each leg.

$$\epsilon_{IAS} = \frac{IAS_{actual} - IAS_{nominal}}{IAS_{nominal}}$$

The relative IAS error provides an indication on how much of the capacity of the IM-algorithm is used. It is interesting to see how much of the control space is used during a run, i.e. how hard the algorithm has to work to compensate for the operational uncertainties.
When a scenario generates large deviations from the nominal speed profile, that is an indication that although the performance of the algorithm may be adequate, but that any additional disturbances might cause the limit of the control space to be reached, and performance is no longer guaranteed.

9.3.5 Control Space Limit

During the simulations, the ASTAR algorithm was allowed to issue a maximum speed change of 10% of the nominal speed for the current segment of the trajectory. All instances were recorded of situations where a 10% speed change was calculated not to be enough to meet the IM spacing requirements. Hitting a control space boundary, however, is *not* an indication that the spacing requirements for that run will not be met, as all the parameters change constantly. It is only an indication of the number of times the control limit of the algorithm is reached

9.4 Quantitative Data Results

9.4.1 Spacing Error

Table 16 shows the spacing error found during the simulations, split over the different conditions. Based on interviews with air traffic controllers, acceptable performance (green) was derived to be 95% of the aircraft meeting their assigned spacing goal within the FIM equipment tolerance of ±9.9 sec (APPENDIX A).

It is clear that in almost all conditions more than 95% of the aircraft were able to meet their spacing goal. It can be seen that manual speed control by the pilot degrades the performance, compared to the Autothrottle scenarios. Furthermore, the wind error seems to have a negative effect, especially on the MCP scenarios, where the combination of these uncertainties yields worse results. The navigation accuracy and the timing accuracy both have a small effect on the spacing error.

The combination of Wind Field 2 and speed control via the MCP during the pre-inbound peak period between 7-8 o'clock is the only combination that fails to meet the 95% of traffic within 9.9 sec. The same conditions provide no problem between 8-9 o'clock. At first glance it may seem odd that the algorithm performs better when there is *more* traffic. What causes these results is the fact that in 8-9AM scenario, the airport switches to two landing runways, and runway 18R now handles the traffic from only two initial approach fixes, SUGOL and RIVER, instead of all four IAFs during the pre-inbound peak single runway operation. Since all scenarios have predominantly southwesterly winds, the disturbance effect of the wind uncertainties is larger for the 4 IAF scenario (7-8AM) than for the 2 IAF scenario (8-9AM). Especially the errors in ground speed estimation will be the same for aircraft coming from the same direction and encountering the same head wind, while the errors are aggravated when aircraft fly on more reciprocal tracks. Furthermore, the disturbing effect of having three merge points, instead of two introduces an extra uncertainty to the 7-8AM scenarios.

Table 16. Percentage of runs where the spacing error at the ABP was within ±9.9 sec. Green means more than 95% of the aircraft meet the goal, red means less than 95%.

Spacing Error
Time of Day: 7-8 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	99.69	100.00	CTA 0	99.00	100.00	CTA 0	90.88	99.63
	CTA 15	99.81	100.00	CTA 15	98.75	100.00	CTA 15	89.38	99.75
	CTA 30	99.63	100.00	CTA 30	98.75	100.00	CTA 30	89.31	99.38
ANP 0.15	CTA 0	99.38	100.00	CTA 0	98.44	100.00	CTA 0	89.63	99.63
	CTA 15	99.06	100.00	CTA 15	97.44	100.00	CTA 15	89.69	99.44
	CTA 30	99.00	100.00	CTA 30	97.50	100.00	CTA 30	89.56	99.00
ANP0.30	CTA 0	98.69	100.00	CTA 0	97.06	99.94	CTA 0	90.88	98.75
	CTA 15	98.38	100.00	CTA 15	97.06	99.94	CTA 15	90.69	98.50
	CTA 30	98.19	100.00	CTA 30	97.19	99.94	CTA 30	89.94	98.06

Spacing Error
Time of Day: 8-9 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	100.00	100.00	CTA 0	99.63	100.00	CTA 0	98.13	100.00
	CTA 15	100.00	100.00	CTA 15	99.81	100.00	CTA 15	98.38	99.88
	CTA 30	100.00	100.00	CTA 30	99.19	100.00	CTA 30	97.75	99.75
ANP 0.15	CTA 0	100.00	100.00	CTA 0	99.50	100.00	CTA 0	97.44	100.00
	CTA 15	100.00	100.00	CTA 15	99.13	100.00	CTA 15	98.13	99.88
	CTA 30	100.00	100.00	CTA 30	99.00	100.00	CTA 30	96.88	99.81
ANP0.30	CTA 0	100.00	100.00	CTA 0	98.38	100.00	CTA 0	95.56	99.94
	CTA 15	99.81	100.00	CTA 15	98.00	100.00	CTA 15	96.06	99.63
	CTA 30	99.69	100.00	CTA 30	97.94	99.94	CTA 30	96.06	99.56

The error bars in Figure 14 and Figure 15 show the means and 95% confidence intervals for the spacing error during the 7-8AM and 8-9AM scenarios, among all CTA errors.
It is clearly visible that the MCP runs have a much higher spread in spacing error than the AT runs, also the mean error seems larger for the MCP cases. However, the means do not vary much with wind scenario or ANP.
Wind uncertainty shows to be an important factor, with the spread increasing from WF0 to WF2.
The effect of decreasing navigation accuracy (ANP 0.00 to 0.30) does not seem to generate an increase in spacing error.

Comparing the data between the 7-8AM and 8-9AM runs, generally the same effects can be seen, although the overall spread is less for the 8-9AM runs. As explained above, this seems to be due to the extra merge point in the 4 IAF scenarios (7-8AM) and the fact that wind errors are more pronounced in the 7-8AM runs.

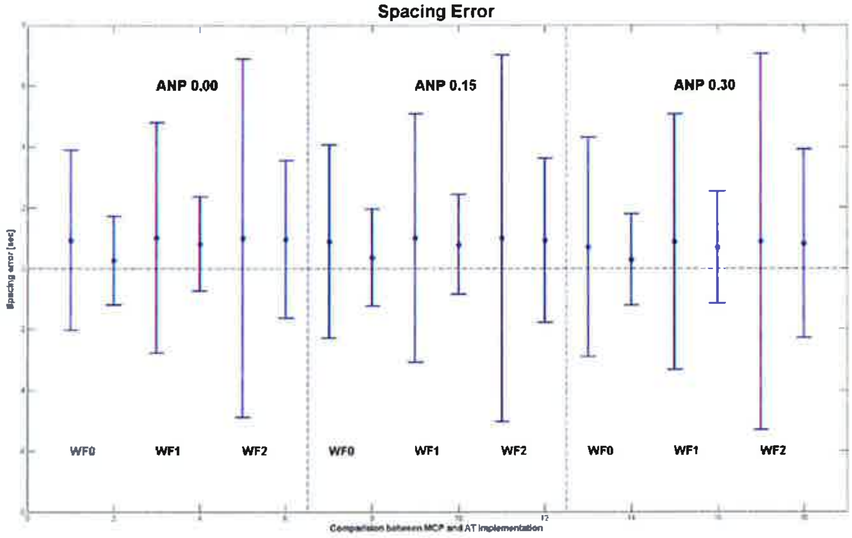


Figure 14. The means and 95% confidence intervals for the spacing error in the **7-8AM** runs among all CTA errors
For each condition the left bar indicates MCP usage, and the right bar AT.

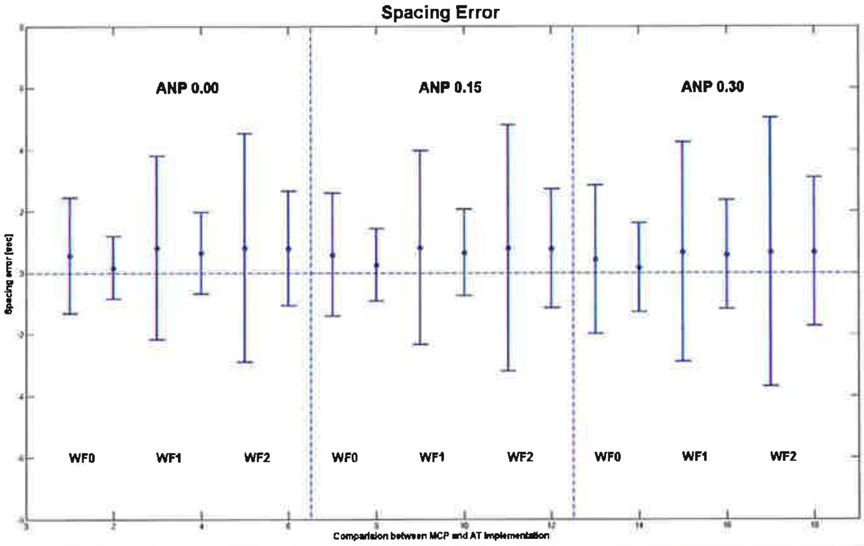


Figure 15. The means and 95% confidence intervals for the spacing error in the **8-9AM** runs among all CTA errors For each condition the left bar indicates MCP usage, and the right bar AT.

Figure 16 and Figure 17 show the spacing error for the different parameters, this time for all navigation errors and varying CTA errors. The same effects can be seen for varying wind fields and the difference between MCP and AT runs.

It can be concluded that the navigation accuracy (ANP) and the timing error over the IAF (CTA) only have a minor effect on the overall performance of the IM-algorithm.

The major influences on the spacing error are the automation level (MCP/AT), wind factor (WF) and time of day scenario.

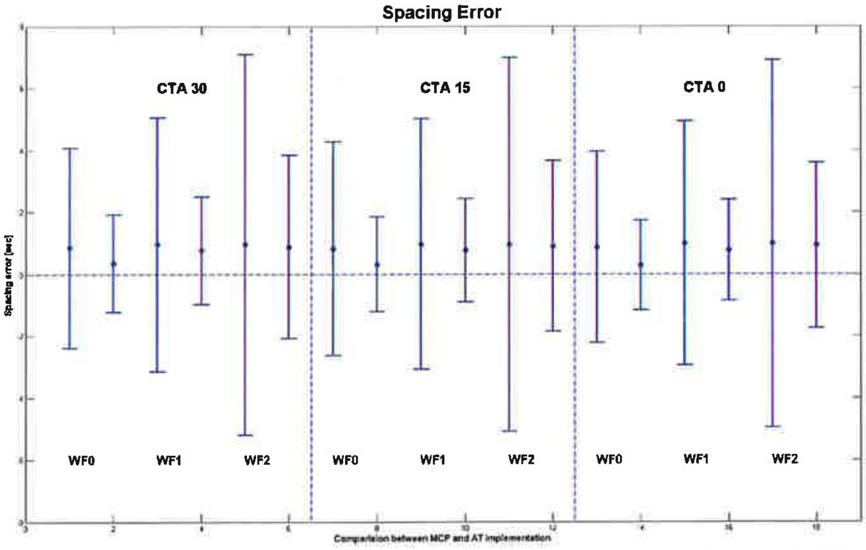


Figure 16.The means and 95% confidence intervals for the spacing error in the **7-8AM** runs for all ANP implementations. For each condition the left bar indicates MCP usage, and the right bar AT.

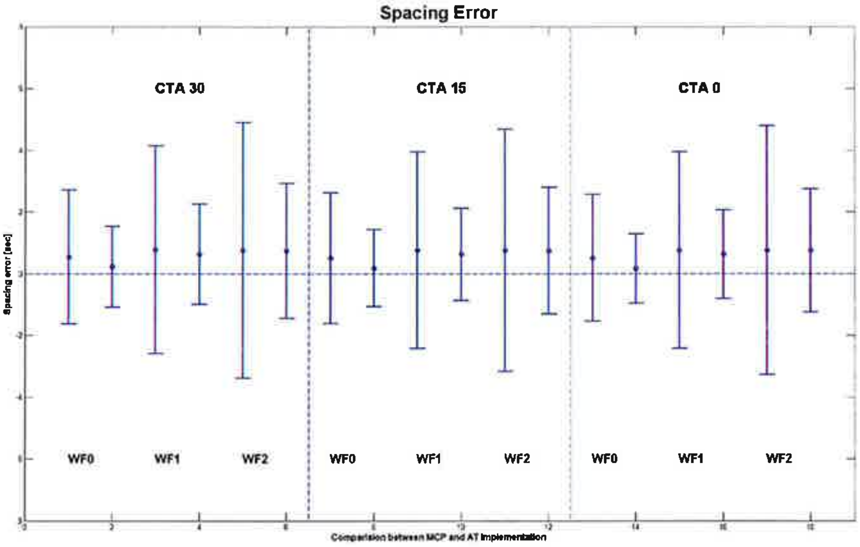


Figure 17.The means and 95% confidence intervals for the spacing error in the **8-9AM** runs for all ANP implementations. For each condition the left bar indicates MCP usage, and the right bar AT.

9.4.2 Normalized Range Error

As the ASTAR-algorithm achieves a spacing in time, it is interesting to see what the actual distance behind the lead is when the ownship reaches the achieve-by point to evaluate how close the aircraft are with respect to both their desired spacing distance and separation minima.

When analyzing the results, it was initially found that the aircraft were on average flying closer to their lead aircraft than the required separation minimum. Further analysis showed that this was due to the fact that by the time an aircraft arrives at the achieve-by point, the lead will already be decelerating for the final part of the approach. This was not taken into account when defining the required spacing interval.

A short simulation was performed where the 160 kts speed limit was removed from the last merge point, and it was found that the aircraft performed flawlessly, without any violation of the separation minima.

It is therefore safe to conclude that the IM-spacing algorithm works fine, but that the calculation of the spacing requirement at the ABP needs to be corrected.

9.4.3 Minimum Range

To verify that all aircraft are safely separated during the entire procedure, the minimum distance between the aircraft is logged between the IAF and the Achieve-By Point. Minimum range is logged between IAF and Achieve-By Point and should never be less than 3 Nm, see Table 17.

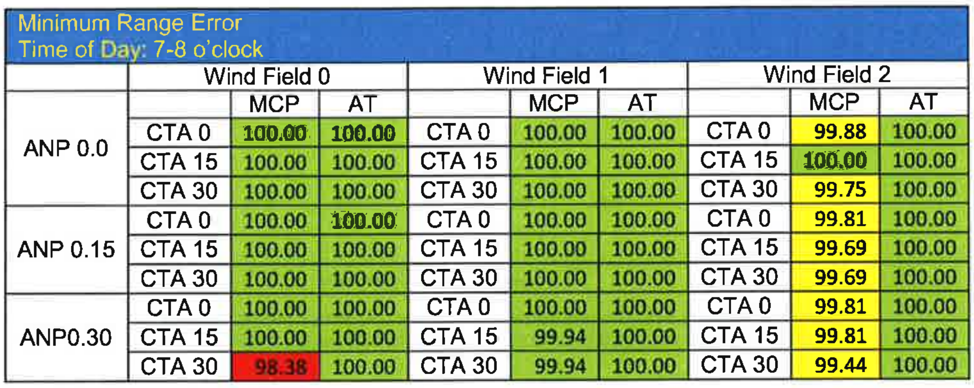
What is not indicated in the table is the fact that during the runs 100% of the aircraft remained more than 2.5 NM separated at all times.

Again we see better performance in the higher traffic density 8-9AM than in the 7-8AM, and better performance for the autothrottle than the pilot manually adjusting the speeds through the MCP.

There is only one combination of factors that yielded unsatisfactory performance and that is the CTA 30, MCP scenario with wind field 0. Apparently the large timing error over the IAF of 30 seconds, combined with the pilot delays when using the MCP and having exactly correct wind

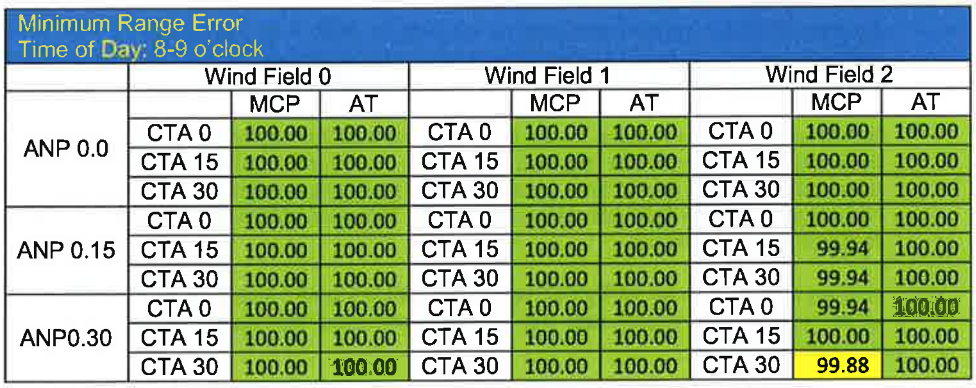
estimates, as opposed to the other scenarios where the head wind is more than expected, results in the aircraft being so early that the algorithm cannot slow the aircraft down fast enough to maintain more than 3.0 NM spacing.
This does not mean that during these runs the correct spacing error was not achieved. As was shown in Table 16, this particular combination of uncertainties does not result in an increase in spacing error. The minimum spacing during these runs generally occurs early on in the procedure, after which the aircraft correct the spacing error and continue to space normally.

Table 17. Percentage aircraft that always maintain >= 3.0 NM from their Lead. Green indicates more than 99.9%, yellow between 99.0-99.9%, red less than 99.0%.



Minimum Range Error
Time of Day: 7-8 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	99.88	100.00
	CTA 15	100.00	100.00	CTA 15	100.00	100.00	CTA 15	100.00	100.00
	CTA 30	100.00	100.00	CTA 30	100.00	100.00	CTA 30	99.75	100.00
ANP 0.15	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	99.81	100.00
	CTA 15	100.00	100.00	CTA 15	100.00	100.00	CTA 15	99.69	100.00
	CTA 30	100.00	100.00	CTA 30	100.00	100.00	CTA 30	99.69	100.00
ANP0.30	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	99.81	100.00
	CTA 15	100.00	100.00	CTA 15	99.94	100.00	CTA 15	99.81	100.00
	CTA 30	98.38	100.00	CTA 30	99.94	100.00	CTA 30	99.44	100.00



Minimum Range Error
Time of Day: 8-9 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	100.00	100.00
	CTA 15	100.00	100.00	CTA 15	100.00	100.00	CTA 15	100.00	100.00
	CTA 30	100.00	100.00	CTA 30	100.00	100.00	CTA 30	100.00	100.00
ANP 0.15	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	100.00	100.00
	CTA 15	100.00	100.00	CTA 15	100.00	100.00	CTA 15	99.94	100.00
	CTA 30	100.00	100.00	CTA 30	100.00	100.00	CTA 30	99.94	100.00
ANP0.30	CTA 0	100.00	100.00	CTA 0	100.00	100.00	CTA 0	99.94	100.00
	CTA 15	100.00	100.00	CTA 15	100.00	100.00	CTA 15	100.00	100.00
	CTA 30	100.00	100.00	CTA 30	100.00	100.00	CTA 30	99.88	100.00

9.4.4 Relative IAS Error

The relative IAS error is a measurement to indicate how much the aircraft deviated from the nominal profile speed on that leg, providing a measure for the amount of control spaced used.

ASTAR has a control space of ±10% of the nominal leg speed. The Root Mean Square of each aircraft is taken and the median value for all aircraft for a given condition is given in Table 18. More than 5% speed deviation is considered a significant use of the available control space, as this equates to an average 50% usage of the control space. More than 8% speed deviation (80% control space usage) is considered the limit of acceptable use.

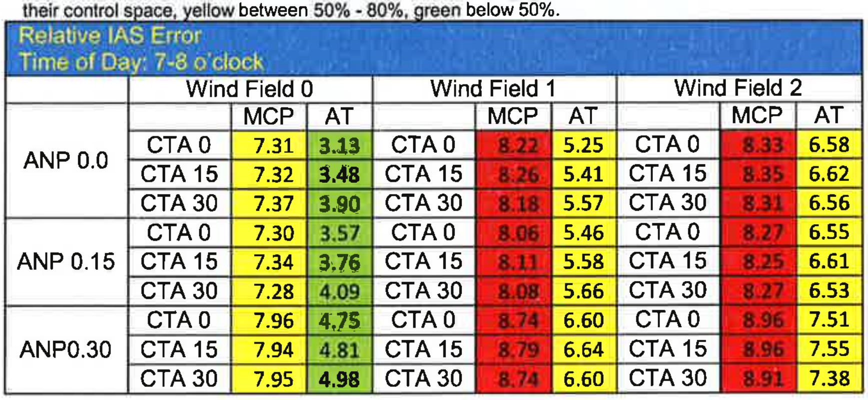
The relative IAS error provides a measure for the average speed deviation and as such it provides no information on whether the control limit is temporarily reached during a particular simulation run.

It is clear from Table 18 that the autothrottle provides better performance. In terms of control space use, it is roughly twice as efficient as the MCP scenario. Furthermore, the navigation accuracy has a negative effect on control space usage, as does the timing accuracy over the IAF. The average relative IAS error increase with lower navigation accuracy (ANP0.00-0.30) and also for larger timing errors over the IAF (CTA0-30).

Wind prediction errors have a strong effect on the relative IAS error, as the algorithm has to work hard to correct the spacing errors due to these errors.

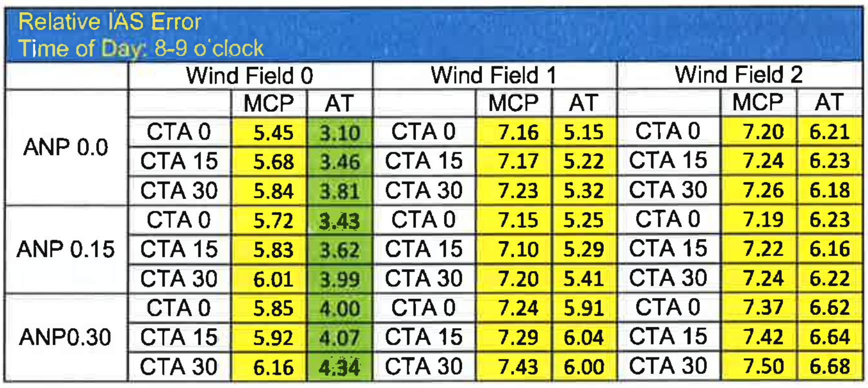
Again the 8-9AM inbound peak scenario performs better than the 7-8AM scenario.

Table 18. Median of the RMS-values of the speed deviation [%]. Red means 50% of the aircraft used more than 80% of their control space, yellow between 50% - 80%, green below 50%.



Relative IAS Error
Time of Day: 7-8 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	7.31	3.13	CTA 0	8.22	5.25	CTA 0	8.33	6.58
	CTA 15	7.32	3.48	CTA 15	8.26	5.41	CTA 15	8.35	6.62
	CTA 30	7.37	3.90	CTA 30	8.18	5.57	CTA 30	8.31	6.56
ANP 0.15	CTA 0	7.30	3.57	CTA 0	8.06	5.46	CTA 0	8.27	6.55
	CTA 15	7.34	3.76	CTA 15	8.11	5.58	CTA 15	8.25	6.61
	CTA 30	7.28	4.09	CTA 30	8.08	5.66	CTA 30	8.27	6.53
ANP0.30	CTA 0	7.96	4.75	CTA 0	8.74	6.60	CTA 0	8.96	7.51
	CTA 15	7.94	4.81	CTA 15	8.79	6.64	CTA 15	8.96	7.55
	CTA 30	7.95	4.98	CTA 30	8.74	6.60	CTA 30	8.91	7.38



Relative IAS Error
Time of Day: 8-9 o'clock

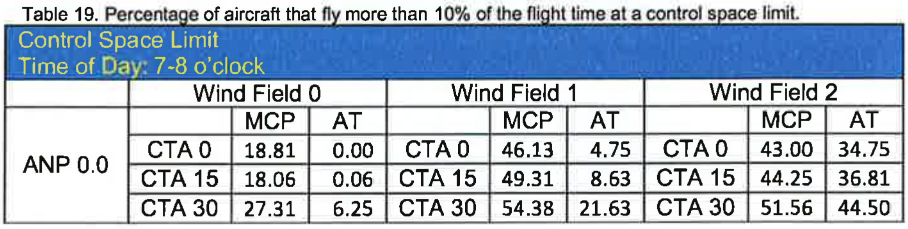
	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	5.45	3.10	CTA 0	7.16	5.15	CTA 0	7.20	6.21
	CTA 15	5.68	3.46	CTA 15	7.17	5.22	CTA 15	7.24	6.23
	CTA 30	5.84	3.81	CTA 30	7.23	5.32	CTA 30	7.26	6.18
ANP 0.15	CTA 0	5.72	3.43	CTA 0	7.15	5.25	CTA 0	7.19	6.23
	CTA 15	5.83	3.62	CTA 15	7.10	5.29	CTA 15	7.22	6.16
	CTA 30	6.01	3.99	CTA 30	7.20	5.41	CTA 30	7.24	6.22
ANP0.30	CTA 0	5.85	4.00	CTA 0	7.24	5.91	CTA 0	7.37	6.62
	CTA 15	5.92	4.07	CTA 15	7.29	6.04	CTA 15	7.42	6.64
	CTA 30	6.16	4.34	CTA 30	7.43	6.00	CTA 30	7.50	6.68

9.4.5 Control Space Limit

ASTAR indicates when the boundary of the control space has been reached and that more control space is required to achieve the spacing goal. The time where maximum control was required was logged for all simulation runs. Hitting a control space boundary is not an indication that the spacing goal cannot be achieved as the environment is dynamic and things change constantly.

Table 19 shows a strong correlation between the timing error over the IAF (CTA) and the amount of aircraft that run into a control limit when spacing behind their lead.

Table 19. Percentage of aircraft that fly more than 10% of the flight time at a control space limit.



Control Space Limit
Time of Day: 7-8 o'clock

	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	18.81	0.00	CTA 0	46.13	4.75	CTA 0	43.00	34.75
	CTA 15	18.06	0.06	CTA 15	49.31	8.63	CTA 15	44.25	36.81
	CTA 30	27.31	6.25	CTA 30	54.38	21.63	CTA 30	51.56	44.50

ANP 0.15	CTA 0	22.69	0.00	CTA 0	47.00	10.63	CTA 0	46.25	36.44
	CTA 15	22.50	0.19	CTA 15	47.88	15.13	CTA 15	47.94	38.75
	CTA 30	29.31	7.44	CTA 30	53.19	26.13	CTA 30	53.06	45.44
ANP0.30	CTA 0	27.13	6.31	CTA 0	42.06	25.31	CTA 0	45.31	44.44
	CTA 15	30.25	8.94	CTA 15	44.44	29.25	CTA 15	48.38	46.94
	CTA 30	39.31	18.94	CTA 30	52.00	37.00	CTA 30	52.94	50.81

Control Space Limit Time of Day: 8-9 o'clock									
	Wind Field 0			Wind Field 1			Wind Field 2		
		MCP	AT		MCP	AT		MCP	AT
ANP 0.0	CTA 0	0.38	0.00	CTA 0	30.38	2.50	CTA 0	44.69	23.44
	CTA 15	1.38	0.31	CTA 15	32.19	6.44	CTA 15	48.31	26.81
	CTA 30	12.56	7.88	CTA 30	40.81	19.38	CTA 30	52.50	38.50
ANP 0.15	CTA 0	2.75	0.00	CTA 0	33.44	6.31	CTA 0	46.69	27.50
	CTA 15	5.06	0.50	CTA 15	35.81	10.56	CTA 15	49.81	31.19
	CTA 30	16.88	8.56	CTA 30	43.75	23.75	CTA 30	54.19	40.75
ANP0.30	CTA 0	14.69	4.69	CTA 0	39.69	26.81	CTA 0	45.69	43.75
	CTA 15	17.00	7.88	CTA 15	42.94	30.19	CTA 15	48.63	47.13
	CTA 30	27.69	17.19	CTA 30	49.44	38.50	CTA 30	54.38	53.13

9.4.6 Individual effects

An analysis was made to see if any individual parameter is responsible for large variations in the performance of the IM-algorithm. Table 20 provides an overview of the performance of all the simulation runs, distributed only to a single parameter. No effect can be shown for any of the parameters, indicating that an individual uncertainty is not a problem for the IM-algorithm. Only when unfavourable conditions add up, are the limits of the control space reached and do the spacing performance suffer.

Table 20. Effect of individual parameters on the spacing error, minimum range, IAS error and control space limits.

Time of Day: 7-8 o'clock				
	Spacing error	Min range	IAS error	Control space
7-8 o'clock	97.68	99.93	$\bar{x}$ = 6.93	31.66
8-9 o'clock	99.31	99.99	$\bar{x}$ = 6.02	26.58

Navigation accuracy				
	Spacing error	Min range	IAS error	Control space
ANP 0.0	98.79	99.99	$\bar{x}$ = 6.16	24.96
ANP 0.15	98.54	99.97	$\bar{x}$ = 6.26	27.43
ANP 0.30	98.16	99.92	$\bar{x}$ = 6.83	34.98

Wind Field				
	Spacing error	Min range	IAS error	Control space
WF0	99.76	99.96	$\bar{x}$ = 4.97	11.91
WF1	99.21	99.99	$\bar{x}$ = 6.64	31.32
WF2	96.52	99.93	$\bar{x}$ = 7.18	44.13

Initial spacing error				
	Spacing error	Min range	IAS error	Control space
CTA 0	98.61	99.98	$\bar{x}$ = 6.37	24.84
CTA 15	98.52	99.98	$\bar{x}$ = 6.41	27.22
CTA 30	98.36	99.92	$\bar{x}$ = 6.48	35.31

Implementation				
	Spacing error	Min range	IAS error	Control space
MCP	97.17	99.92	$\bar{x} = 7.40$	36.97
AT	99.82	100.00	$\bar{x} = 5.21$	21.28

9.5 Discussion

First of all it has to be concluded that IM-spacing works. The simulation batch study shows that strings of up to 40 aircraft can be safely spaced, while arriving at 35 aircraft per hour. For the chosen levels of wind field errors, navigation errors and timing accuracy, IM-spacing is possible using the ASTAR algorithm to control the spacing interval. Keeping in mind that this batch study did not aim to find the limits of the IM-concept, but merely researched the feasibility of introducing the IM-concept to the Schiphol operation, no conclusions on minimum navigation accuracy, minimum timing accuracy or minimum wind prediction accuracy can be given. However, given the fact that the simulated levels of accuracy caused the algorithm to use up to 80% of its control space for the most unfavourable combinations, it can be assumed that current day performance forms a good lower limit.

It is apparent from the results is that linking the algorithm directly to the autothrottle system yields far better performance, than having the pilots set the speeds manually through the MCP.

Further analysis of the simulation batch study results show that the ASTAR algorithm is able to cope with all disturbances individually, and for the autothrottle scenarios is able to correct the most unfavourable combinations. Although the performance is adequate in almost all scenarios, the spread in the spacing error increases when uncertainties are introduced.
No effects on spacing performance were found for the different levels of navigation accuracy and the timing accuracy over the IAF. Analysis of the control space usage showed, however, that the algorithm is working closer to its limits when the navigation and timing accuracy are reduced, thereby lowering the robustness of the algorithm against further disturbances.

Main conclusions:

- The IM-concept works for the scenarios investigated in the batch study;
- The IM-concept works for the current level of navigation performance RNAV1, introduction of higher precision will improve the robustness of the system;
- The timing accuracy as aimed for by SARA is sufficient for implementing IM-operations, but higher levels will improve the robustness of the system;
- Wind prediction error has a large influence on the spacing performance;
- Direct coupling to an autothrottle system greatly improves performance over manual speed selections;
- A larger number of merge points reduces the overall performance; and
- Having trajectories with opposite wind effect amplifies the effect of wind prediction errors.

Secondary conclusions:

- The use of RF-legs makes implementation easier, but it is possible to work with fly-by waypoints;
- Navigation performance (ANP-level) does not greatly influence the IM-performance, but it does cause large control space usage; and
- Timing accuracy over IAF (CTA) does not greatly influence the IM-performance, but it does cause large control space usage.

References

1. ICAO, "Continuous Descent Operations (CDO) Manual", Doc 9931, First Edition, 2010
2. EUROCAE, "Safety, Performance and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management (ASPA-FIM)", EUROCAE ED-195, September 2011
3. RTCA, "Safety, Performance and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management (ASPA-FIM)", RTCA DO-328, June 2011
4. FAA/EUROCONTROL, "Principles of ASAS", June 2001 (http://adsb.tc.faa.gov/RFG/po-asas71.pdf)
5. EUROCAE WG51/RTCA SC-186 ADS-B Requirements Focus Group (RFG) (http://adsb.tc.faa.gov/RFG.htm)
6. SESAR, "D3 - The ATM Target Concept", September 2007 (http://www.sesarju.eu/news-press/documents-reports)
7. Knowledge & Development Centre Mainport Schiphol, "Study of Airborne & Ground Surveillance Applications: How to support the ATM System of the Netherlands", KDC/2009/0067, March 2009
8. Osaguera-Lohr, R. M.; *et al*, "Evaluation Of Operational Procedures For Using A Time-Based Airborne Interarrival Spacing Tool", AIAA 2002-5824, 2002
9. Ivanescu, Dan, *et al*, "Design of an Airborne Spacing Director to Minimise Pilot Speed Actions", 6th USA/Europe Air Traffic Management R&D Seminar, Baltimore, Maryland, USA, June 2005
10. Ivanescu, Dan, *et al*, "Towards Performance Requirements for Airborne Spacing – A Sensitivity Analysis of Spacing Accuracy", AIAA 2006-7784, 6th AIAA ATIO Conference, Wichita, Kansas, USA, September 2006
11. Hoffman, Eric, *et al*, "Airborne Spacing: Managed vs. Selected Speed Mode on the Flight Deck", AIAA 2006-7782, 6th AIAA ATIO Conference, Wichita, Kansas, USA, September 2006
12. Barmore, Bryan, "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations", 26th Digital Avionics Systems Conference, Portland, Oregon, USA, October 2006
13. Barmore, Bryan E., *et al*, "Simulation Results for Airborne Precision Spacing along Continuous Descent Arrivals", AIAA 2008-8931, ICAS 2008 Congress including the 8th AIAA ATIO Conference, Anchorage, Alaska, USA, September 2008
14. Abbott, Terence S., "A Brief History of Airborne Self-Spacing Concepts", NASA/CR-2009-215695, February 2009
15. Murdoch, Jennifer L., *et al*, "Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations", 8th USA/Europe Air Traffic Management R&D Seminar, Napa, California, USA, June 2009
16. Van Schaik, F.J., "Introduction to Air Traffic Management (AE4428)", TU-Delft, Delft, 2010
17. AMAN status review 2009, Cooperative Network Design, EUROCONTROL, Edition number 0.2, 17 February 2009
18. Knowledge & Development Centre Mainport Schiphol, Concept of operation (CONOPS), "Speed and Route Advisor (SARA)", KDC/2007/0092 v1.0, 2007
19. SESAR 5.6.6, "D09 – IT2 Safety and Performance Requirements", (to be published)
20. Weitz, Lesley A., Hurtado John E., "String Stability Analysis of Selected Speed Control Laws for Interval Management", AIAA 2012-4595, AIAA Guidance, Navigation and Control Conference, Minneapolis, Minnesota, USA, August 2012.
21. Knowledge & Development Centre Mainport Schiphol, "Operational Services and Environment Definition – ASAS Interval Management", KDC/2011/0024, March 2011
22. Bussink F.J., *et al*, "A fast-time simulation environment for airborne merging and spacing research", Digital Avionics Systems Conference, 2004, DASC 04, The 23rd, Vol.1, IEEE, 2005.
23. Verhoeven, R.P.M, et al, "OPTIMAL D7.3.1-2 NLR GRACE/NARSIM ACDA Real-Time Simulation Report", November 2008.
24. Consiglio, Maria C., et al, "Human In The Loop Simulation Measures of Pilot Response Delay in a Self-Separation Concept of Operations", 27th International Congress of the Aeronautical Sciences, ICAS 2010, 2010.

Document information

Document information	
Start process	
Document type	Operational Performance Assessment
Title	ASAS Interval Management in the Schiphol TMA
Part	-
Initiated by	KDC
Related to	-
Document number	KDC/2012/0069
Version number	V1.0
Version date	02-11-2012
Status	First release

Summary

This document provides the results of the Operational Performance Assessment of a proposed ASAS-IM Operational Application for Schiphol airport. The aim of the performance analysis is to fully characterize the minimum performance of the system.

Key words

CDA / CDO	High Capacity
ASAS	
Spacing	
SARA	
Interval Management	
Fixed Arrival Routes	

Security classification

Not classified

Version control

Version	**Version date**	**Section**	**Remarks**
1.0	02-11-2012	All	First release

APPENDIX A ANALYSIS OF IM TOLERANCE AT SPL

a. Description of the IM Operation

In the SPL IM concept, the IM Tolerance is determined for a CDO Arrival with Termination Point at the Final Approach Point (FAP) and the Achieve-by point at the Intermediate Approach Fix (IF). While the CDO may begin at the top of descent, the IM operation starts at the Initial Approach Fix. The concept is trajectory based meaning that spacing pairs may initially not be on the same route.

Different time-based Assigned Spacing Goals are derived from wake-vortex separation standards and are assumed based on the aircraft categories in each aircraft pair.

b. Operational Goal

The operational goal is time of day dependent, with a maximum throughput of 35 aircraft per hour per runway (ac/hr/rwy). Whereas the IM Operation is terminated at the FAP, the operational goal is measured at either the Planned Termination Point / FAP (method 1) or Achieve-by Point / IF (method 2) The IM Tolerance and FIM Equipment Tolerance needed at the FAP or IF is determined such that the throughput goal is met.

Method 1 uses the methodology as described in the FIM SPR [2,3]. Method 2 uses a simpler approach based on current day operations. The main difference is that in nominal situations no controller action is foreseen in method 1, whereas in method 2 the controller dynamically instructs the aircraft, after passing the IF, to reduce speed in order to maximize runway throughput as in current operation. The main disadvantage of method 1 is that an accurate estimate of the time-to-go between FAP and runway threshold needs to be calculated for each aircraft. This calculation requires, amongst others, the planned final approach speeds of each aircraft and accurate meteorological information (wind, temp). In particular, planned final approach speeds with a high accuracy are not readily available on the ground. Note that a one knot error in the final approach speed translates in approximately one second spacing error during the final approach.

c. Method 1

i. Methodology for Deriving the IM Tolerance

The IM Tolerance is derived using the following methodology:

- The average Spacing Interval at the runway threshold is computed assuming:
  - a time-based wake-vortex minimum separation standard equal to the 99.9% bound on the spacing performance; and
  - a representative aircraft-type mix for the operation.
- The spacing variability that yields the throughput goal is determined. The IM tolerance at the threshold is the 95% bound on the spacing performance at the threshold.
- The IM Tolerance needed at the Planned Termination Point / FAP is determined.
- The FIM Equipment Tolerance needed at the Planned Termination Point / FAP is determined.

ii. Spacing Interval calculation

The radar and wake-vortex minimum separation standard is assumed to be the primary driver for the Spacing Intervals between aircraft categories at the runway threshold. In non-IM Operations, controllers are assumed to be controlling aircraft to prevent Spacing Intervals that cause these minimum separation standards to be violated. Separation standards are provided in distance and are converted to time by assuming appropriate final approach speeds for representative aircraft types in each category.

Table 21 and Table 22 show the minimum separation standards in distance and time, respectively. These values were calculated using the average groundspeed at the threshold per category (Table 23).

Table 21: Minimum separation standards in distance [Nm]

		Lead aircraft			
		Heavy	B757	Medium	Light
IM aircraft	Heavy	4	4	3	3
	B757	5	5	3	3
	Medium	5	5	3	3
	Light	6	6	5	3

Table 22: Minimum separation standards in time [sec]

		Lead aircraft			
		Heavy	B757	Medium	Light
IM aircraft	Heavy	100	100	75	75
	B757	137	137	82	82
	Medium	136	136	82	82
	Light	187	187	155	93

Table 23: Average groundspeed at threshold [kts]

	Heavy	B757	Medium	Light
GS at threshold	143.3	131.1	132.3	115.8

The time-based minimum separation standards can be expressed in matrix form, which eases subsequent mathematical development. The column index represents the Target Aircraft in the pair, and the row index represents the IM Aircraft in the pair.

$$w = \begin{bmatrix} \mathbf{100} & \mathbf{100} & \mathbf{75} & \mathbf{75} \\ \mathbf{137} & \mathbf{137} & \mathbf{82} & \mathbf{82} \\ \mathbf{136} & \mathbf{136} & \mathbf{82} & \mathbf{82} \\ \mathbf{187} & \mathbf{187} & \mathbf{155} & \mathbf{93} \end{bmatrix}$$

The assumed Spacing Intervals between aircraft at the runway threshold are such that the minimum separation standard represents the 95% bound on the spacing performance, i.e. representing the Nominal Spacing Bounds as described in Section 6.1. A spacing variability $\sigma_{\text{threshold}}$ is assumed to model the spacing performance at the threshold.

$$\textit{Spacing Interval}_{threshold} = w + 1.96\sigma_{threshold}$$

It should be noted that a single standard deviation is assumed for all aircraft-type combinations, but the extension to standard deviations as a function of aircraft-type combinations is trivial.

The second criterion is the 99.9% bound on the spacing performance[7], i.e., the Controller Intervention Threshold (Section 6.1). The main differences are the minimum radar separation, assumed at 2.5 NM instead of 3 NM, and the value of the normal distribution for 99.9% instead of 95%, being 3.29 instead of 1.96

$$\textit{Spacing Interval}_{threshold} = w + 3.29\sigma_{threshold}$$

---

[7] The 99.9% bound on the spacing performance means that 1 out of 1000 aircraft cross the Controller Time Intervention Threshold; therefore, 1 out of 2000 aircraft (i.e., 99.95% bound) cross the Controller Time Intervention Threshold on the side of the distribution where the Spacing Interval between aircraft is smallest.

For an assumed aircraft-type mix, the average Spacing Interval at the runway $\bar{t}_{threshold}$ is computed.

$$\bar{t}_{threshold} = \sum_{i=1}^{3}\sum_{j=1}^{3}\left(Spacing\ Interval_{threshold}(i,j)\right)p(i)p(j)$$

Here, p(i) for i = 1,2,3 is the probability of a Heavy, a B757, or a Medium aircraft, respectively, in the sequence. The contribution of Light aircraft is found to be negligible for the Schiphol operation.

The throughput at the runway threshold is then determined from the average Spacing Interval.

$$throughput_{threshold}(\text{aircraft/hour}) = \frac{3600}{\bar{t}_{threshold}}$$

iii. Probability of wake turbulence category combinations in the sequence

To determine the throughput at the runway threshold, an analysis is performed to determine the probability of pairs of specific aircraft wake turbulence category combinations. Data was obtained for aircraft arriving and landing at Schiphol during the summer period of 2010, the data set contained six months of operations.

Figure 18 shows the distribution over the four wake turbulence categories of aircraft arriving at Schiphol during the Summer of 2010.

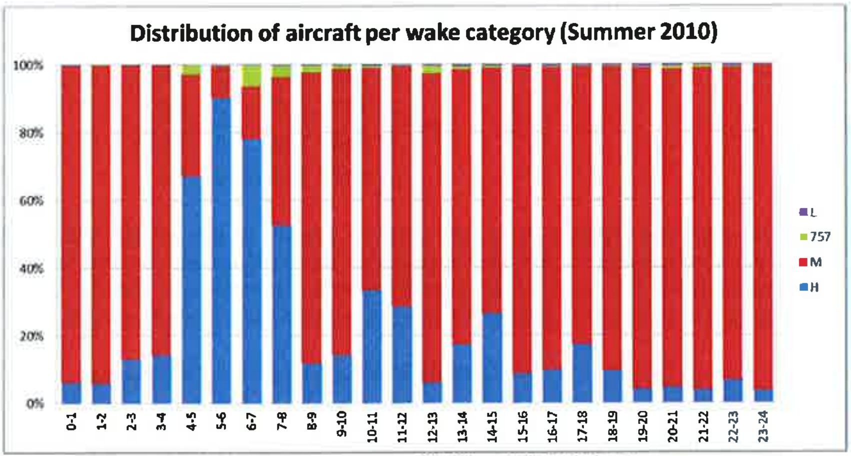


Figure 18: Distribution of arriving aircraft per wake turbulence category

From the same dataset the distribution of WTC combinations (e.g. Heavies followed Mediums) was derived. The results are presented in Figure 19. For example, as a result of this analysis the traffic mix for 8-9am gives p(1)p(3) = 0.1020 and p(1)p(1) = 0.0184; this means that there is a 10.2% probability that a Heavy aircraft is followed by a Medium in the landing sequence and there is a 1.84% probability that a Heavy is followed by another Heavy.

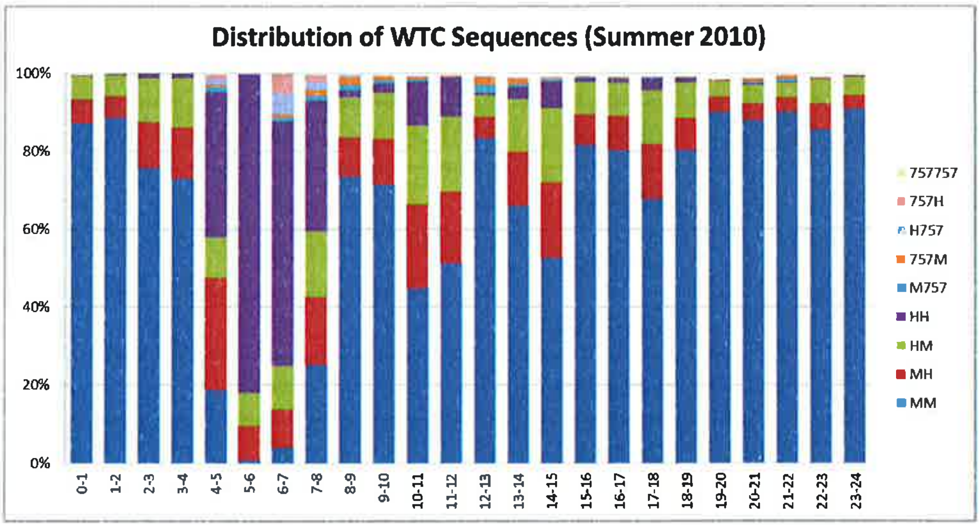


Figure 19: Distribution of aircraft pairs per wake turbulence category (WTC) combinations

iv. Operationally-Required Throughput

The average throughput per single runway depends on the time of day. Analysis of the Schiphol 2010 data reveals an inbound peak in the morning between 8:00-9:00am, which requires a throughput of 35 ac/hr/rwy. This peak is repeated in the evening between 7:00-8:00pm. During the nightly hours throughput demand does not exceed 25 ac/hr/rwy, while during the day and evening (with exception of the morning and evening peaks) this number does not exceed 30 ac/hr/rwy.

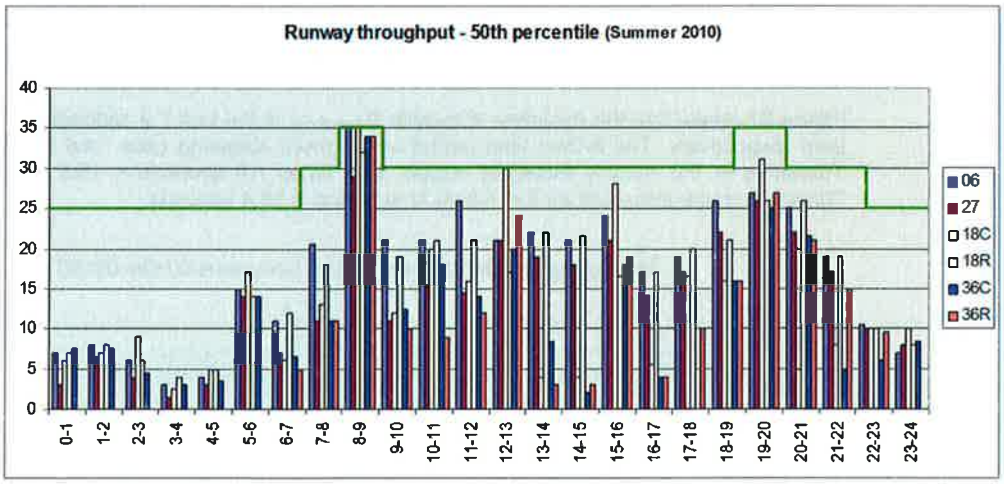


Figure 20: Runway throughput for the main landing runways at Schiphol

The average throughput is used because it is directly coupled to the average characteristics of the traffic mix as given in Figure 18 and Figure 19. If the distribution of the various wake-turbulence categories is significantly different during a specific day or even hour, this strongly influences the throughput that may be realized during that day or hour.

For this study, the operationally-required runway throughput is assumed as shown in Table 24.

Table 24: Operationally required runway throughput

Time Of Day	*Required Throughput (ac/hr/rwy)*
7:00-8:00	**30**
8:00-9:00	**35**
9:00-19:00	**30**
19:00-20:00	**35**
20:00-22:00	**30**
22:00-7:00	**25**

7:00-9:00am

The achievable throughput can now be determined for every hour of the day as function of the spacing variability $\sigma_{threshold}$. This is based on the formulas given in Section ii and the distribution of wake-turbulence category combinations given in Figure 19 in paragraph iii.
Analysis revealed that the 99.9% criteria (i.e., Controller Intervention Threshold criteria), rather than the 95% criteria (i.e., Nominal Spacing Bound criteria), results in the more conservative IM tolerance. Therefore only the results for this criterion are presented. Figure 21 shows the results for the representative aircraft mix between 7am-9am local time. The solid red line shows the achievable throughput between 7-8am and the solid blue line shows the achievable runway throughput between 8-9am, both as function of the spacing variability $\sigma_{threshold}$. The dashed green lines show the desired runway throughput, 30 ac/hr for 7-8am and 35 ac/hr for 8-9am.
The point where the achievable and desirable throughput lines cross indicates the maximum allowable spacing variability. The maximum allowable IM Tolerance at the runway threshold is a 95% value. Assuming a normal distribution this equals 1.96 times $\sigma_{threshold}$.

Figure 21 reveal that the minimum allowable $\sigma_{threshold}$ is 8.4 and 7.9 seconds for 7-8am and 8-9am respectively. The 8-9am time period is the more stressing case, and the associated IM Tolerance at the runway threshold equals 1.96 times 7.9 seconds = 15.5 seconds. The IM Tolerance at the threshold for the 7-8am time period is 16.4 seconds.

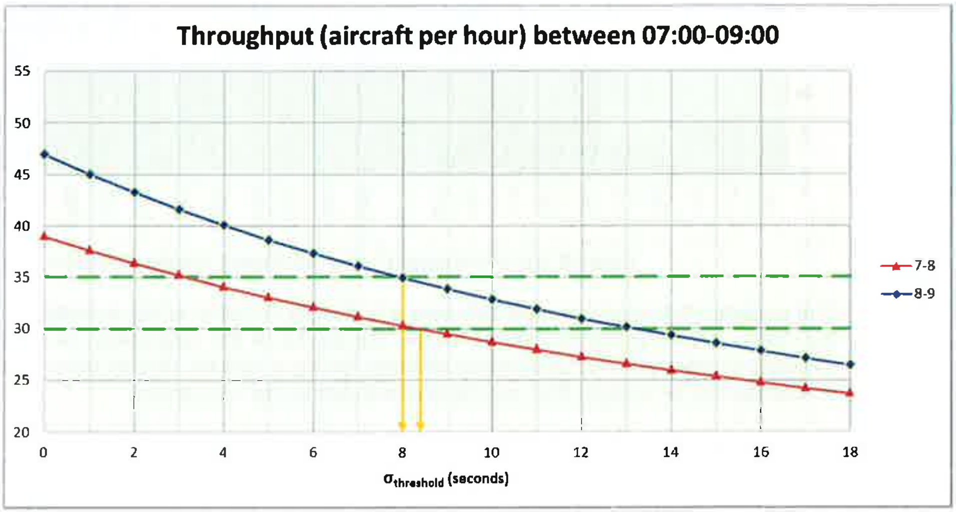


Figure 21: Throughput at the runway threshold as a function of spacing variability (99.95% bound < 2.5/4/5 NM)

9:00am-7:00pm

The throughput demand between 9am and 7pm is 30 ac/hr/rwy. Figure 22 shows that the maximum allowable $\sigma_{threshold}$ for 30 ac/hr is 10.6 seconds. Therefore, the maximum allowable IM Tolerance at the threshold for the 9am-7pm time period is 1.96 times 10.6 = 20.8 seconds.

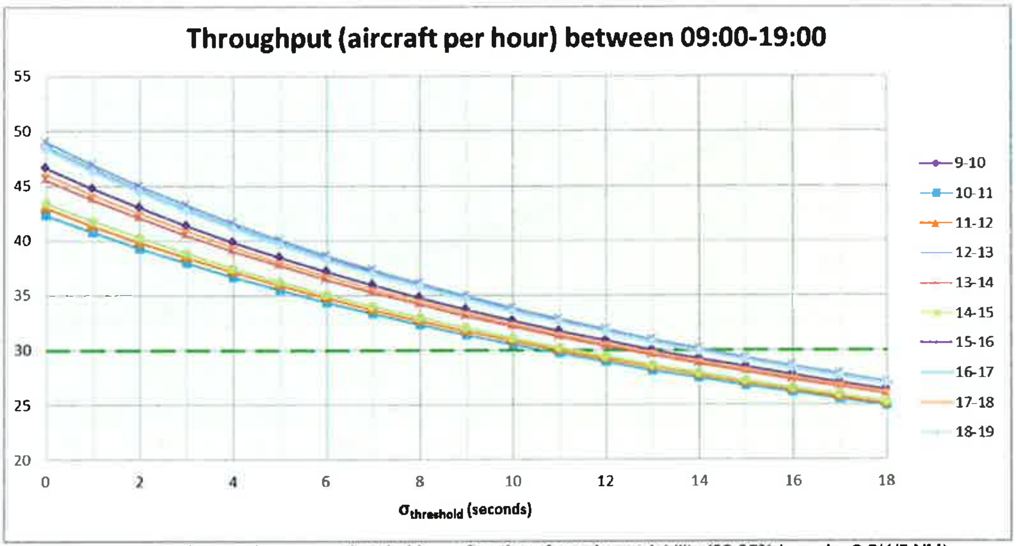


Figure 22: Throughput at the runway threshold as a function of spacing variability (99.95% bound < 2.5/4/5 NM)

7:00-8:00pm

The throughput demand between 7-8pm is 35 ac/hr/rwy. Figure 23 shows that the maximum allowable $\sigma_{threshold}$ for 35 ac/hr is 9.6 seconds. Therefore, the maximum allowable IM Tolerance at the threshold for the 7-8pm time period is 1.96 times 9.6 = 18.7 seconds.

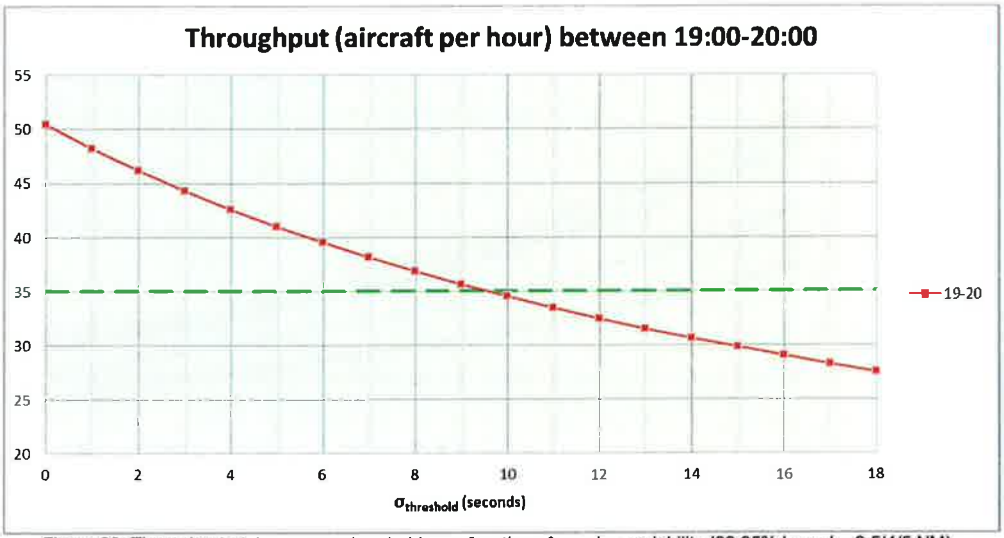


Figure 23: Throughput at the runway threshold as a function of spacing variability (99.95% bound < 2.5/4/5 NM)

8:00-10:00pm

The throughput demand between 8-10pm local time is 30 ac/hr/rwy. Figure 24 shows that the maximum allowable $\sigma_{threshold}$ for 30 ac/hr is 14.6 seconds. Therefore, the maximum allowable IM Tolerance at the threshold for the 8-10pm time period is 1.96 times 14.6 = 28.5 seconds.

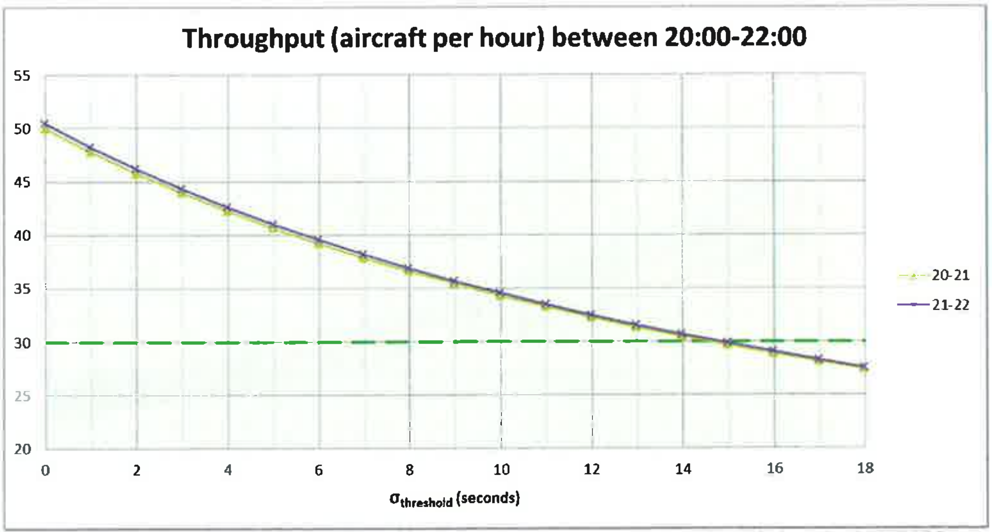


Figure 24: Throughput at the runway threshold as a function of spacing variability (99.95% bound < 2.5/4/5 NM)

10:00pm-7:00am

The throughput demand per runway between 10pm and 7am local time is 25 ac/hr. Figure 25 shows that the maximum allowable $\sigma_{threshold}$ for 25 ac/hr is 13.0 seconds. Therefore, the maximum allowable IM Tolerance at the threshold for the 10pm-7am time period is 1.96 times 13.0 = 25.5 seconds.

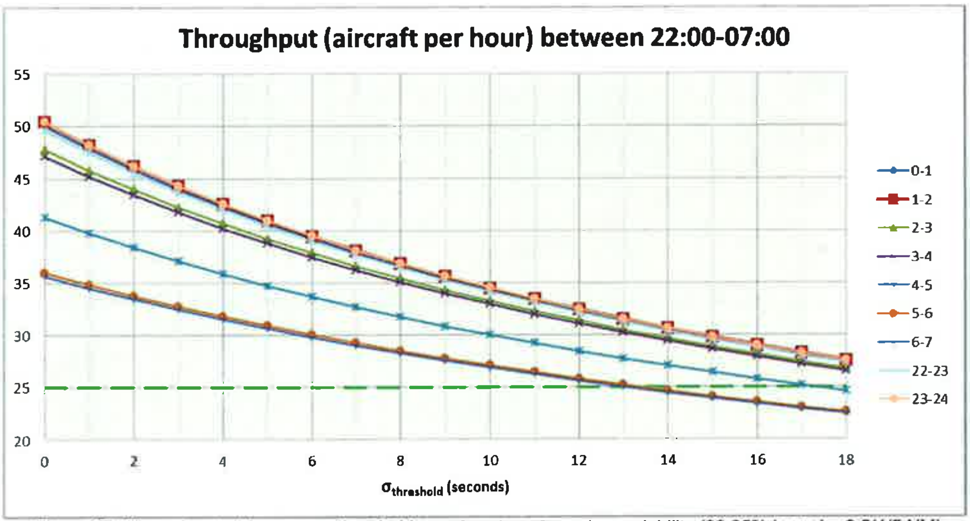


Figure 25: Throughput at the runway threshold as a function of spacing variability (99.95% bound < 2.5/4/5 NM)

v. Resulting IM Tolerances and FIM Equipment Tolerances

Table 25 presents a summary of the maximum allowable IM Tolerances at the threshold. It is concluded that morning peak between 8-9am is the most stressing condition. Therefore, the IM Tolerance at the runway threshold is set at 15.5 seconds.

Table 25: Summary of IM Tolerances at the threshold as a function of time of day

Time Of Day	***Required Throughput (ldg/hr/rwy)***	***Pr(spacing interval < 2.5/4/5 NM) < 0.05%***	
		$\sigma_{threshold}$ **(sec)**	**IM Tolerance (sec)**
7:00-8:00	**30**	8.4	**16.4**
8:00-9:00	**35**	7.9	**15.5**
9:00-19:00	**30**	10.6	**20.8**
19:00-20:00	**35**	9.6	**18.7**
20:00-22:00	**30**	14.6	**28.5**
22:00-7:00	**25**	13.0	**25.5**

However, since the IM operations will terminate at the FAP, the IM Tolerance at the FAP needs to be determined. This value can be calculated by considering the spacing uncertainty between the FAP and runway threshold. Figure 26 illustrates a sample nominal speed profile, this speed profile is used to model the spacing uncertainty between the FAP and runway threshold.

The spacing error will develop as a function of six independent operational uncertainties of both the IM aircraft and Target Aircraft.

- variation in speed at the FAP (nominal 160 kt)
- variation in location where the deceleration to the Final Approach Speed (FAS) starts (nominal 4 NM)
- variation in deceleration rates
- variation in CAS flown due to instrument errors
- variation in groundspeed flown due to wind errors
    - only the **difference in** headwind encountered by two consecutive aircraft is important, and not the difference between predicted and actual wind of individual aircraft (under the assumption that the ground system uses the same wind predictions for consecutive aircraft).
- variation in FAS flown, with contributions of:
    - flight crew planned FAS vs. actual FAS
    - ground planned FAS vs. flight crew planned FAS
    - guidance and control
    - instrument errors (already covered by one of the above-mentioned bullets)
    - wind errors ((already covered by one of the above-mentioned bullets)

Table 26 gives an overview of the assumed 95% bound on the errors and the resulting spacing errors. As these error contributions are considered to be independent, the total spacing error may be derived by calculating the Root Sum Square (RSS) of the individual spacing errors. Table 27 provides the assumed contributions of (95% bound) on the FAS error of 8 knots.

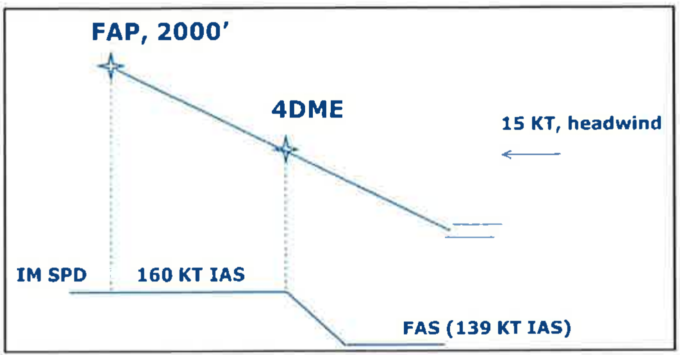


Figure 26: Sample speed profile between FAP and runway threshold

Table 26: Spacing error contributions of both IM and Target aircraft between FAP and runway threshold

Error contributor	**Conservative error, 95% bound**	**Resulting spacing error**
Initial speed	+/- 5 kt	0.88 sec
Start deceleration	+/- 0.25 NM (150kt → 6 sec, 80ft)	1.49 sec
Deceleration rate	+/- 0.30 kt/sec	0.53 sec
Instrument error	+/- 2 kt	3.70 sec
Headwind	+/- 2 kt	3.70 sec
FAS	+/- 8 kt	9.40 sec
Total (Root Sum Squared, RSS)		10.91 sec

Table 27: Error contributions for the Final Approach Speed

FAS error contributor	**Conservative error, 95% bound**
Flight crew planned vs. actual FAS	5 kt
Ground planned vs. flight crew planned	4 kt (10% MLW difference ~ 7-8 kt FAS difference)
Instrument error	N/A
Guidance and control	4 kt (min 0 kt, max 5 kt)
Headwind	N/A
Total (Root Sum Squared, RSS)	7.6 kt

Given the IM Tolerance at the runway threshold (Table 25) and the spacing uncertainty between FAP and runway threshold of 10.9 seconds, the IM Tolerance at the FAP can now be determined by using the RSS method. For example, the IM Tolerance at the FAP then becomes 11.0 seconds for 8-9am.

The next step is to determine the FIM Equipment Tolerance based on the IM Tolerance and the uncertainty in the state data of both IM and Target Aircraft. This uncertainty is given in APPENDIX B. For an ADS-B environment and an assumed speed at the FAP of 150 kt, the spacing error contribution due to the uncertainty in state data is 3.33 seconds. The FIM Equipment Tolerance can now be calculated using the RSS method. Table 28 shows the values for the 8-9am time period. Similarly, the values are calculated for each time period of the day. Table 29 gives the end results, being the IM Tolerances and FIM Equipment Tolerances at the FAP.

Table 28: Derivation of IM Tolerance and FIM Equipment Tolerance at the FAP for 8-9am

IM Tolerance at runway threshold	**15.5 seconds**
Spacing uncertainty FAP – threshold	**10.9 seconds**
IM Tolerance at FAP	**11.0 seconds**
Uncertainty State Data @ 150 kt along path speed	**3.33 seconds**
FIM Equipment Tolerance at FAP	**10.5 seconds**

Table 29: IM and FIM Equipment Tolerances at the FAP

Time Of Day	***Required Throughput (ldg/hr/rwy)***	***Tolerances at FAP***	
		IM Tolerance (sec)	**FIM Equipment Tolerance (sec)**
7:00-8:00	**30**	12.3	**11.8**
8:00-9:00	**35**	11.0	**10.5**
9:00-19:00	**30**	17.7	**17.4**
19:00-20:00	**35**	15.2	**14.8**
20:00-22:00	**30**	26.3	**26.1**
22:00-7:00	**25**	23.1	**22.8**

For the most-stressing condition between 8-9am local time, i.e., the morning peak with relatively many Heavy aircraft compared to the evening peak, the required IM Tolerance and FIM Equipment Tolerance at the Planned Termination Point / FAP are 11.0 and 10.5 seconds respectively.

The IM Tolerance analysis (method 1) results in the following performance requirements:

1. For IM Operations at SPL, the IM Tolerance at the Planned Termination Point / FAP shall be equal to or less than 11.0 seconds.
2. For IM Operations at SPL, the FIM Equipment Tolerance at the Planned Termination Point / FAP shall be equal to or less than 10.5 seconds.

d. METHOD 2

An alternative method is proposed to derive the tolerances based on current day operations. In current day operations the aircraft are spaced at the beginning of the final approach, at approximately 8-10 NM from the threshold. The controller aims to deliver the aircraft at the minimum separation standard plus 1 NM, e.g. a Medium-Medium pair is delivered at 3+1=4 NM, a Heavy-Heavy pair at 5 NM and a Heavy-Medium pair at 6 NM.

The beginning of the final approach coincides with the Achieve-by Point / Intermediate Approach Fix (IF). Therefore, the tolerances are derived for this point.

The IM Tolerance is derived using the following steps (using Nominal Spacing Bounds criteria):

- The average spacing distance is computed assuming:
  - a representative aircraft-type mix for the operation.
  - a spacing distance of the minimum separation standard + 1 NM
- The average spacing time is determined based on a nominal airspeed at the Achieve-by Point and a design headwind component.
- The average spacing time is multiplied with a desired throughput that gives the minimum total time for all aircraft to cross the IF.
- The remaining total time is computed by subtracting the minimum total time from 3600 seconds.
- The remaining time per aircraft is determined by dividing the remaining total time by the desired throughput.
- The remaining time per aircraft is the 5% on the single side of the normal distribution, i.e. it is the 90% value of the normal distribution. The IM Tolerance is now computed by determining the 95% value of the normal distribution.

Similar steps are used for the Controller Intervention Threshold criterion. The differences are as follows: in step 1 the spacing distance is set at the minimum separation standard instead of the minimum separation standard + 1 NM and in step 6 the remaining time per aircraft is 0.1% to 1% instead of 5%. The analysis has shown that the most-stressing conditions are related to the Nominal Spacing Bounds, therefore only those results are discussed below.

The representative aircraft-type mix is given in Figure 18 and Figure 19. And the desired spacing distance is given in the table below.

Table 30: Desired distance spacing [NM] at the Achieve-by Point / IF

		Lead aircraft		
		Heavy	B757	Medium
IM aircraft	Heavy	5	5	4
	B757	6	6	4
	Medium	6	6	4

For 8-9am this results in an average distance spacing of 4.26 NM. For a conservative groundspeed at the IF of 165 kt (e.g., a nominal speed of 190 kt IAS and a design headwind of 25 kt), the average time spacing is 93.03 seconds. Given a desired throughput of 35 ac/hr, the total minimum time for these 35 aircraft is 35 times 93.03 = 3256 seconds.

This means that the 'remaining' total time is 344 seconds for the hour under consideration, and 9.83 seconds per aircraft.

Now assume an average Assigned Spacing Goal of 93.03 + 9.83 = 102.86 seconds to achieve the operationally required throughput of 35 ac/hr, the 9.83 seconds may be used as a measure for the tolerance on the lower side.
The operational requirement that the distance spacing between aircraft pairs should be at least the minimum separation distance plus 1 NM, 95% of the time, is used to derive the IM Tolerance. For an assumed normal distribution of the spacing error the single-sided 5% probability value should then be at least 9.83 seconds.
This corresponds to the 1.645σ value of the standard normal distribution. The IM Tolerance, being the 1.96σ value of the standard normal distribution, is calculated by multiplying 9.83 seconds with 1.960/1.645, the result is an IM Tolerance of 11.71 seconds. Similar to method 1, the FIM Equipment is computed using the root sum square method. For a conservative along path speed of 165 kt the Measured Spacing Interval Uncertainty is 3.11 seconds (Table 34 in APPENDIX B). The resulting FIM Equipment Tolerance for the 8-9am time period is 11.3 seconds.

Table 31 gives an overview of the maximum allowable tolerances at the Achieve-by Point / Intermediate Approach Fix (IF) for the various periods of the day when applying method 2.

Table 31: IM and FIM Equipment Tolerances at the Intermediate Approach Fix (IF)

Time Of Day	***Required Throughput (ldg/hr/rwy)***	***Tolerances at IF***	
		IM Tolerance (sec)	**FIM Equipment Tolerance (sec)**
7:00-8:00	**30**	17.5	**17.2**
8:00-9:00	**35**	11.7	**11.3**
9:00-19:00	**30**	24.2	**24.0**
19:00-20:00	**35**	16.4	**16.1**
20:00-22:00	**30**	36.2	**36.1**
22:00-7:00	**25**	40.8	**40.7**

For the most-stressing condition between 8-9am local time (the morning peak) the required IM Tolerance and FIM Equipment Tolerance at the Achieve-by Point / IF are 11.7 and 11.3 seconds respectively.

After executing the Fast-Time Simulations as described in Section 9 a need was determined to further refine method 2. Three elements are introduced for this refinement:

- A conversion from CAS to TAS, resulting in a conservative 5 knots increase of the assumed groundspeed at both IF and FAP.
- A nominal speed profile beyond the IF that includes a deceleration to cross the FAP at 160 knots IAS.
- A minimum distance of 4.0 NM between the Achieve-by Point and FAP.

For a slightly modified along path speed of 170 kt at the IF the Measured Spacing Interval Uncertainty is 3.04 seconds (Table 34 in APPENDIX B).

Table 32 gives an overview of the maximum allowable tolerances at the Achieve-by Point / Intermediate Approach Fix (IF) for the various periods of the day when applying the refined method 2.

Table 32: IM and FIM Equipment Tolerances at the Intermediate Approach Fix (IF) – refined method

Time Of Day	***Required Throughput (ldg/hr/rwy)***	***Tolerances at IF***	
		IM Tolerance (sec)	**FIM Equipment Tolerance (sec)**
7:00-8:00	**30**	13.6	**13.2**
8:00-9:00	**35**	10.4	**9.9**
9:00-19:00	**30**	21.5	**21.2**
19:00-20:00	**35**	15.9	**15.6**
20:00-22:00	**30**	35.6	**35.5**
22:00-7:00	**25**	36.0	**35.8**

For the most-stressing condition between 8-9am local time (the morning peak) the required IM Tolerance and FIM Equipment Tolerance at the Achieve-by Point / IF are 10.4 and 9.9 seconds respectively.

The IM Tolerance analysis (refined method 2) results in the following performance requirements:

3. For IM Operations at SPL, the IM Tolerance at the Achieve-by Point / IF shall be at most 10.4 seconds.

4. For IM Operations at SPL, the FIM Equipment Tolerance at the Achieve-by Point / IF shall be at most 9.9 seconds.

APPENDIX B MEASURED SPACING INTERVAL UNCERTAINTY

The State Data Quality performance requirements and assumptions have been specified in the FIM SPR [2,3]. The FIM SPR defines the minimum performance on the Target Aircraft surveillance and the IM Aircraft State Data Quality needed to support IM Operations.
The Measured Spacing Interval uncertainty (95%) attributed to surveillance and IM State Data Quality has been taken directly from the FIM SPR and is presented in the tables below.

Table 33 presents the Measured Spacing Interval uncertainty for the minimum State Data Quality referred to as Performance Level 1 and provide the Measured Spacing Interval uncertainty in time as a function of along-path speed, where speeds ranging from 100 to 350 knots.
Table 34 presents the Measured Spacing Interval uncertainty for State Data Quality referred to as Performance Level 2 when State Data Quality is better for horizontal position accuracy. The increased accuracy of horizontal position enables smaller Measured Spacing Interval uncertainties and hence supports tighter IM Tolerance values (i.e., horizontal position accuracy is 0.1 NM instead of 0.3 NM). Table 34 provides the Measured Spacing Interval uncertainty in time as a function of along-path speed, where speeds ranging from 100 to 350 knots.

Table 33: Measured Spacing Interval Uncertainty in Time (95%) due to State Data Quality (Performance Level 1, Speeds: 100 to 350 knots

Row #	Ownship or Surveillance Source	Error Source	Source Uncertainty (95%, except bias on rows 8, 14, and 20)	Spacing Uncertainty (Sec) as a function of Speed Along Path Speed (knots) 100	150	200	250	300	350
1	**Ownship** **(IM Aircraft)**	Horizontal Position Accuracy	0.3 NM	8.65	5.77	4.32	3.46	2.88	2.47
2		Latency - Compensated	3.0 sec latency with 10 m/s Hor. Vel. Acc.	0.47	0.31	0.23	0.19	0.16	0.13
3		Differential Latency - Uncompensated	0.5 sec	0.50	0.50	0.50	0.50	0.50	0.50
4		***Subtotal Ownship***	*(Root Sum Square)*	***8.68***	***5.80***	***4.36***	***3.50***	***2.93***	***2.52***
5	**ADS-B** **(Target Aircraft)**	Horizontal Position Accuracy	0.3 NM	8.65	5.77	4.32	3.46	2.88	2.47
6		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	2.0 sec. Tx, 7.0 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	1.74	1.16	0.87	0.69	0.58	0.50
7		Latency - Uncompensated Jitter	0.3 sec (95%)	0.30	0.30	0.30	0.30	0.30	0.30
8		Latency - Uncompensated Bias	0.3 sec bias	0.30	0.30	0.30	0.30	0.30	0.30
9		***Subtotal ADS-B***	*(RSS, except add latency bias)*	***9.13***	***6.19***	***4.72***	***3.84***	***3.26***	***2.84***
10		***Total ADS-B and Ownship***	*(RSS, except add latency bias)*	***12.68***	***8.56***	***6.51***	***5.28***	***4.46***	***3.88***
11	**ADS-R** **(Target Aircraft)**	Horizontal Position Accuracy	0.3 NM	8.65	5.77	4.32	3.46	2.88	2.47
12		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	3.0 sec. Tx, 10.0 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	2.71	1.81	1.35	1.08	0.90	0.77
13		Latency - Uncompensated Jitter	0.4 sec (95%)	0.40	0.40	0.40	0.40	0.40	0.40
14		Latency - Uncompensated Bias	0.3 sec bias	0.30	0.30	0.30	0.30	0.30	0.30
15		***Subtotal ADS-R***	*(RSS, except add latency bias)*	***9.37***	***6.35***	***4.85***	***3.95***	***3.35***	***2.92***
16		***Total ADS-R and Ownship***	*(RSS, except add latency bias)*	***12.85***	***8.68***	***6.60***	***5.35***	***4.53***	***3.94***
17	**TIS-B** **(Target Aircraft)**	Horizontal Position Accuracy	0.3 NM	8.65	5.77	4.32	3.46	2.88	2.47
18		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	3.25 sec. Tx, 12.1 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	3.40	2.26	1.70	1.36	1.13	0.97
19		Latency - Uncompensated Jitter	1.0 sec (95%)	1.00	1.00	1.00	1.00	1.00	1.00
20		Latency - Uncompensated Bias	0.75 sec bias	0.75	0.75	0.75	0.75	0.75	0.75
21		***Subtotal TIS-B***	*(RSS, except add latency bias)*	***10.09***	***7.02***	***5.50***	***4.60***	***4.00***	***3.59***
22		***Total TIS-B and Ownship***	*(RSS, except add latency bias)*	***13.50***	***9.29***	***7.20***	***5.95***	***5.13***	***4.55***
Col. #	1	2	3	4	5	6	7	8	9

Table 34: Measured Spacing Interval Uncertainty in Time (95%) due to State Data Quality (Performance Level 2, Speeds: 100 to 350 knots)

Row #	Ownship or Surveillance Source	Error Source	Source Uncertainty (95%, except bias on rows 8, 14, and 20)	Spacing Uncertainty (Sec) as a function of Speed Along Path Speed (knots) 100	150	200	250	300	350
1	**Ownship** **(IM Aircraft)**	Horizontal Position Accuracy	0.1 NM	2.88	1.92	1.44	1.15	0.96	0.82
2		Latency - Compensated	3.0 sec (95%), with 10 m/s Hor. Vel. Acc.	0.47	0.31	0.23	0.19	0.16	0.13
3		Differential Latency - Uncompensated	0.5 sec	0.50	0.50	0.50	0.50	0.50	0.50
4		***Subtotal Ownship***	*(Root Sum Square)*	***2.96***	***2.01***	***1.54***	***1.27***	***1.09***	***0.97***
5	**ADS-B** **(Target Aircraft)**	Horizontal Position Accuracy	0.1 NM	2.88	1.92	1.44	1.15	0.96	0.82
6		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	2.0 sec. Tx, 7.0 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	1.74	1.16	0.87	0.69	0.58	0.50
7		Latency - Uncompensated Jitter	0.3 sec (95%)	0.30	0.30	0.30	0.30	0.30	0.30
8		Latency - Uncompensated Bias	0.3 sec bias	0.30	0.30	0.30	0.30	0.30	0.30
9		***Subtotal ADS-B***	*(RSS, except add latency bias)*	***3.68***	***2.56***	***2.01***	***1.68***	***1.46***	***1.31***
10		***Total ADS-B and Ownship***	***(RSS, except add latency bias)***	***4.79***	***3.33***	***2.60***	***2.18***	***1.90***	***1.70***
11	**ADS-R** **(Target Aircraft)**	Horizontal Position Accuracy	0.1 NM	2.88	1.92	1.44	1.15	0.96	0.82
12		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	3.0 sec. Tx, 10.0 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	2.71	1.81	1.35	1.08	0.90	0.77
13		Latency - Uncompensated Jitter	0.4 sec (95%)	0.40	0.40	0.40	0.40	0.40	0.40
14		Latency - Uncompensated Bias	0.3 sec bias	0.30	0.30	0.30	0.30	0.30	0.30
15		***Subtotal ADS-R***	*(RSS, except add latency bias)*	***4.28***	***2.97***	***2.32***	***1.93***	***1.68***	***1.50***
16		***Total ADS-R and Ownship***	***(RSS, except add latency bias)***	***5.26***	***3.64***	***2.84***	***2.37***	***2.06***	***1.84***
17	**TIS-B** **(Target Aircraft)**	Horizontal Position Accuracy	0.1 NM	2.88	1.92	1.44	1.15	0.96	0.82
18		Latency - Compensated [Tx, Update Interval, Rx] [Assumes 0.1g accel./decel.]	3.25 sec. Tx, 12.1 sec. Update Int., 3.0 sec. Rx, with 10 m/s Hor. Vel. Acc.	3.40	2.26	1.70	1.36	1.13	0.97
19		Latency - Uncompensated Jitter	1.0 sec (95%)	1.00	1.00	1.00	1.00	1.00	1.00
20		Latency - Uncompensated Bias	0.75 sec bias	0.75	0.75	0.75	0.75	0.75	0.75
21		***Subtotal TIS-B***	*(RSS, except add latency bias)*	***5.31***	***3.88***	***3.19***	***2.79***	***2.54***	***2.37***
22		***Total TIS-B and Ownship***	***(RSS, except add latency bias)***	***6.19***	***4.47***	***3.64***	***3.16***	***2.85***	***2.64***
Col. #	1	2	3	4	5	6	7	8	9