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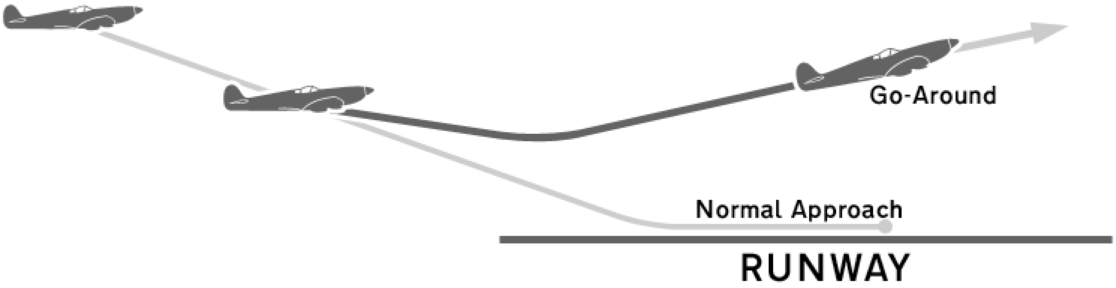
Technical Inventory for Go-around Detection (TIGARD)

Final Report



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Summary

There are situations where the detection of a missed approach (MA) or a go-around (GA) by the air traffic controller comes too late to assure that the procedure can be carried out without causing a conflict with other traffic movements. This is especially true for those situations where the notification of the go-around by the pilot comes late via R/T. Late awareness of a missed approach is a safety risk, especially when convergent runways are in use. For the pilot it is not the call to ATC but the safe navigation of the aircraft which has the highest priority when making a go-around. Thus, critical time may be lost to separate aircraft when the controller is unaware of a missed approach and is dependent of an R/T call by the pilot.

This study aims at finding a solution for assisting the air traffic controller in the timely detection of a missed approach or go-around. To this end, the study first has a look at the definition of a missed approach and a go-around, which comprises a description of the operational procedures associated with MA and GA and an identification of certain conditions and related indicators for MA and GA. Further, it describes the different types of sensor information that can be used to detect both the conditions and the indicators. The considered sensor information includes Mode-C, Surveillance Radar Data Processing Groundspeed, and Mode-S Flight Status (weight-on-wheels switch or strut switch). Other possibilities such as data from the runway incursion system RIASS and the radar tracker ARTAS are explored as well.

As a second step the study develops an algorithm that uses the sensor information in the most beneficial manner to timely indicate the initiation of MA and GA. A first indication of the time difference between initiation of the MA/GA and the possibility of detection is given. Possible shortcomings of the algorithm due to exceptional situations are explored and should be considered in a study that aims to further refine the algorithm and the detection thresholds.

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Abbreviation	**Description**
A/T	Auto Throttle
AAA	Amsterdam Advanced ATC
ADS	Automatic Dependent Surveillance
AGL	Above Ground Level
ALAR	Approach and Landing Accident Reduction
APP	Approach
ARTAS	ATM Radar Tracker and Server
ASTERIX	All Purpose Structured EUROCONTROL Automated Radar Information Exchange
ASTRA	Airport Surveillance Tracker
ATC	Air Traffic Control
ATCO	Air Traffic Controller
BDS	Binary Data Store
CAS	Calibrated Air Speed
CAST	Commercial Aviation Safety Team
CIR	Circular
CON	Continuous
CS	Certification Specification
DA	Decision Altitude
DH	Decision Height
EASA	European Aviation Safety Agency
ES	Extended Squitter
FAP	Final Approach Point
FCOM	Flight Crew Operating Manual
FCU	Flight Control Unit
FDM	Flight Data Monitoring
FL	Flight Level
FMS	Flight Management System
FSF	Flight Safety Foundation
GA	Go-around
GP	Glide Path
IAF	Initial Approach Fix
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization

IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
KLM	Koninklijke Nederlandse Luchtvaart Maatschappij
LVL CHG	Level Change (Autopilot Mode)
LVNL	Luchtverkeersleiding Nederland
MA	Missed Approach
MAPt	Missed Approach Point
MCP	Mode Control Panel
MDA	Minimum Descent Altitude
MDH	Minimum Descent Height
MLAT	Multi-lateration
M-SSR	Mono-pulse Secondary Surveillance Radar
NLR	Nationaal Lucht-en Ruimtevaartlaboratorium
NM	Nautical Miles
OEI	One Engine Inoperative
PANS-OPS	Procedures for Air Navigation Services - Aircraft Operations
PM	Pilot Monitoring
PNF	Pilot Not Flying
PSR	Primary Surveillance Radar
QNH	Pressure Normal Height (Altimeter Setting)
R/T	Radio/Telephony
RA	Radio Altitude
RIASS	Runway Incursion Alert System Schiphol
RWY	Runway
SOP	Standard Operating Procedures
SSR	Secondary Surveillance Radar
TAR	Terminal Approach Radar
TDOA	Time Difference of Arrival
TO/GA	Take-off Go-around
TRK	Tracker
UAT	Universal Access Transceiver
VDL	VHF Datalink
VFR	Visual Flight Rules

VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VNAV	Vertical Navigation (Autopilot Mode)

1 Introduction

1.1 Background

There are situations where the detection of a missed approach (MA) or a go-around (GA) by the air traffic controller comes too late to assure that the procedure can be carried out without causing a conflict with other traffic movements. This is especially true for those situations where the notification of the go-around by the pilot comes late via R/T. Late awareness of a missed approach is a safety risk, especially when convergent runways are in use. For the pilot it is not the call to ATC but the safe navigation of the aircraft which has the highest priority when making a go-around. Thus, critical time may be lost to separate aircraft when the controller is unaware of a missed approach and is dependent of an R/T call by the pilot.

This study aims at finding a solution for assisting the air traffic controller in the timely detection of a missed approach or go-around.

1.2 Project Scope and Objective

This study first has a look at the definition of a missed approach and a go-around, which comprises a description of the operational procedures associated with MA and GA and an identification of certain conditions and related indicators for MA and GA. Further, it describes the different types of sensor information that can be used to detect both the conditions and the indicators. The considered sensor information includes Mode-C, Surveillance Radar Data Processing Groundspeed, and Mode-S Flight Status (weight-on-wheels switch or strut switch). Other possibilities such as data from the runway incursion system RIASS and the radar tracker ARTAS are explored as well.

As a second step the study develops an algorithm that uses the sensor information in the most beneficial manner to timely indicate the initiation of MA and GA. A first indication of the time difference between initiation of the MA/GA and the possibility of detection is given. Possible shortcomings of the algorithm due to exceptional situations are explored and should be considered in a study that aims to further refine the algorithm and the detection thresholds.

1.3 Objective of Document

The present document presents all described elements of the project scope. It starts with a definition of the project approach. The first part of the analysis will look at the definition and associated procedures of MAs and GAs. The second part will look into indicators for MA and GA. In a third step, sensor capabilities are described. Finally, a first attempt will be made to define an algorithm for detection of MA/GA, which will give a first impression of the performance of a possible support tool in terms of timeliness and accuracy. Exceptional situations and their consequences for detection will be highlighted.

1.4 Project Approach

This project aims at finding a solution for assisting the air traffic controller in the timely detection of a missed approach (MA) or go-around (GA). To this end, the study first has a look at the definition of a missed approach and a go-around, which comprises a description of the operational procedures associated with MA and GA and an identification of certain conditions and related indicators for MA and GA.

From the definition of a MA and GA, indicators are identified that may be used in the detection of MA and GA. The usability of these indicators may vary during the different phases of the manoeuvre (and thus in time).

These indicators need to be available in the ground system. Thus, they will be provided by either a sensor system or another ground-based system. An initial assessment on the usability of these indicators for determining MA and GA will be performed. The usability of an indicator will depend on its quality attributes during the different phases of the approach and landing manoeuvre as well as the model in which it will be used for determining the GA or MA.

The quality attributes of interest are availability, accuracy, resolution, and timeliness.

Availability; is the indicator available in the target system and/or in all phases of the manoeuvre?

Accuracy; is a measure for the degree of closeness of the observations to the actual (true) value.

Resolution; is a measure of the detail in which the indicator is expressed.

Timeliness; is a measure for the response time or time-delay between a change (step change) in the actual (true) value and the observed resulting step change in the indicator.

An algorithm for determining a MA and/or GA will be developed based on the assumption that *any situation which is not a Missed Approach or Go-Around must be a landing.*

Therefore, when a model for the approach and landing manoeuvre can be defined, the measure of non-conformance of the observations with that model will be a measure of certainty for concluding that the observed aircraft is actually performing a MA or GA. Different models may need to be developed for different sets of indicators. It is further expected that the approach and landing manoeuvre will need to be divided into several distinctive phases and that in each phase a different model or set of indicators can be used.

As in all hypotheses testing, a decision based on a statistical test may be correct or erroneous. When erroneous, two types of error can be made: false positives and false negatives.

Table 1-1: Types of Error in MA/GA Detection

		Aircraft is actually performing a MA/GA	
		True	***False***
Non-conformance with landing model, i.e. conclude that aircraft is performing MA/GA	***False***	False Positive	Correct outcome
	True	Correct outcome	False Negative

Both error-types are undesirable, but from an operational point of view, one error type might be more undesirable than the other. This needs to be investigated, as it will have an effect on the choice of indicators/algorithm.

The operational acceptability of the algorithm for detecting MA/GA depends on its accuracy and timeliness. The accuracy is defined by the ratio of correct outcome versus false (positive and negative) outcome. The timeliness depends on whether the indication is in-time or too late. This needs to be assessed by operational experts. A dependency between timeliness and accuracy is expected.

Two datasets (system recordings) are provided by LVNL
1. A dataset with system recordings of flights performing a MA or GA,
2. A dataset with system recordings of flights performing nominal and non-nominal landing manoeuvres.

Of the first dataset, the exact actual time of initiating the MA/GA needs to be derived or retrieved as well and it needs to cover MA/GA in all phases of the approach and landing manoeuvre.

The strategy for developing an algorithm for detecting MA/GA is then defined as follows:
1. A (sub)set of available indicators is selected.
2. A model for a typical approach and landing is defined for this (sub)set of indicators. This model may take time or phase of the manoeuvre into account.
3. An observed dataset of indicators will be compared with the expected behaviour (the model) in time or phase. A difference (or non-conformance) between the observation and the model will be an indication that the aircraft is performing a MA or GA.
4. The measure of certainty by which a MA or GA can be detected will depend on the quality of the indicators.
5. It will be assessed in how far a variation of the non-conformance threshold will have an impact on the quality of the algorithm, i.e. accuracy and timeliness.
6. Different (sub)sets will be compared for their accuracy and timeliness in different phases of the landing manoeuvre.

Table 1-2: Simple Example for Algorithm Development

	Algorithm	***Simple Example***
1	A (sub)set of available indicators is selected.	*Use vertical rate information.*
2	A model for a typical approach and landing is defined for this (sub)set of indicators. This model may take time or phase of the manoeuvre into account.	*The model:* *The vertical rate is expected to be negative (i.e. descending) throughout the whole manoeuvre.*
3	An observed dataset of indicators will be used to compare with the expected behaviour (the model) in time or phase. A difference (or non-conformance) between the observation and model will be an indication that the aircraft is performing a MA or GA.	*For both datasets provided by LVNL:* *Use vertical rate, to compare with the model in each phase. When the vertical rate from the dataset exceeds a threshold, conclude MA/GA.*

4	The measure of certainty by which a MA or GA can be detected will depend on the quality of the indicators.	*Determine the effect of quality of indicators on the number of correct outcome vs. false positive and false negatives and timeliness of the algorithm. E.g. compare use of tracker algorithm vertical rate or Mode-S vertical rate.*
5	It will be assessed how varying the non-conformance threshold will have an impact on the quality of the algorithm, i.e. accuracy and timeliness.	*Determine the effect of varying the non-conformance threshold on the accuracy and timeliness of the algorithm. Use different thresholds; e.g. +100 ft/min +500 ft/min, etc.*
6	Different (sub)sets will be compared for their accuracy and timeliness in different phases of the landing manoeuvre.	*Compare result.*

2 Definition of Missed Approach and Go-around

2.1 Definitions

In order to assess the issue of ground based missed approach/go-around detection, it is first required to clearly define what is meant with "Missed Approach" and "Go-around". It is also required to define a number of terms related to the notion of missed approach or go-around.
These definitions are all based on common definitions as found in official ICAO documentation.

A general definition of the missed approach procedure is [ICAO PANS-OPS]:

> ***Missed Approach Procedure***. *The procedure to be followed if the approach cannot be continued*.

In general, it is found that the terms "missed approach" and "go-around" are used frequently as synonyms. However, from a formal viewpoint, the term "missed approach" is used if the approach is discontinued when an IFR approach is executed and the term "go-around" is used when the approach is discontinued from a VFR approach or the visual segment of an IFR approach.

Because the term "missed approach" or "go-around" is used in relation to discontinuation of the approach is important to define how the approach phase is formally defined.
In [CAST/ICAO Taxonomy] the approach is defined as:

> ***Approach:***
> *Instrument Flight Rules (IFR): From the Initial Approach Fix (IAF) to the beginning of the landing flare.*
> *Visual Flight Rules (VFR): From the point of VFR pattern entry, or 1,000 feet above the runway elevation, to the beginning of the landing flare.*

This definition of the notion "approach" widens the area where a missed approach can occur to substantial distance from the airport. For the present study the interest is focused on discontinuation of the final approach. For this reason the definition of approach in the present study is limited to the final approach, defined as follows:

> ***Final Approach:***
> *Instrument Flight Rules (IFR): From the Final Approach Fix (IAF) or Final Approach Point (FAP) to the beginning of the landing flare.*
> *Visual Flight Rules (VFR): From 1,000 feet above the runway elevation, to the beginning of the landing flare.*

As can be deduced from the above definitions, the approach phase ends at the initiation of the landing flare. This infers that formally the term missed approach or go-around cannot be used below the flare initiation altitude (usually between 30 and 50 ft AGL). However, in the context of the present study, it is also important to take into consideration the case when the landing is discontinued, because from the perspective of ATC controller situational awareness, this case is at least of equal importance as the missed approach case.

In the [CAST/ICAO Taxonomy] the landing phase is defined as:

> ***Landing:***
> *From the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing.*

Discontinuation of the landing is commonly referred to as a balked landing [ICAO CIR 301, AN/174], defined as:

> ***Balked Landing*:**
> *A landing manoeuvre which is unexpectedly discontinued.*

Other terms that are sometimes used to describe the discontinuation of a landing are rejected landing or aborted landing [Airbus]:

> ***Rejected Landing or Aborted Landing:***
> *A go-around manoeuvre initiated after touchdown of the main landing gear or after bouncing.*

Although not specifically stated, a rejected landing is regarded as an unexpected discontinuation of the landing. In case the discontinuation is pre-planned it is considered to be a touch-and-go landing, i.e.:

> ***Touch-and-go Landing:***
> *A pre-planned go-around manoeuvre initiated after touchdown of the main landing gear.*

Based on the given definitions the concept of "go-around detection" in the present project is scoped to include the following:

- The missed approach (limited to the final approach phase);
- The go-around (limited to the final approach phase);
- The balked landing;
- The rejected/aborted landing;
- Touch-and-go[1].

2.2 Operational Procedures for Missed Approach and Go-around

The go-around and missed approach is flown using the Go-Around and Missed Approach procedure as described in the Flight Crew Operating Manual (FCOM). These procedures can differ somewhat per aircraft type/manufacturer, depending also on available equipment, avionics, engine type etc.
However, in general the basic elements of the manoeuvre are more or less similar. Here, a generic description is given, based on a frequently used aircraft type.
In Figure 2-1 an example Go-around/Missed Approach procedure is depicted.

In general the following cases are discriminated:

- Go-Around and Missed Approach – All Engines Operating
- Go-Around and Missed Approach – One Engine Inoperative
- Go-Around After Touchdown

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[1] By including touch-and-go within the scope this manoeuvre will inherently be identified as a "go-around", although it concerns a planned manoeuvre (e.g. for training purposes). Acceptability of this approach needs feedback from ATCOs.

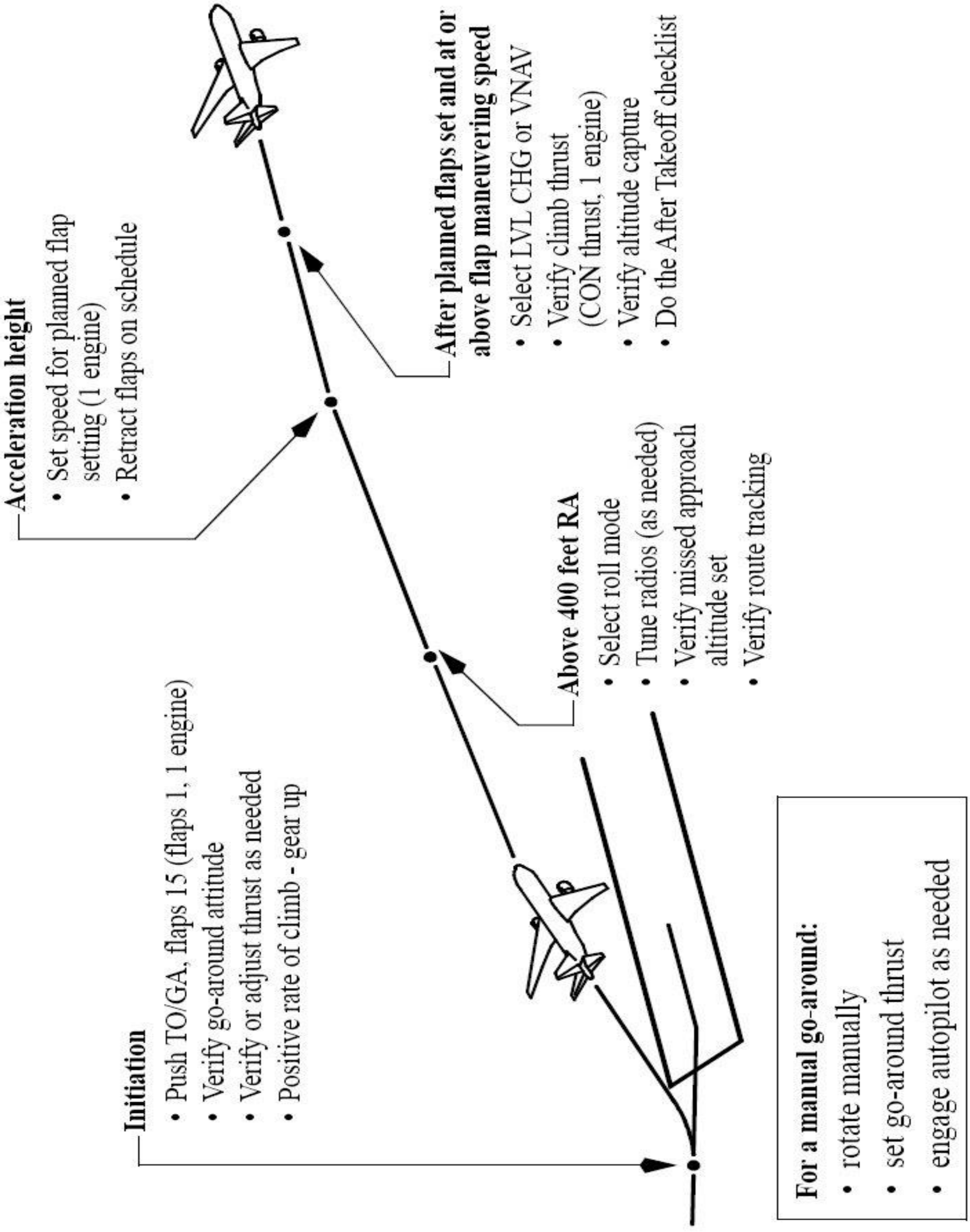

Figure 2-1: Example for a Go-around/Missed Approach Procedure

Go-Around and Missed Approach – All Engines Operating

The go-around and missed approach procedure is generally performed in the same manner whether an instrument or visual approach is flown.
The initiation of a go-around is normally initiated by pushing the TO/GA button, and subsequently selecting the appropriate go-around flap setting. The pilot needs to verify that GA thrust is applied, either automatically in case the A/T is engaged or manually.
At positive rate of climb the gear is selected up.

After go-around initiation the aircraft is initially pitched up to a go-around pitch attitude (maximally in the range 15 – 18 degrees, but close to the ground this may be less). Thereafter, the pitch mode transitions to speed control as the rate of climb increases (by means of speed-on-elevator). Usually the controlled speed must be at least V[2]$_2$ + 10 kts. When the aircraft is flown in speed-on-elevator mode, the resulting climb rate is undetermined, and depends on the available GA thrust, aircraft weight and configuration. However, in many aircraft the achievable climb rate is limited to 2000 ft/min during the go-around. When this limit is reached, excess power is used to further accelerate, while maintaining the established climb rate. In case the selected missed approach altitude is fairly close to the go-around initiation altitude, maximum achieved climb rate may be further reduced in order to avoid overshooting the go-around altitude.

Laterally, most aircraft are controlled to maintain either the heading or track angle, memorized at TO/GA initiation, until at least reaching 400 ft RA. Thereafter an appropriate roll mode is selected, to guide the aircraft along the required missed approach track. It is a pilot task to verify route tracking

At acceleration height flaps are further retracted, and the aircraft will accelerate to a speed associated with the selected flap setting. The acceleration height is specified based on safety, obstruction clearance, airplane performance or noise abatement requirements. A common value is 1000 ft.

Go-Around and Missed Approach – One Engine Inoperative

The procedure for go-around and missed approach in case of one engine inoperative (OEI) is very similar to the procedure for all engines operating. Differences are mainly due to the fact that OEI approaches are usually performed at a reduced flap setting, and during the go-around lower flap settings are used in order to reduce drag. Clearly during an OEI go-around the achievable climb rate is reduced. In many cases it is possible to select full thrust for a limited period of time by means of pressing TO/GA a second time. This will increase climb performance. Many modern aircraft will be able to achieve a 1000 ft/min climb rate OEI. However, clearly there are aircraft that are not able to achieve this. A minimum requirement [EASA CS25.121] is that at least a climb gradient of 2.1% can be achieved (at 160 kts CAS this is around 350 ft/min).

Go-Around and Missed Approach after Touchdown

If a go-around is initiated before touchdown and touchdown occurs during the manoeuvre usually a normal go-around procedure is performed.

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[2] V_2 is the minimum climb speed that must be reached at a height of 35 ft above the runway surface, in case of an engine failure

If a go-around is initiated after touchdown but before thrust reverser selection, usually speed brakes are automatically retracted and auto brakes (if available) disarmed as thrust levers are advanced. Subsequently a normal go-around procedure is performed.

Once reverse thrust has been initiated following touchdown, a full stop landing must be made. Safe flight is not possible when the engine remains in reverse.

2.3 Normal Approach Characteristics and Stable Approach Criteria

Normal Approach Characteristics
In the context of the present project it is important to be able to find parameters and associated criteria that are suited to make a clear distinction between a normal approach and a missed approach. For this reason it is relevant to define the characteristics of a normal approach.

First of all, a distinction has to be made between a precision and non-precision approach. A precision approach is characterized by provision of both lateral and vertical guidance, usually by means of the ILS system.
Due to the provision of vertical guidance the aircraft can be actively guided downwards to the decision altitude/height, which is defined as follows:

> ***Decision altitude (DA) or decision height (DH).***
> *A specified altitude or height in the precision approach or approach with vertical guidance at which a missed approach must be initiated if the required visual reference to continue the approach has not been established.*

This implies that once at the DA/DH the visual requirements are not met, directly a missed approach must be initiated from the descend path to the missed approach trajectory. This will lead to some height loss from the missed approach initiation height (30 – 50 ft). It will also lead to a rapid change from the initial descent rate to the missed approach climb rate. Normally, the average descent rate at the glide path is around 700 ft/min, with a range of roughly ±300 ft/min.
Therefore, the initiation of a missed approach from a precision approach at or before DH/DA will be characterised by a rapid change in vertical velocity of roughly 1000 ft/min at least. This may therefore be a good indicator to determine the missed approach initiation.

For a non-precision approach the situation is different, though. A non-precision approach is flown without vertical guidance, but by means of a step-down procedure to a minimum descent altitude/height, which is defined as follows:

> ***Minimum descent altitude (MDA) or minimum descent height (MDH)***.
> *A specified altitude or height in a non-precision approach or circling approach below which descent must not be made without the required visual reference.*

Upon reaching the MDA/MDH it is not required to initiate a missed approach, because level flight at this altitude/height may be continued until reaching the so-called missed approach point, which is defined as:

> ***Missed approach point (MAPt).***
> *That point in an instrument approach procedure at or before which the prescribed missed approach procedure must be initiated in order to ensure that the minimum obstacle clearance is not infringed.*

Therefore a non-precision approach may include level segments during the final approach. So, initiating a missed approach from a non-precision approach may lead to a substantially less distinct change in vertical velocity.
Consequently, for a missed approach detection algorithm, using vertical velocity as indicator, it might be more problematic to identify missed approaches initiated from a non-precision approach[3].

Stable Approach Criteria
Most standard operating procedures (SOPs) of airline operators include definition of stable approach requirements. When such requirements are not met at a given altitude, a missed approach has to be initiated. For any missed approach identification concept, it is important to be aware of these requirements, as they constitute boundaries within which a normal and stable approach procedure should be executed.

Usually the stable approach requirements are derived from, or similar to, the requirements, as derived by the Flight Safety Foundation in their ALAR (Approach and Landing Accident Reduction) research.

The relevant recommendations of the FSF ALAR study are as follows.

The minimum stabilization height to achieve a stable approach is:

- 1000 ft above airport elevation in instrument meteorological conditions (IMC); or
- 500 ft above airport elevation in visual meteorological conditions (VMC)

At the minimum stabilization height and below, a call should be made by the pilot not flying/pilot monitoring (PNF/PM) if any flight parameter exceeds the established criteria. Any time an approach is not stabilized at the minimum stabilization height or becomes non-stabilized below the minimum stabilization height, an immediate go-around must be initiated.
Characteristics of a stable approach are:

- Airspeed between V_{ref} and V_{ref} + 20 kts IAS;
- Aircraft is in the correct landing configuration;
- Sink rate is not greater than 1000 ft/min;
- Instrument Landing System (ILS) approaches must be flown within one dot[4] of the glide slope and localizer.

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[3] Because at Schiphol the large majority of approaches are precision approaches, it could be reasoned that some increased propensity of non-precision approaches for nuisance go-around identification is potentially acceptable.

[4] This is a measure for the deflection of glide slope and localizer, which is shown as dots on the cockpit indicators.

3 Indicators for Missed Approach and Go-around

3.1 Procedural Indicators

Based on the generic MA/GA procedure as described in Chapter 2.2 the following procedural indicators for missed approach initiation can be identified:

- Activation of the TO/GA button;
- Retraction of the gear;
- Retraction of the flaps;
- Application of go-around thrust;
- Thrust reverser activation.

3.2 Necessary Aircraft State Vector Conditions

The state vector of an aircraft is in general determined by four elements, each consisting of three components to define the aircraft motion in three dimensions, relative to an earth fixed reference axes system.
The elements of are:

- Position: [x,y,z];
- Velocity: [u,v,w];
- Attitude: [ψ,θ,φ];
- Angular rates: [p,q,r].

Clearly other definitions of the state vectors are possible, but they will always be transformations of the above defined state vectors. Specific output vectors can always be made by combining the state vector elements.

To determine the aircraft motion relative to the air, also the state vector of the atmospheric conditions needs to be defined.
This environmental state vector can be defined as follows:

- Windspeed: [u_w,v_w,w_w];
- Temperature: [T];
- Pressure at sea level: [P0];
- Lapsrate: [λ]

In addition to the state vectors that determine the aircraft motions, also a state vector defining the aircraft characteristics can be defined.
The aircraft configuration state vector is here defined as:

- Aircraft type
- Aircraft weight
- Flaps/Slats
- Gear
- Thrust reverser (if equipped)
- Air/Ground switch

If the motion of the aircraft is to be determined relative to a specific runway, also the characteristics of this runway need to be known, in particular:

- Runway direction
- Location of the threshold
- Runway length
- Location of the ILS GP and Localizer transmitters.

In the context of go-around detection specific state parameters, derived from above mentioned state vectors, are of interest.
The following parameters have been identified:

- Position
- Vertical velocity
- Airspeed
- Groundspeed
- Barometric altitude (QNH)
- Height above ground
- Distance to threshold
- Distance to departure end of runway
- Position (lateral and vertical) relative to the nominal glide path
- Track angle
- Pitch angle
- Aircraft type

4 Sensor Capabilities

4.1 Detection of Procedural Indicators

4.1.1 Description of Available Sensors

In Chapter 3.1 a list is provided of potential procedural parameters that can be used to identify go-around initiation.
However, based on the previous paragraphs it is clear that no surveillance system exists today that is able to observe these procedural parameters on ground.

4.1.2 Description of Sensor Capabilities

Not applicable.

4.1.3 Observability of Procedural Indicators

Although procedural indicators would most likely be the strongest indicators to identify go-around indication, their application in ground-based go-around detection is currently considered to be not feasible.

4.2 Detection of State Vector Conditions

4.2.1 Description of Available Sensors

The surveillance sensors that are available today can be listed according to the technique used by the sensor to detect an object.

The following classes can be distinguished:

<u>Primary detection (PSR)</u>
The principle of the primary (surveillance) radar (PSR) is based on the principle of receiving back an earlier transmitted signal by that same radar. The target does not have to be fitted with specific equipment to be detected by the PSR; therefore PSR is also called a non-cooperative sensor.

Present as part of the combined radars: Luik, TAR-4
Present as part of the Mode-S combined radars: Leeuwarden, Soesterberg, Twente, Volkel, Woensdrecht, Bertem, Nordholz, Debden

<u>Secondary detection (SSR)</u>
The principle of the secondary (surveillance) radar (SSR) is based on the principle of receiving back a reply to an earlier transmitted signal by that same radar. The difference with primary radar is that SSR radar interrogates a transponder onboard the aircraft. When the transponder is not responding, the aircraft will be invisible to the SSR radar. Therefore, SSR radar is also called a cooperative sensor.

Present as part of the combined radars: Luik, TAR-4

<u>Mono-pulse Secondary detection (M-SSR)</u>
Mono-pulse Secondary (Surveillance) Radar (M-SSR) is an improved version of the SSR. The improvement lies in the better azimuth accuracy and therefore a better overall accuracy.

Selective Interrogation detection (Mode-S)
Mode-S (S stands for Selective Interrogation) radar is an extension to the (M)SSR; Mode-S radar also interrogates a transponder, but it is capable to interrogate only specific selected aircraft based on a calling list and performing a Roll-Call interrogation. Mode-S radars are still able (and need to do so to build up the calling list) to interrogate all aircraft using an All-Call interrogation.

Present: Eelde, TAR-1, Den Helder, MLT, Dusseldorf, Boulogne
Present as part of the Mode-S combined radars: Leeuwarden, Soesterberg, Twente, Volkel, Woensdrecht, Bertem, Nordholz, Debden

Automatic Dependent Surveillance detection (ADS)
An ADS-B-out equipped aircraft determines its own position using a global navigation satellite system and periodically broadcasts this position and other relevant information to potential ground stations and other aircraft with ADS-B-in equipment. ADS-B can be used over several different data link technologies, including Mode-S Extended Squitter (1090 ES), VHF data link (VDL Mode 4), and Universal Access Transceivers (UAT).

Present: WNZ

Multi-Lateration detection (MLAT)
The principle of Multi-Lateration is based on the fact that a signal, emitted by a transmitter is returned by an object and the returns are received by multiple receivers. Based on the time difference of arrival (TDOA) of the reflections at the different receivers, the position of the object can be determined by a central Multi-Lateration system that processes the information from the receivers. There should be at least 4 receivers and they may be spread over an area ranging from a few meters to several kilometres.

Present: MLT, WNZ

Tracked detection (TRK)
Several tracker systems exist, which take as input the information from several sensors and compute the best possible position of an object, taking into account the fact that the sensor information is only partial, incorrect or biased. The way that a tracker is performing the combination of input data can vary and a rough division between systems based on the way they compute the object position can be made along the following principles:

- build intermediate tracks (one per object per sensor) and select the ‘best’ track as the tracked position of the object
- build intermediate tracks (one per object per sensor) and perform a weighting / averaging algorithm to compute the tracked position of the object
- build one single system track per object which is updated with the information from all sensors using a plot-to-track association algorithm

Present: ARTAS, ASTRA

4.2.2 Description of Sensor Capabilities

The technique to detect an aircraft strongly defines the capabilities of the sensor. Therefore, below, we will define the various capabilities that are present for the different detection techniques, the advantages and disadvantages.

PSR
Primary radar data provides only a timestamp (the time the radar has detected the object), a range (shortest distance from radar to object), and azimuth (the angle, normally relative to the North, at which the object is detected).

Note that some types of radar (not only PSR radars, but also other types of radar) provide some basic tracking function inside the radar itself. These radars are then called local trackers producing local tracks which have an X and Y position (relative to the radar position) as well as a ground speed and a course.

The advantage of PSR radar is that the detection will work with any aircraft, regardless of the type of equipment available in the aircraft and whether that equipment is working properly or not.

The disadvantage of the PSR radar is that no identification of the object is obtained, nor is a credible height of the object provided.

Accuracy of PSR radar is normally between 50-100m for range and 0.1-1.5 degrees for azimuth (note that the azimuth accuracy decreases as the range increases).

SSR
Secondary radar data provides the same information as PSR radar (time, range, and azimuth) as well as Mode-A and Mode-C information.

The advantage of the SSR radar is the presence of Mode-A information, as this provides identification of the aircraft (unique within a certain time frame and area), and the presence of Mode-C information, as this provides relative height information based on the measured air pressure.

The disadvantage of the SSR radar is that the aircraft becomes invisible if the SSR-transponder onboard the aircraft is not working. The usage of the SSR-transponder reply may lead to interference between aircraft in close proximity, so that the Mode-A and/or Mode-C values can become garbled. Furthermore, the Mode-C height does not provide an absolute height where the ground height corresponds to a fixed Mode-C value.

Accuracy of SSR radar is normally between 50-100 m for range and 0.1-1.5 degrees for azimuth (note that the azimuth accuracy decreases as the range increases), the resolution of the Mode-C height is 100 ft, but the accuracy depends on weather conditions.

M-SSR
M-SSR provides the same information as SSR radar.

The advantage of the M-SSR radar is the higher accuracy in azimuth and the fact that fewer transponder interrogations are used (compared to SSR radar) due to which garbling of codes diminishes.

Accuracy of M-SSR radar is normally between 50-100 m for range and 0.1 degrees for azimuth (note that the azimuth accuracy decreases as the range increases), the resolution of the Mode-C height is 100 ft, but the accuracy depends on weather conditions.

Mode-S

Mode-S radar data provides the same information as SSR radar (time, range, azimuth, Mode-A, and Mode-C) as well as a Mode-S code and so-called BDS registers.

The advantage of the Mode-S radar is the presence of a Mode-S code which (theoretically) is unique for an aircraft, this way providing a one-to-one identification of radar data to object. Furthermore, the BDS register can provide a (pre-defined) (sub)set of information from the Flight Management System of the aircraft itself.

The disadvantage of Mode-S radar is the fact that the interrogation of the BDS registers has to be defined in the radar itself and if the radar does not interrogate a specific BDS register, although the aircraft’s transponder is capable of delivering that register, the information will not be provided by the transponder and therefore not be available in the radar data. Furthermore, there is no indication in the BDS registers at which time the data was applicable.

Accuracy of Mode-S radar is normally between 50-100 m for range and 0.1 degrees for azimuth (note that the azimuth accuracy decreases as the range increases), the resolution of the Mode-C height is 25 ft, but the accuracy depends on weather conditions.

ADS

ADS provides a satellite based position (WGS84), an ICAO 24-bit address (this is equal to the Mode-S code) as well as information from the Flight Management System via BDS registers.

ADS provides an absolute height reference via the WGS84, so the ground height is a fixed value for a certain location on earth in the WGS84 system. Furthermore, ADS information is broadcasted by the aircraft itself at a rate of normally one report per second and ADS does not rely on interrogation.

A disadvantage of the ADS system is the absence of a time stamp at which the data is applicable; this holds for the position as well as the information in the BDS registers. The timestamp of an ADS report is attached to the message by the ADS ground station and therefore may be significantly different from the time of appliance of the data.

The accuracy of ADS data is very much relying on the satellite system used; for GPS valid position figures are: within 2.5m 50% of the time and within 7m 95% of the time.

MLAT

MLAT makes use of SSR or Mode-S transponders. This means that MLAT can provide time, 2D-position, height (geometric), Mode-A, Mode-C, Mode-S, and BDS registers. Furthermore, the MLAT system can compute its own geometric height.

As MLAT can provide up to hundreds of reports per second, the update rate is very high, but in real-world systems an update rate of around 1 update per second is common.

The disadvantage of the MLAT system is the poor geometric vertical position accuracy at higher levels and the non-uniform accuracy in horizontal position (accuracy is very much depending on the positioning of receivers and the relative position of the object with respect to these receivers).

The accuracy of MLAT can be in the order of meters in core areas of the MLAT system.

Tracking

A tracking system normally outputs a state vector for each object. The state vector normally has the following components (based on the ARTAS TRK):

- X, Y position
- Height (barometric and/or geometric)
- Course
- Ground Speed
- Transversal Acceleration
- Rate of Climb/Descent
- Mode-A, Mode-S identification
- Mode of Flight

Furthermore, the tracker is also capable of producing bias information and accuracy information on the sensors.

The advantage of a tracking system over individual sensors lays in the capability of the tracker to estimate the biases on the individual sensors and complete the (partial) information of one sensor with the (partial) information of another sensor. The estimated position by the tracker should not be worse than the best sensor available, but normally it is expected to be better.

The disadvantage of a tracker system is related to the processing time needed by the tracker to compute the tracked object state.

The actual accuracy of the tracker depends on the accuracy of the input sensors and the number of sensors covering the particular area where the object is located.

The frequency with which the track is updated can vary; sometimes a tracker has several modes in which it can output the data. The ASTRA and ARTAS tracker both have three modes:

- Periodic output:
  the complete air situation picture is refreshed after a specific delay; this delay can be defined by the user of the system.
- Synchronized output:
  the air situation picture is refreshed sector by sector, in sync with the actual rotation of a specific radar; this radar can be defined by the user of the system.
- A-periodic output:
  the air situation picture is updated immediately as the tracker has computed a new position for a track somewhere in the coverage of the tracker. There is no relation in time or place between one update and the next one.

4.2.3 Observability and Applicability of the State Vector

In Chapter 3.2 a list is provided of potential state vector parameters that can be used to identify go-around initiation.
Based on the inventory provided in the previous two paragraphs each of these parameters will be assessed, in relation to observability by ground-based sensors, and the associated feasibility of application in a go-around detection algorithm.

Identification
Identification is important to be able to analyse the profile of a single aircraft without mixing updates from other aircraft with the current aircraft under investigation.

Identification is provided by all sensors except the PSR sensors, although different sensors may provide different type of identification. The tracker is a special case in that it tries to link the different identification codes into one single track. Identification becomes more trustworthy from SSR/M-SSR – Mode-S/MLAT/ADS – Tracker.

For sensors other than PSR, identification is **(very) well** observable and usable.

Position
The position of the aircraft is needed to compute the distance to runway and runway related aeronautical elements like runways start, runway end, thresholds, etc.

Position is provided by all sensors, but not all sensors provide position in a sensor independent metric. Given some sensor position information, all position information given by any sensor can be translated into an integrated common reference system.

Position is **very well** observable and usable.

Vertical velocity
The vertical velocity can be used to determine whether a given vertical speed threshold is crossed (beginning an indicator for a go-around indication).

For SSR, M-SSR, Mode-S and MLAT sensors, vertical velocity may be derived from the height information, although the accuracy may become too low.
For Mode-S, ADS, and MLAT systems, the vertical velocity may be extracted from BDS register 6.0 (Barometric Altitude Rate and Inertial Vertical Velocity).

For Tracking, the tracker provides the vertical rate (Rate of Climb/Descent) as part of the track state vector.

For sensors Mode-S, ADS, MLAT, and tracker, vertical velocity is **(very) well** observable and usable.

Airspeed
The Airspeed can be used in stable approach criterion, and after touchdown to establish crossing of low speed boundary.

Air speed is only provided in the BDS registers BDS 5.0 (True Airspeed) and BDS 6.0 (Indicated Airspeed)

The airspeed is **only available in BDS** registers and the usability may be **highly dependent** on the presence and quality of wind information.

In BDS register BDS 4.4 wind speed, wind direction and turbulence are available.
For sensors Mode-S, ADS, MLAT, and tracker, selected altitude is **poorly** observable and **well** usable. BDS register 4.4 is currently not interrogated by LVNL sensors.

Groundspeed
The Groundspeed can be used in stable approach criterion, and after touchdown to establish crossing of low speed boundary.

Groundspeed is available from local trackers, from the BDS registers BDS 5.0 (Ground Speed) and from the tracker. For the other sensors, the groundspeed may be derived from position.

For sensors Mode-S, ADS, MLAT, and tracker groundspeed is **(very) well** observable and usable. For all other sensors groundspeed is **well** observable and usable.

Barometric altitude
Barometric altitude can be used to determine flight phase, calculate vertical speed by calculating the change over several measurements, and go-around identification after touchdown.

Barometric height is available for SSR, M-SSR, Mode-S, MLAT, and tracker sensors.

Barometric height can only be used to determine the height above ground when the QNH value is known.

For sensors SSR, M-SSR, Mode-S, ADS, MLAT, and tracker, barometric altitude is **well** observable and usable.

In BDS register BDS 4.0 also selected altitude (MCP/FCU and FMS) are available which can be used for the intended height of the aircraft. For sensors Mode-S, ADS, MLAT, and tracker, selected altitude is **poorly** observable and **well** usable.

Height (above ground)
Height can be used to determine vertical deviation from nominal glide slope, flight phase, calculate vertical speed by calculating the change over several measurements, and go-around identification after touchdown.

Height is only provided by ADS, MLAT, and tracker sensors.

For sensors ADS, MLAT, and tracker, height is **(very) well** observable and usable.

Distance to threshold
The distance to threshold can be used for flight phase definition and to determine angular glide slope/localizer deviation.

The distance to threshold is determined based on the runway information and the position of the aircraft. Therefore, observability and usability depend solely on the observability and usability of the position parameter.

Distance to departure end of runway
The distance to departure end of runway can be used to identify low go-around.

The distance to departure end of runway is determined based on the runway information and the position of the aircraft. Therefore, observability and usability depend solely on the observability and usability of the position parameter.

Position (lateral and vertical) relative to the nominal glide path
The position relative to the nominal glide path can be used to identify the stable approach criterion.

The relative position is determined based on the runway information and the position of the aircraft. Therefore, observability and usability depend solely on the observability and usability of the position parameter.

Track angle
The track angle can be used to identify lateral deviation.

The track angle is available from local trackers, the BDS registers BDS 5.0 (True Track Angle) and from the tracker. For the other sensors, the track angle may be derived from two consecutive positions.

For sensors Mode-S, ADS, MLAT, and tracker track angle is **(very) well** observable and usable. For all other sensors, track angle is **well** observable and usable.

Roll angle
The roll angle can be used to identify lateral deviation.

The roll angle is available from the BDS registers BDS 5.0 (Roll Angle).

The roll angle is **only available in BDS** registers.

For sensors Mode-S, ADS, MLAT, and tracker, roll angle is **poorly** observable and **well** usable.

The tracker does compute a turn rate which can be used for the same purpose and is **very well** observable and usable.

Pitch angle
The pitch angle can be used to determine whether an aircraft starts to climb fast (beginning an indicator for a go-around indication).

No sensor is capable of detecting this parameter and therefore this parameter is **not** observable or usable.

Aircraft type
The aircraft type potentially can relate airspeed deviations to aircraft reference speed.

The aircraft type might be obtained when the Mode-A code of the aircraft can be related to the flight plan. However, having the correlation to the flight plan still does not give information about the actual weight carried by the aircraft.

Mode-A is provided by SSR, M-SSR, Mode-S, ADS, MLAT and tracker sensors.

For these sensors aircraft type is **poorly** observable and usable.

Aircraft type is also available in BDS register BDS 2.5 where aircraft type, engine type and model designation are present. For sensors Mode-S, ADS, MLAT, and tracker aircraft type is **poorly** observable and **well** usable (register BDS 2.5 is currently not interrogated by the LVNL sensors).

4.3 Conclusions for Optimum Use of Sensors

Given the LVNL situation wanting to detect go-around around the Schiphol airport, the following sensors cannot be used as they have no coverage over Schiphol:

- Eelde
- Dusseldorf
- Nordholz
- Luik
- Debden

Sensors which are situated somewhat further away from Schiphol airport, but having sufficient coverage for the approach phase are (type and revolution time in brackets):

Den Helder	(Mode-S, 6.00 s)
Leeuwarden	(Combined Mode-S, 4.00 s)
Volkel	(Combined Mode-S, 4.00 s)
Woensdrecht	(Combined Mode-S, 4.00 s)

Sensors that have excellent coverage over Schiphol airport and/or the runways are:

MLT	(Mode-S, 4.00 s)
TAR-1	(Mode-S, 4.19 s)
TAR-4	(Combined, 4.05 s)
Soesterberg	(Combined Mode-S, 4.00 s)
ARTAS tracker	(for APP: TAR-1 synchronized service)

From the observations in Chapter 4.2, the observation can be made, that the tracker is the best sensor to be used.

For almost all parameters, the tracker is capable of providing the information. Furthermore, the advantage of the tracker is also that possible errors of a particular sensor in a single measurement (so-called outliers) can be detected and ignored/corrected as well as biases that can be present in the measurements of the various sensors.

The usage of tracker data comes at the price of some delay due to the processing. Looking at the LVNL situation, the total delay from sensor detection to track update can increase up to 2-3 seconds. The tracker itself is responsible for approximately 0.5 second when taking into account only the sensors that have good visibility on approach and lading areas.

If these 2 second delays become critical, using directly the plots of sensors in parallel to the usage of track data might decrease the elapsed time between the start of a go-around procedure and the detection by the algorithm. However, in that case the sensor data needs to be handled with care due to stochastic and systematic errors than can be present on the data.

Based on the assumption that the tracker output is used as input for the algorithm, Table 4-1 provides an overview of criteria that are usable. The ARTAS system outputs its data in the so-called ASTERIX format for category 030. The resolutions are taken from this output format.

Note that due to the fact that the tracker is producing a synchronized service, updates from the ARTAS system are always received with a 4.19 s interval.

Internally however, the individual sensors may provide information at a different (higher) rate and the ARTAS system internally processes this information at the rate the information is provided. This means that for, for instance, MLT, each ARTAS update is supported by 1 MLT update, but once in every 22 updates, two MLT updates have been processed between two consecutive ARTAS updates.

Furthermore, BDS registers are only available (by ARTAS design) for the radar that is the synchronized source. This means that BDS registers are only retrieved from TAR-1 data (still at a rate of 4.19 s).

Table 4-1: Overview of Sensor Capabilities

Item	**Accuracy**[*]	**Resolution**	**Update Rate [s]**
Identification: Mode-A	-	1	4.19
Identification: Mode-S	-	1	4.19
Identification: Aircraft Address	-	1	4.19
Position (X, Y)	Estimate in I030/110	1/64 NM ≈ 28.9m	4.19
Vertical Velocity	Estimate in I030/230	$(½)^{10}$ FL/s ≈ 5.86 ft/min	4.19
Airspeed	Aircraft dependent	2 kts	4.19 (BDS 5.0)
Groundspeed	Estimate in I030/190	$(½)^{14}$ NM/s ≈ 0.22 kts	4.19
Barometric Altitude	Estimate in I030/165	¼ FL + indication QNH corrected	4.19
Height	Estimate in I030/135	¼ FL + indication height source	4.19
Track Angle	Estimate in I030/190	$360^{\circ} / 2^{14} \approx 0.0055^{\circ}$	4.19
Turn Rate	Estimate in I030/250	¼ °/s	4.19
Roll Angle	Aircraft dependent	$45/256^{\circ} \approx 0.18^{\circ}$	4.19 (BDS 5.0)
Pitch Angle	-	-	-

[*] I030 is referring to ASTERIX category 30 and is followed by a field number

5 Algorithm Development

5.1 High Level Algorithm Description

The core of the algorithm for detecting MA/GA, as is described in Chapter 5.4, will use one indicator or a set of indicators that will be compared to a threshold. An exceedance of the threshold will either directly or after some time delay lead to the detection of an MA/GA. The system built around this core will need to make several decisions based on the available data before reaching the core. It is foreseen that the following steps will need to be made:

1. Data acquisition
2. Determine eligibility of flight
3. Determine approach type
4. Determine phase of flight
5. Selection of indicator(s) and model
6. Compute non-conformance
7. Indicate MA/GA detection

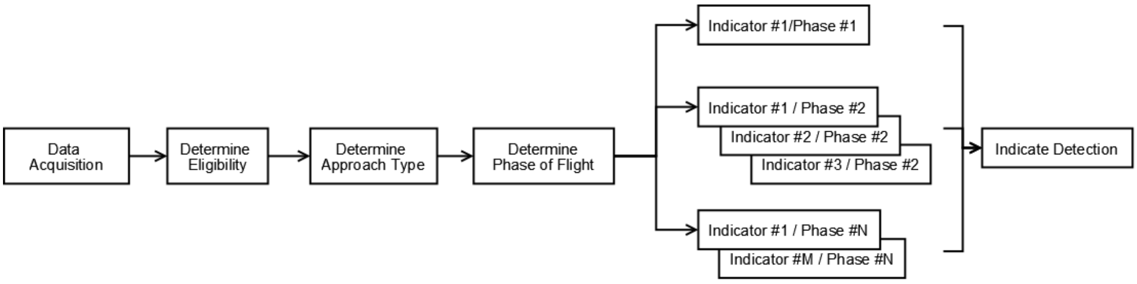


Figure 5-1: Steps for a Controller Support Tool Indicating MA/GA

5.1.1 Data Acquisition

Not all data will be available at once or all the time. It is expected that data needs to reach some level of quality or completeness before it can be used.

5.1.2 Determine Eligibility of Flight

Not all flights need to be monitored. The most obvious example for this are flights which are not intending (by flight plan) to land. Some data can thus be filtered out at this stage.

5.1.3 Determine Approach Type

The type of approach (precision vs. non-precision) has a deep impact on the algorithm and its settings, so there needs to be a process determining the approach type.

5.1.4 Determine Phase of Flight

The selection of an indicator or a set of indicators and their thresholds depends on the phase of the landing manoeuvre.

5.1.5 Selection of Indicator(s) and Model

When the data is complete, the flight has been found eligible for monitoring, the type of approach is known and the phase of flight is known, the correct indicator or set of indicators and the corresponding model and thresholds can be selected.

5.1.6 Compute Non-Conformance

The non-conformance of each indicator and its model can be computed and individually assessed.

5.1.7 Indicate Detection

Based on all non-conformance information the algorithm will indicate MA/GA detection.

5.2 Division of Flight Phases

It is expected that the core algorithm will use different indicators and different settings or thresholds for different phases of flight. In Figure 5-2 an illustration of these different phases is given. The project team foresees that these phases are necessary for development of the algorithm.

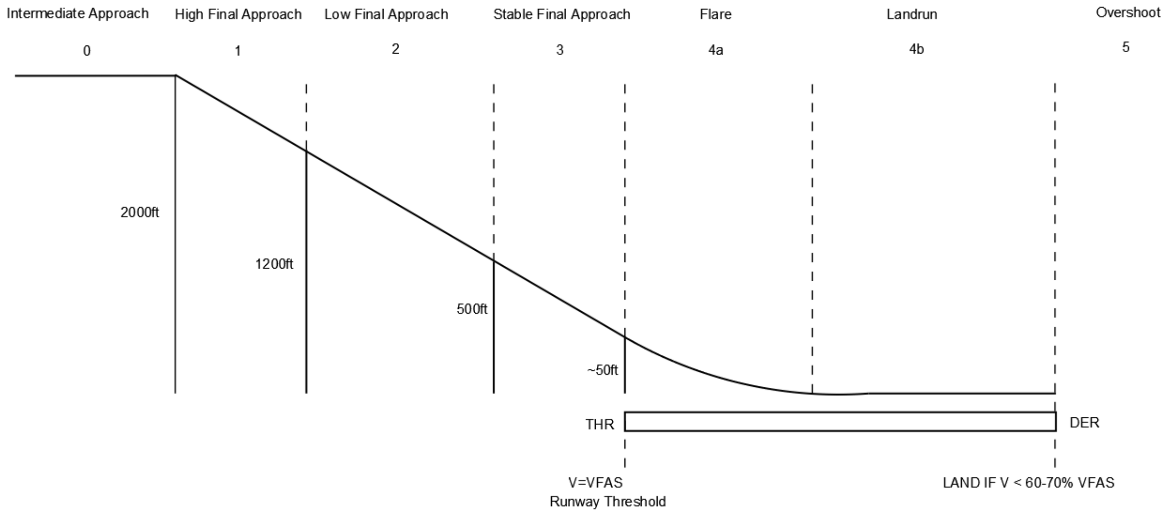


Figure 5-2: Approach and Landing Phases

Phase 0: Intermediate Approach. This phase covers the phase before entering the final approach, ending at approx. 2000 ft.

Phase 1: High Final Approach. This phase will start at or around the Initial Approach Fix at approx. 2000 ft and will continue down to 1200 ft.

Phase 2: Low Final Approach. This phase starts when the high final approach phase ends and will continue until reaching 500 ft.

Phase 3: Stable Final Approach. This phase starts when the low final approach phase ends and continues until the flare-manoeuvre is initiated. Since the flare initiation height differs for various aircraft types, a fixed height is used (initially 50 ft will be used).

Phase 4: Flare and Landing. This phase covers the situation when the aircraft is located above or on the runway surface and is further divided into two sub-phases:

> **Phase 4a: Flare manoeuvre**. This phase starts when the stable final approach phase ends and continues until the aircraft touches the runway.
>
> **Phase 4b: Landing run**. This phase starts when the flare manoeuvre phase ends and continues until the speed of the aircraft drops below a given threshold or until the aircraft reaches the end of the runway.

Phase 5: Overshoot. This phase starts when the aircraft proceeds beyond the Departure End of the Runway (DER) in case no landing has occurred during the landing run.

5.3 Description of Algorithm for Procedural Indicators

Within the present study, it has been established that certain procedural indicators are very strong indicators for defining an algorithm to identify MA/GA initiation (see Chapter 3.1). However, it has also been indicated that these procedural indicators are usually not observable for ground-based detection systems.

Technically, it will be possible to specifically downlink the required parameters from the aircraft to the ground for the purpose of MA/GA detection. This would clearly enhance the capabilities to successfully determine the MA/GA initiation event with minimal time delay. However, at the same time it would increase complexity, due to the required down-link functionality, that most likely would only be used for a local and specific application at Schiphol Airport. It is expected, that this added complexity will incur disproportional cost. Also it is as yet not proven that satisfactory MA/GA detection performance cannot be achieved by using available state vector data.

For this reason, an algorithm based on procedural indicators has not been further elaborated in the present study and focus has been put on algorithms using state vector parameters (see the next section).

5.4 Description of Algorithm for State Vector Conditions

The algorithm for MA/GA detection has been designed to use the minimum amount of readily available data. This concerns the basic data that is currently processed by the ARTAS tracker algorithm and stored by LVNL in their information management system. This basic data contains the aircraft position [x,y], Mode-C altitude (corrected) and groundspeed.
The resolution of these data is:

- Position [x,y]: 1/64 NM
- Mode-C altitude: 100 ft
- Groundspeed: 1 kts

The update rate is 4.19 s.

The tracker algorithm is capable of providing data at higher resolution and higher update rate, and also additional parameters could be provided (see Chapter 4.2). However, for the initial design phase it has been opted to use only the mentioned data with given characteristics in order to establish what performance can be achieved based on this minimal, but readily available, set of data.

Additional or more accurate data can be used to enhance performance, if required. Such refinements are considered part of a more detailed design phase which is out of scope for the current project.
The MA/GA detection algorithm itself is tailored to the flight phases as depicted in Figure 5-2.

The functioning of the initial go-around detection algorithm in conjunction with the associated design considerations are given below per flight phase.

Phase 0: Intermediate Approach. The algorithm is disabled. No MA/GA manoeuvres will be detected in this phase.

Phase 1: High Final Approach. In this phase, the selected MA/GA altitude may be below or slightly above the actual altitude of the aircraft. This means that MA/GA detection cannot be based on rate of climb (i.e. positive change of altitude), because the aircraft may need to descend to the selected MA/GA altitude. Groundspeed is also not a suitable parameter to detect a go-around event in this phase. Therefore, the algorithm can only use position and altitude information. Based on the known position and the intended runway for landing, an estimate can be made of the aircraft's deviation from the nominal glide path[5]. The current algorithm uses a 5 dot positive (above) deviation from the nominal glide path to signal a MA/GA event. The 5 dot threshold has been selected as a compromise between detection time for a precision approach that is aborted to intercept the selected MA/GA altitude and a wide enough area to accommodate non-precision and visual approaches without undue sensitivity for false alerts.

Phase 2: Low Final Approach. In this phase, an MA/GA will be characterised by the aircraft climbing to the selected MA/GA altitude. At the same time, in this phase the aircraft may still be manoeuvring to reach stable approach criteria (which should be achieved, at least, at 500 ft under VMC). Therefore, substantial deviations from the nominal glide path may still occur in this phase as part of normal operation. To reduce sensitivity to nuisance alerts, the algorithm has been designed to signal an MA/GA event in case a positive change of altitude has been detected over a period of two subsequent samples (i.e. over a period of 8.38 sec).

Phase 3: Stable Final Approach. In this phase, it can be assumed that the aircraft has been stabilized on the nominal glide path. Therefore, the aircraft will have a stable descent gradient and will fly close to the nominal glide path. The algorithm has been designed to signal an MA/GA event in case a 2 dot positive (above) deviation from the nominal glide path and a single positive change of altitude has been detected. This will reduce the potential time delay in MA/GA detection, as compared to Phase 2, without undue increase in sensitivity for nuisance alerts.

Phase 4: Flare and Landing. In this phase, the aircraft is located above the runway surface, normally within an altitude range of 0 to 50 ft AGL. Due to the fact that aircraft may pass high over the threshold and considering the 100 ft resolution of the altitude data, the algorithm considers an altitude less than or equal to 100 ft AGL as normal in this phase. The algorithm memorizes the groundspeed when passing over the threshold, and considers the aircraft to have landed in case the groundspeed drops below 60% of the memorized threshold groundspeed. When a

---

[5] This deviation is converted into dots on the glide slope indicator in the cockpit in order to account for a comparison with the stable approach criteria.

landing is detected, the MA/GA detection is disabled.
When a landing is not detected, an MA/GA event will be detected when the altitude is in excess of 200 ft AGL.

Phase 5: Overshoot. In case the aircraft passes over the departure end of the runway, the aircraft has clearly failed to land and therefore is assumed to conduct an MA/GA, regardless of the achieved altitude. Therefore, any aircraft entering this phase will be signalled by the algorithm as having initiated an MA/GA.

6 Results for Application of Algorithm

6.1 Analysis of Available Missed Approach and Go-around Data

6.1.1 Data Files and Processing

For the purpose of demonstrating the performance of the initial go-around detection algorithm, LVNL has provided NLR with the ARTAS tracker data for all missed approach cases in 2011. In total, 330 cases have been provided.
Two data files were delivered. One file contained the recorded missed approach trajectories from the ARTAS tracker, consisting of the following eleven parameters:

- 'FLIGHT_ID'
- 'TRACK_ID'
- 'MODE_A'
- 'T'
- 'X'
- 'Y'
- 'MODE_C'
- 'SPEED'
- 'HEADING'
- 'MODE_OF_FLIGHT'
- 'STATUS'

The second file contained additional information for each individual missed approach case, such as flight identification, aircraft type, runway, wind direction and velocity, and Mode-C correction, etc.

With aid of the Mode-C correction, the provided Mode-C flight level has been corrected for ambient pressure.
From the available parameters in the dataset, only parameters 'X', 'Y', corrected 'MODE_C' and 'SPEED' have been used to demonstrate the initial detection algorithm. The parameter 'STATUS', indicating weight on wheels, has not been used, although it could be envisaged that using this parameter could be of merit in MA/GA detection. The reason is, that for the provided MA/GA cases the ‘STATUS’ parameter never flagged a transition to ground status, and therefore provides no information that could help in MA/GA detection.

6.1.2 Results of Initial MA/GA Detection Algorithm

From the 330 cases provided to NLR, 293 cases were identified as missed approach cases suitable to demonstrate the MA/GA detection algorithm.
The file contained a number of cases that are not considered real MA/GA cases. In particular, this concerned a number of break-off procedures (RWY 27 to RWY 24, RWY 22 to RWY 24 and RWY 06 to RWY 04). These break-off procedures were apparently part of the dataset, while actually no MA/GA procedure had been performed. These cases have been discarded. Also a number of flight inspection flights with the PH-LAB have been discarded. This reduced the number of cases of interest to 293, as mentioned (see also Chapter 6.1.3).

For each of the remaining 293 cases, the MA/GA detection algorithm has been applied to identify the moment of MA/GA detection.
In all cases, the algorithm positively identified a particular point representative for the MA/GA.

The question of interest here is how much delay is present before the MA/GA is flagged. To calculate this delay, it would be necessary to have information about the real (true) point in time where the go-around has been initiated by the pilot. For this reason, KLM has been asked to provide these data for relevant cases, based on their FDM (Flight Data Monitoring) program. However, within the timeframe of the present study, this information has not been forthcoming.

Consequently, an estimate has been made, based on the available data of the actual MA/GA initiation event. The following process has been followed:
From the identified MA/GA point in time, it is searched backwards in time to find the lowest altitude. The time of lowest altitude is considered the "actual" go-around initiation time. Clearly, this may lead to optimistic results, because it may be assumed that the "real" MA/GA has been initiated a few seconds before reaching the lowest altitude. This should be taken into consideration when observing the results of the MA/GA detection algorithm.
In case the point of lowest altitude cannot be established (for instance because the MA/GA is initiated at higher altitude and the aircraft has to descend to the selected MA/GA altitude), the MA/GA is assumed to have been initiated when the glide path deviation is more than 2 dots. In some cases, this latter criterion cannot be satisfied either due to a situation (most likely visual approaches) where the aircraft is descending steep from above the glide path and never enters within 2 dots deviation. In those cases, the detection delay is declared incomputable.

The results of the detection algorithm are further discussed below.

From the available 293 go-around cases, the algorithm found the following distribution of MA/GA detection per phase:

- Phase 1 (high final approach): 33 cases
- Phase 2 (low final approach): 96 cases
- Phase 3 (stable final approach): 127 cases
- Phase 4 (flare and landing): 37 cases
- Phase 5 (overshoot): 0 cases

A histogram of the estimated MA/GA detection height (i.e. the height at which the detection algorithm identifies the MA/GA event) is given in Figure 6-1.
It is shown that there are three peaks. One peak is at around 2000 ft, representing aircraft that fail to intercept the glide slope. The second peak is between 1000 and 1500 ft, representing aircraft that apparently fail to meet stable approach criteria. The third and largest peak is in the range of 200 to 300 ft, representing aircraft that make a low MA/GA or balked landing, in case satisfactory landing criteria have not been met. Therefore, this distribution appears to be logical and thus supports the correct functioning of the algorithm.

The performance of the detection algorithm is illustrated in Figure 6-2. It shows the histograms of the detection delay per flight phase.
The statistical properties of the detection performance are given in Table 6-1.
It is shown, that best and most consistent detection performance is achieved in Phase 3. This seems logical as this phase is the most stable and well defined phase of the approach, and therefore it is easier to detect deviations from the normal approach. In the other phases, this is more difficult, and therefore larger mean delays and larger standard deviations are found. In particular, it is shown that cases with delays in the order of 30 to 40 seconds do occur. These cases should be further investigated to see whether refinement of the algorithm can improve performance.

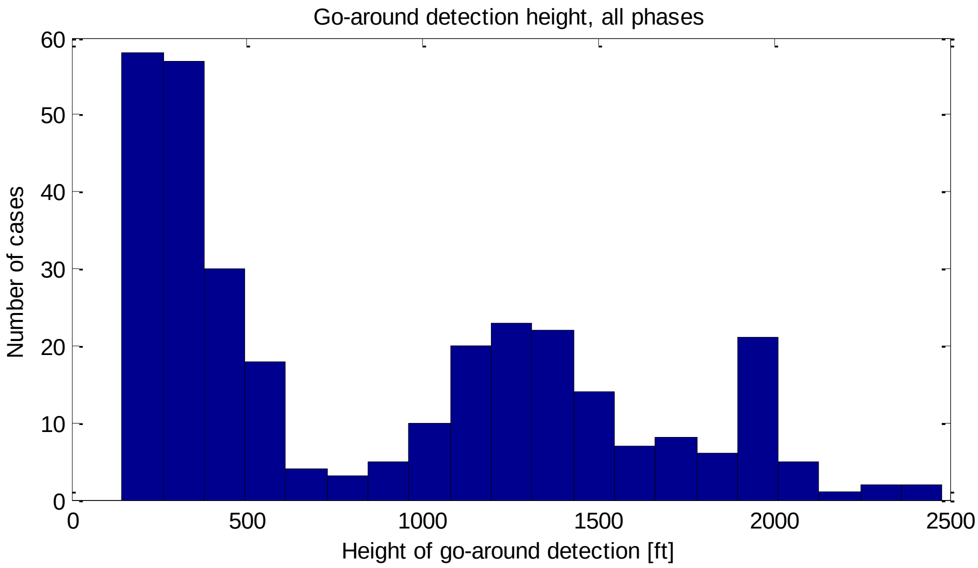


Figure 6-1: Go-around Detection Height for All Cases

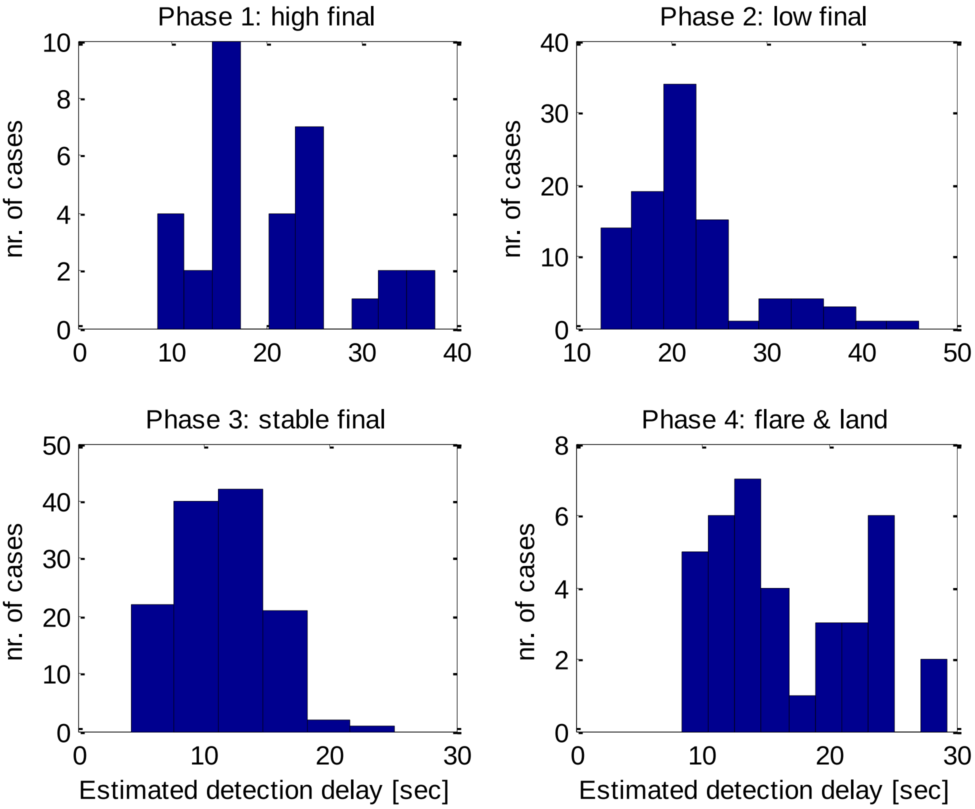


Figure 6-2: Estimated Detection Delay per Approach Phase

Table 6-1: Detection Performance of Initial Algorithm

	MEAN [SEC]	STANDARD DEVIATION [SEC]
Phase 1	20.6	8.1
Phase 2	21.5	6.8
Phase 3	10.7	4.4
Phase 4	16.9	6.3

In general, it is concluded that, given the quality of the data used and the rather crude design of the initial algorithm, the resulting performance of the algorithm is encouraging. It is expected that performance and consistency of the MA/GA detection algorithm can be significantly improved when using data of higher quality (higher update rates and higher resolution) and when additional parameters (e.g. vertical speed) are used. Higher quality data and additional parameters are within the capabilities of the ARTAS tracker and other available sensors, as discussed in Chapter 4.

6.1.3 Spurious Cases

The MA/GA detection algorithm, as discussed in the previous sections, functions fairly well in case of standard and relatively stable precision approaches. However, the analysis of the LVNL MA/GA data has shown that approaches do occur that significantly deviate from such "standard" approaches, such as visual approaches and break-off procedures. An MA/GA detection algorithm should ideally be capable to cope with such approaches without missing an MA/GA procedure and without false detection.

A few examples of such cases are given, in order to illustrate how the present algorithm reacts to such spurious cases and where future algorithms could be improved to cope with such cases.

The first example is a precision approach to RWY 27 with a break-off at around 700 ft to land on RWY 24.

The vertical profile of this particular approach is shown in Figure 6-3.

It is shown that the aircraft follows the glide slope towards RWY 27 and then, at around 700 ft, breaks off to land on RWY 24. At Schiphol this is a fairly common procedure. However, due to the current design of the algorithm, this leads to false MA/GA detection because the algorithm assumes that the aircraft is going to land on RWY 27 and establishes that the aircraft is overshooting this runway without landing. The algorithm erroneously signals this as an MA/GA.

Future algorithms should therefore be designed to cope with this situation, either by adding information on the intended landing runway, or otherwise incorporating more "intelligence" to establish that the aircraft is performing a break-off procedure.

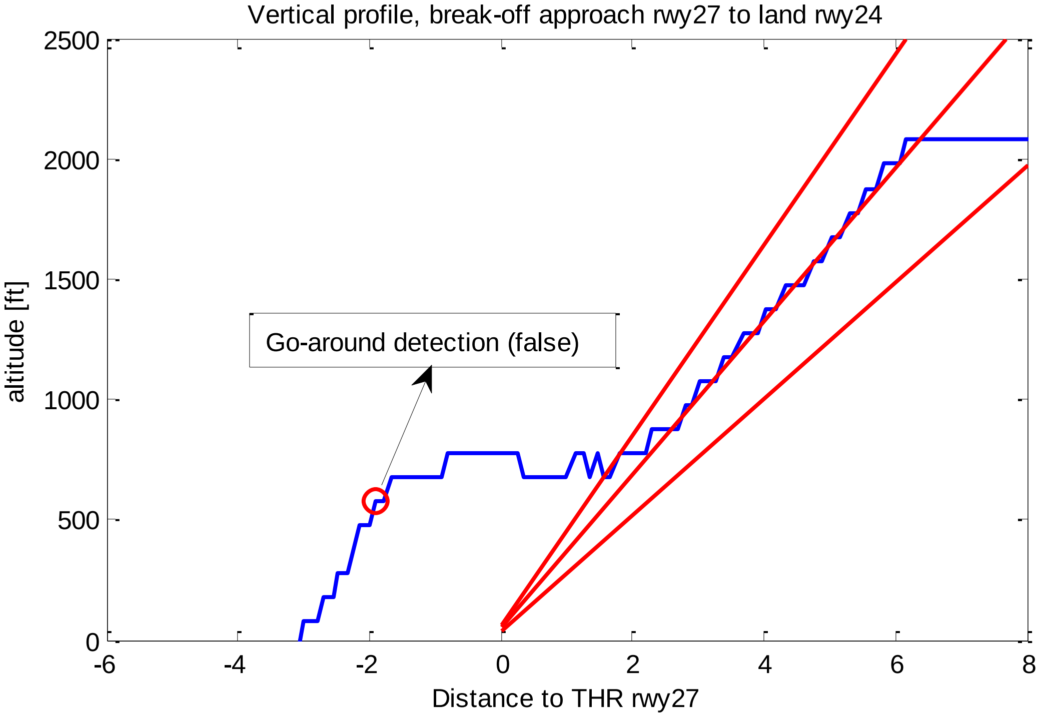


Figure 6-3: Example Approach RWY 27 with Break-off to RWY 24 (False Detection)

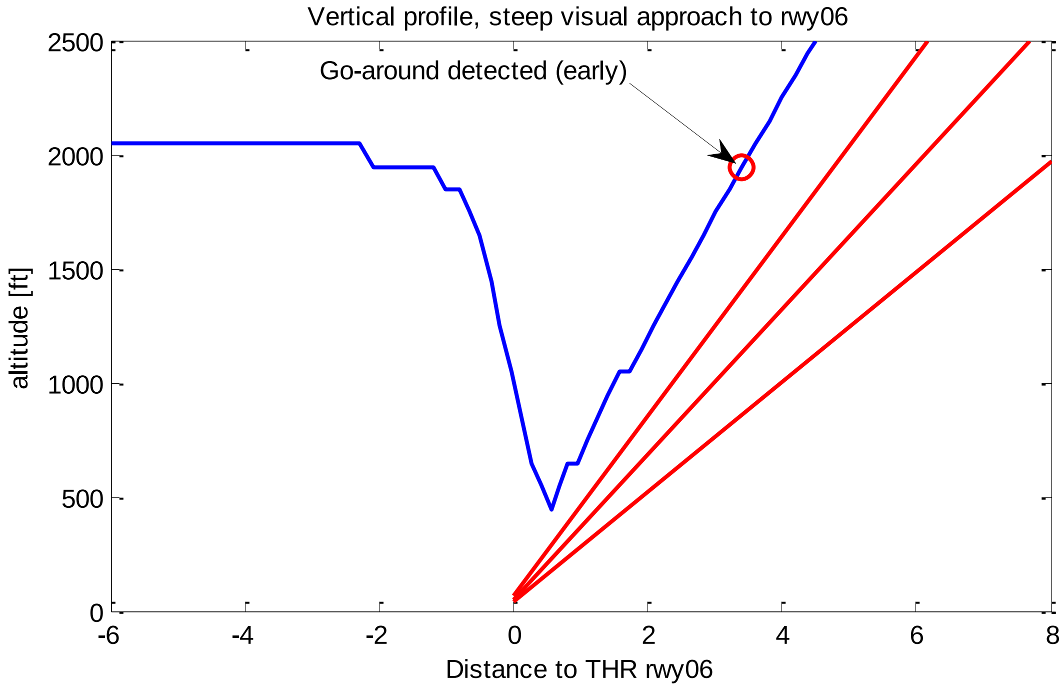


Figure 6-4: Example Steep Visual Approach to RWY 06 (Early Detection)

A second example is given Figure 6-4. It concerns a steep and (most likely) visual approach towards RWY 06. The aircraft approaches from well above the nominal glide slope. In fact, when the aircraft descends below 2000 ft, it is over 5 dots above the nominal glide slope. For the detection algorithm, this signals an MA/GA. However, in reality the aircraft continues its approach too close to the threshold where it initiates an MA/GA, as it is still at 500 ft at that point. In this particular case, the algorithm in fact gave a warning before the actual MA/GA was initiated. This can be considered as an early warning or a false warning in case the aircraft would have continued to land. Clearly, a future algorithm should be able to cope with these situations, either by discriminating between precision and visual approaches, or by improving the detection algorithm in particular in Phase 1 of the approach.

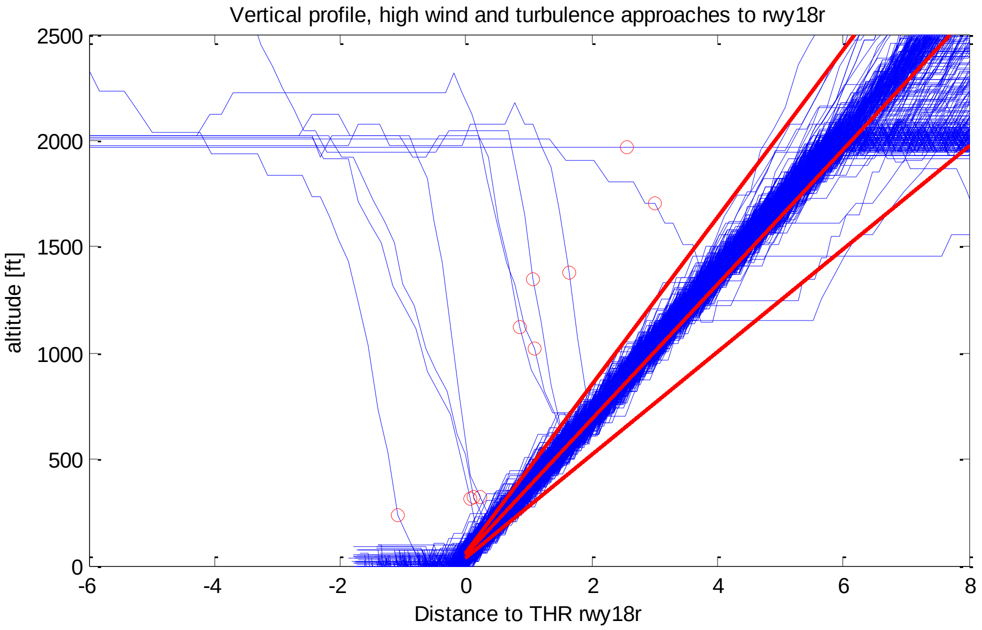
6.1.4 Sensitivity to Nuisance Alerts

As discussed in Chapter 1.4, the feasibility of an MA/GA detection algorithm does not only depend on the performance of successful detection, but also on the resilience against nuisance alerts. Apart from the spurious cases discussed in the previous section, the algorithm must also be robust enough to account for variations that can occur in normal operation, in particular under high wind and turbulence conditions.
In order to test the performance of the algorithm under such conditions, LVNL has provided NLR with additional data files containing approach cases that were specifically selected for high wind and turbulence conditions.
These data were provided for approaches to RWY 18C and RWY 18R. Since RWY 18C is less frequently used under the selected conditions, only 124 cases were identified that met the required high wind conditions. For RWY 18C a total of 755 cases were identified.

For both runways the data has been processed in a way that is similar to the processing of the earlier MA/GA cases, and the detection algorithm was applied to each of the approaches.
For RWY 18C all 124 cases passed without leading to an MA/GA detection alert.
For RWY 18R the algorithm issued 10 MA/GA alerts out of the 755 approaches. Closer analysis, however, showed that due to the fact that the cases had been selected based on high wind conditions the dataset also contained a number of actual MA/GA cases. These cases were correctly identified by the algorithm.
All normal landings passed the algorithm without issuing of an alert.
In Figure 6-5 the vertical profiles of all approaches to RWY 18R are shown, including the missed approach cases with the point of MA/GA detection.
This illustrates that the algorithm functions well under the given conditions.

Clearly, the fact that around 1 in 75 approaches has led to a missed approach is indicative of the strong wind and turbulence conditions. Under normal conditions, the missed approach rate is around 1 in 1000 approaches.

Therefore, it is concluded that the MA/GA detection algorithm is relative insensitive to aircraft disturbances from wind and turbulence, and that it is well capable to discriminate between missed approaches and normal landings under such conditions.



- *745 normal landings and 10 missed approaches*
- *red circles indicate point of go-around detection*

Figure 6-5: Approaches to RWY 18R under High Wind Conditions

6.2 Conclusions Regarding Application of Algorithm

Based on the analysis in this Chapter, the following conclusions can be drawn:

- The present go-around detection algorithm is an initial design using only readily available parameters with limited update rate and resolution;
- The algorithm is, in general, able to detect a go-around initiation in all phases of the approach;
- The performance of the algorithm is best during the stable approach phase, from approximately 500 ft down to 50 ft: average detection delay is around 11 seconds;
- The algorithm performs slightly less (higher detection delay and larger spread) in the other phases, but still within reasonable limits;
- The algorithm is as yet not very robust against spurious cases, such as break-off approaches and visual approaches, but may be improved by adding more “intelligence” and additional data;
- The algorithm shows favourable robustness against nuisance alerts under disturbed approaches due to high wind and strong turbulence;
- The algorithm indicates that go-around detection using available data from existing sources, such as the ARTAS tracker, is feasible; in particular, when considering that the present algorithm can be further improved by adding more “intelligence”, using data of higher quality and using additional parameters as available within present sensor systems.

7 Summary and Recommendations

This study has outlined an exemplary approach to developing an algorithm for MA and GA detection. Relevant indicators were identified. Based on a thorough investigation of available sensors and their capabilities, a selection of relevant and readily available indicators was made.

A simple model based on location, height and speed parameters has been used to demonstrate the basic capabilities of a detection algorithm. This initial algorithm compared nominal approach and landing procedure models with the actually flown tracks (with limited update rate and resolution). Threshold conditions (dots from the glide slope on cockpit instrument, number of consecutive indications for positive change of altitude, speed above or on runway as compared to speed above threshold) for each phase of the approach and landing procedure were chosen in such a way that undetected MA and GA or false detections could be avoided.

The algorithm shows its best performance in the stable approach phase with an average detection delay of 11 seconds. The algorithm shows less performance (higher average detection delay and larger spread) in other phases, but still within reasonable limits. The algorithm also showed robustness against nuisance alerts with high wind and strong turbulence approaches.

In general, these results are considered promising and MA/GA detection on the basis of existing data sources, such as the ARTAS tracker, is considered feasible.

The recommendations that can be derived from the conclusions on initial algorithm development are thus limited on ways to improve the algorithm in terms of detection delay and, perhaps to a lesser extent, robustness.

This can be achieved by using data of better quality (update rate and resolution), using additional parameters available within the current sensor system (e.g. vertical speed) and adding more intelligence (e.g. improved thresholds) for detecting spurious cases (such as break-off procedures and visual approaches).

8 References

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9 Appendix

Description of MA/GA Detection Algorithm

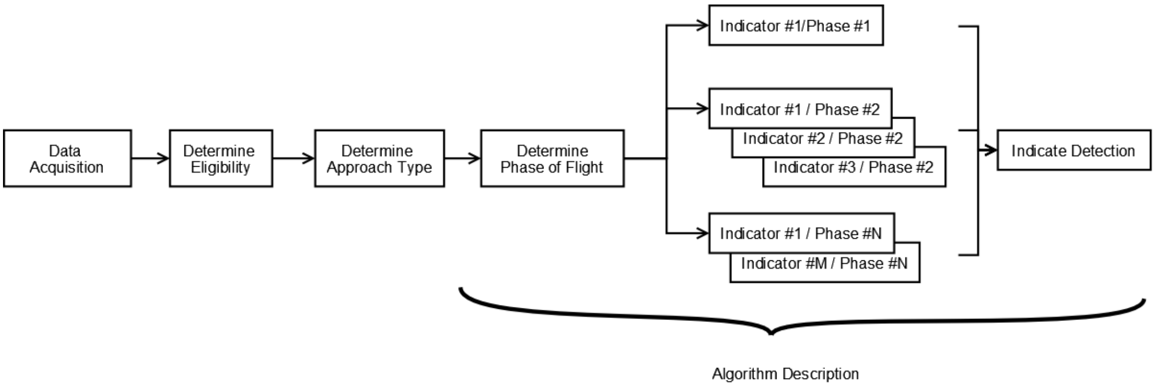

Figure 9-1: Algorithm Development Approach

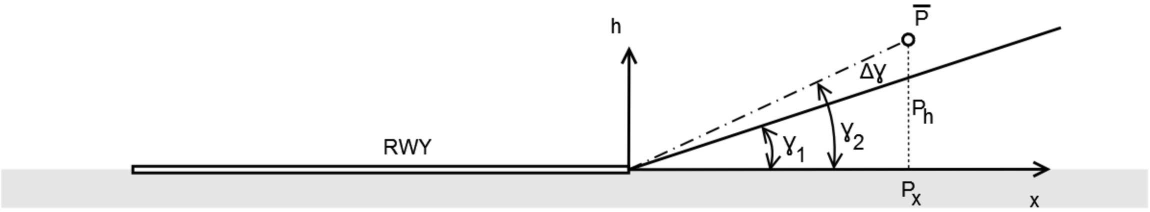

Figure 9-2: Glide Path Deviation

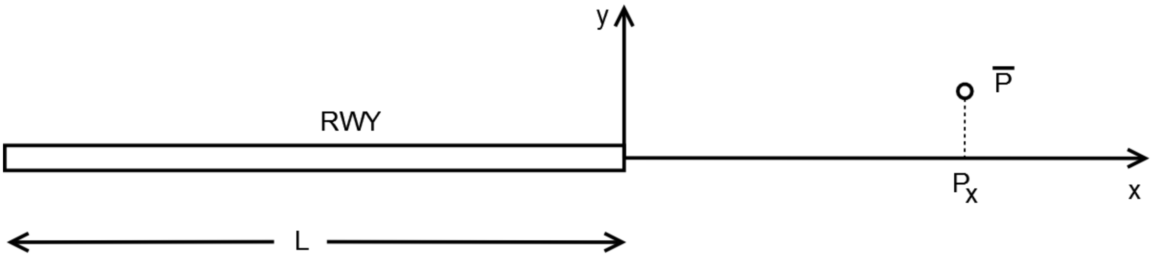

Figure 9-3: Lateral Deviation

Definitions

Define observation with lateral position, height above ground, and groundspeed:

$$\text{Observation } i: \overline{P}^{i} = \begin{bmatrix} P_x \\ P_y \\ P_h \\ P_{v_{GND}} \end{bmatrix}^{i}$$

Determine glide path deviation for each observation (see Figure 9-2):

$$\gamma_1 = glideslope(3°)$$

$$\gamma_2 = \tan^{-1}\left(\frac{P_h}{P_x}\right) \wedge P_x > 0$$

$$\Delta\gamma = \left|\gamma_2 - \gamma_1\right|$$

Determine Phase

Determine applicable approach phase (see Figure 9-2 and Figure 9-3):

$$Phase^i = \begin{cases} if\,(P_x{}^i < -L) \rightarrow \max(5, Phase^{i-1}) \\ if\,(P_h{}^i > 2000\,ft) \rightarrow \max(0, Phase^{i-1}) \\ if\,(2000 \geq P_h{}^i > 1200) \rightarrow \max(1, Phase^{i-1}) \\ if\,(1200 \geq P_h{}^i > 500) \rightarrow \max(2, Phase^{i-1}) \\ if\,(500 \geq P_h{}^i > 50) \rightarrow \max(3, Phase^{i-1}) \\ if\,(P_h{}^i \leq 50) \rightarrow \max(4, Phase^{i-1}) \end{cases}$$

for $i > 1$ and where $Phase^1 = 0$

Detection Rules

Define applicable detection rule (see Figure 9-2 and Figure 9-3):

Phase 1: detection if $\Delta\gamma^i > 1.8°$

Phase 2: detection if $P_h^i > P_h^{i-1} \wedge P_h^{i-1} > P_h^{i-2}$

Phase 3: detection if $P_h^i > P_h^{i-1} \wedge \Delta\gamma^i > 0.72°$

Phase 4: detection if $P_{v_{GND}}{}^{i} \geq 0.6 \cdot v_{THR} \wedge P_h{}^{i} > 200\,ft$

with v_{THR} being the speed above the runway threshold

Phase 5: detection per definition

10 Document Information

Document Information	
Initiating process	KDC
Document type	Result Report
Title	Technical Inventory for Go-around Detection
Part	-
Initiated by	KDC
Related to	-
Document number	KDC/2012/0025
Version number	Final
Version date	16-Apr-2012
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Security Classification
Restricted

Change of Log

Version	**Version Date**	**Section**	**Remarks**
Draft	28-Feb-2012	All	Final draft after project team review
Final	16-Apr-2012	5.1, App.	Final version after KDC review