

Illustrative probabilities of visual acquisition with TCAS I

ACAS on VLJs and LJs – Assessment of safety Level AVAL Project

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EXECUTIVE SUMMARY

Introduction

The Airborne Collision Avoidance System (ACAS II) is a last resort safety net against the risk of mid-air collision. In Europe, the carriage of ACAS is mandatory for civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5,700 kg or a maximum approved passenger seating configuration of more than 19.

The advent of Very Light Jets (VLJ) and Light Jets (LJ) (*i.e.* aircraft weighing less than 5,700 kg) means that in the near future there may be a significant population of aircraft which fall outside the thresholds of the current ACAS II mandate and need to be integrated into the European ATM environment.

EUROCONTROL has initiated the AVAL project (ACAS on VLJs and LJs – Assessment of safety Level) to assess the impact of VLJ and LJ operations on the safety benefits delivered by ACAS II, and whether it is appropriate to extend the ACAS II mandate to include these aircraft.

TCAS I

In some quarters it has been suggested that the appropriate level of equipage for VLJs and LJs is TCAS I (an ACAS I providing traffic advisories on a cockpit display of traffic information) rather than TCAS II version 7.0 (an ACAS II providing resolution advisories in addition to traffic advisories and a cockpit display of traffic information).

Any safety benefit delivered by TCAS I is in the form of an enhancement of the probability of the visual acquisition of other aircraft that constitute a collision hazard, and the subsequent avoidance of these aircraft through 'see-and-avoid' exercised by the pilot.

There is much anecdotal evidence concerning the see-and-avoid principle and the performance of TCAS I but little work of a quantitative nature has been performed.

AVAL Work Package 8

Work Package 8 of the AVAL project has implemented a comparatively simple model of visual acquisition and used it in a set of illustrative scenarios to quantify the probability of visual acquisition of a collision threat under a range of conditions.

The current document forms the final report of Work Package 8.

Work Package 8 has demonstrated the use of the model to quantify the probability of visual acquisition. It has also indicated how the model can be used within fast-time simulations of aircraft encounters to model not only visual acquisition by the pilot, but also his subsequent selection of an avoidance manoeuvre and its effectiveness (or otherwise) in averting a collision. It is planned to carry out such simulations in Work Package 9 of the AVAL project.

Visual Acquisition Model

The model of visual acquisition was originally developed by Lincoln Laboratory. The principal functional factors in visual acquisition are combined to form a comparatively simple mathematical representation of the instantaneous visual acquisition rate. These factors include: the physical size of the threat and the aspect from which it is viewed, the meteorological visibility; the angle of approach of the threat and the closing speed; the search intensity and whether this is enhanced by a TCAS alert.

The instantaneous visual acquisition rate is then integrated in a single algebraic expression enabling the probability of visual acquisition, by a stated time before collision, to be calculated. Calculations of the probability of visual acquisition in a range of collision geometries have been combined to produce colour-coded diagrammatic representations that allow the principal features to be readily assimilated, while individual probabilities for specific geometries can be determined.

Simple Visual Acquisition

The study has shown that equipage with TCAS I can undoubtedly enhance the prospect of visually acquiring a collision threat but only in certain scenarios:

- the enhanced visual acquisition capability provided by TCAS I is most effective against the larger aircraft types such as medium-sized and large passenger aircraft;
- it is less effective against the smaller aircraft types such as GA, military fast jets, and VLJs;
- it is particularly ineffective against small-sized threats with high closing speeds in which there is virtually no prospect of visual acquisition, even when equipped with TCAS I, at the highest closing speeds.

TCAS I is naturally of no benefit in visually acquiring collision threats which approach from behind.

Although effective in certain scenarios when the meteorological visibility is unlimited, this effectiveness is markedly decreased when the visibility decreases. Even at the limit of visibility for VFR the usefulness of TCAS I as an aid to visual acquisition is severely curtailed, even against large-sized threats. This effectiveness is obviously further reduced (ultimately to nil) in IMC.

Potentially incompatible manoeuvres

The study has shown that TCAS I's enhancement of the probability of visually acquiring a collision threat ironically brings with it an increase in the probability that the two aircraft will employ incompatible avoidance manoeuvres. This in turn may decrease or even negate the effectiveness of these manoeuvres.

The effect is most marked in TCAS I equipped aircraft against threats which are equipped with ACAS II since the interval around the time at which an RA will be generated corresponds to times at which the occurrence of visual acquisition is high.

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1. Introduction

1.1. Background

- 1.1.1. The Airborne Collision Avoidance System (ACAS II) is mandatory equipage in ECAC states for all civil fixed-wing turbine-engined aircraft with a maximum take-off mass (MTOM) over 5,700kg, or authorised to carry more than 19 passengers.
- 1.1.2. ACAS II is specified in ICAO SARPs [1] and currently the only implementation is TCAS II Version 7 specified in RTCA MOPS [2].
- 1.1.3. Safety studies have demonstrated that compliance with the resolution advisories (RAs) generated by ACAS II provides a safety benefit in European airspace by reducing the risk of midair collision (see [3] and [4]).
- 1.1.4. However, it should be noted that the precise value of any safety benefit that accrues from equipage with ACAS II is dependent on the traffic patterns and ATM procedures in the airspace in which it is deployed.
- 1.1.5. The advent of new types of light jet (LJ) and very light jet (VLJ)¹ which, due to their small size, are not subject to the ACAS II mandate has the potential to significantly alter traffic patterns in core European airspace, and consequently alter the safety benefit delivered by ACAS II.
- 1.1.6. EUROCONTROL has instigated the AVAL (ACAS on VLJs and LJs – Assessment of safety Level) project to assess the impact of VLJs on the performance of ACAS. Phase I is complete [5] and in Phase II the methods of the earlier safety studies will be applied to the VLJ environment to determine whether there is a safety benefit to be obtained by equipping these aircraft.
- 1.1.7. The AVAL project is primarily focussed on the effects of ACAS II which provides two levels of alert:
 - ‘Traffic Advisories’ (TAs) alert the pilot to the presence of nearby traffic (‘intruders’) that may become a threat to his own aircraft and are accompanied by a display to aid visual acquisition. TAs are intended as precursors to resolution advisories.
 - ‘Resolution advisories’ (RAs) are issued if the diagnosed risk of collision becomes more urgent. An RA provides the pilot with advice on how to regulate or adjust his vertical speed so as to avoid a collision. The sense of RAs against other ACAS II equipped aircraft are coordinated so that the two aircraft choose complementary manoeuvres.
- 1.1.8. Work-packages studying the effects of ACAS I have also been incorporated into the AVAL project. ACAS I provides TAs only which are intended to prompt visual acquisition of the intruder.

¹ Henceforth, for convenience, in this report the acronym “VLJ” will be used to encompass both light jets and very light jets.

1.2. **Current study**

- 1.2.1. In some quarters the results of Phase II of AVAL project have been pre-empted by the suggestion that equipage with TCAS I is appropriate and sufficient for VLJs. TCAS I is an ACAS I that provides traffic advisories and a cockpit display of traffic information.
- 1.2.2. Any mitigation of the risk of mid-air collision resulting from TCAS I equipage is achieved by aiding the visual acquisition of collision threats, and the subsequent exercise of the see-and-avoid principle by the pilot. TCAS I provides TAs but, unlike ACAS II, does not provide RAs.
- 1.2.3. A report published in 1970 [6] concluded that see-and-avoid prevents 97% of collisions at closing speeds up to 200kt, but is only 47% effective when the closing speed is greater than 400kt. Since then much evidence has emerged that suggests that see-and-avoid is insufficiently effective as a mitigation of the risk of mid-air collision² (see, for example, [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], and [18] – a list which is by no means complete).
- 1.2.4. Much of the evidence is circumstantial or anecdotal (and therefore qualitative) and most is primarily concerned with see-and-avoid without the aid of a traffic display. As a first step towards comparing the benefits of TCAS I and ACAS II *quantitatively*, the current study investigates the probability of a pilot visually acquiring the threat when two aircraft are on a collision course.
- 1.2.5. The probability of visual acquisition in various scenarios has been calculated using an implementation of the visual acquisition model developed at Lincoln Laboratory and described in [20].
- 1.2.6. This report concentrates on the probability of flight-crew visually acquiring an intruder (the 'see' component of see-and-avoid). An assessment of the efficacy of manoeuvres in response to visual acquisition (the 'avoid' component) will form the subject of another report within the AVAL project.
- 1.2.7. Structure of the report:
 - the remainder of this introductory section outlines the principles of see-and-avoid (section 1.3) and ACAS (section 1.4);
 - section 2 sets out the features of the collision geometries under investigation, the behaviour of TCAS warning times in such geometries, and describes a diagrammatic representation of collision geometries that is used later to present results;

² A notable exception is the study reported in [19] which concluded that see-and-avoid could be 99% effective in resolving conflicts. However, that study concerned low-flying in uncontrolled airspace by military fast jets and the results are not applicable to the current study: the study assumed military pilots who needed only a 5s warning time to avert a collision; the study considered threats of small physical size (normally GA aircraft). Furthermore, a flaw in the analysis caused the effectiveness of see-and-avoid to be overstated.

- section 3 describes the factors (and their functional relationship) that need to be included in any model of visual acquisition, and then explains how they have been quantified in the current model;
- section 4 describes the specific scenarios that have been investigated in this study – the altitude and speed of own aircraft, and the size and range of speeds of the threat aircraft;
- section 5 presents results and discussion;
- section 6 presents conclusions.

1.3. See-and-avoid

- 1.3.1. The exercise of 'see-and-avoid' is required by ICAO Annex 2 (*Rules of the Air*) [21]. See-and-avoid is the principle by which the pilot of an aircraft conducts a continuous visual scan of the surrounding airspace in order to detect other traffic, that might constitute a threat to his own aircraft, in a timely manner and undertake any avoidance manoeuvre that may be necessary in order to assure the safety of his own aircraft (see, for example, the guidance given by the UK CAA [22] and the FAA [23]).
- 1.3.2. The exercise of the see-and-avoid principle is a requirement when the pilot is responsible for his own separation from other traffic and is good practice in other circumstances even though separation is provided by other means (such as when receiving an ATC service in controlled airspace).
- 1.3.3. The terms "see" and "avoid" are habitually mentioned together. The implication is that the former leads inevitably to the latter: that a threat once seen will be successfully avoided, but this is not necessarily the case. "Visually acquiring" a threat (seeing it and recognising that it is a threat) does not guarantee that the threat can be avoided:
- the threat may be seen too late for any successful avoiding action to be taken;
 - even if the threat is seen in time the avoiding action taken may be negated by a manoeuvre in the same direction by the threat (see, for example, [7]);³
 - last second avoiding action may even increase the risk of collision [24].
- 1.3.4. Notwithstanding the remark made in the second bullet above it is generally assumed that if a threat is visually acquired within some particular time threshold of an impending collision then disaster can be averted by an appropriate avoidance manoeuvre.
- 1.3.5. What value this time threshold should take depends upon many factors. Principal amongst these are the pilot (who must devise and implement the avoidance manoeuvre) and the type of aircraft he is flying.

³ To obviate this eventuality when both aircraft are ACAS II equipped they exchange information so that they choose compatible avoidance manoeuvres. There is also a "tie-break" protocol in the event that two ACAS equipped aircraft simultaneously choose initially incompatible manoeuvres.

1.4. Airborne collision avoidance systems

- 1.4.1. “Airborne Collision Avoidance System” (ACAS) is the ICAO term for on-board avionics systems that operate independently of ATC and mitigate the risk of mid-air collision.
- 1.4.2. There are various levels of ACAS capability:
- ACAS II, as mentioned earlier, provides TAs and RAs and is mandatory for large civil aircraft in European airspace;
 - ACAS I provides TAs only and does not recommend any manoeuvres.
- 1.4.3. ACAS II is specified in ICAO SARPs [1] and currently the only implementation is TCAS II Version 7 specified in RTCA MOPS [2].
- 1.4.4. There is currently only one implementation of ACAS I, viz. TCAS I. TCAS I is specified in RTCA MOPS [25] – SARPs for ACAS I are published in ICAO Annex 10, volume IV [1] but are limited to interoperability with ACAS II and interference limiting issues. No international implementation of ACAS I is planned at the ICAO level, but TCAS I is mandated in the USA for certain smaller aircraft.
- 1.4.5. The surveillance and threat detection functions of TCAS I operate in a similar way to ACAS II, but with different threat detection thresholds. Both systems provide a cockpit display of traffic information (CDTI) or ‘traffic display’: a plan-position indicator showing the relative positions and altitudes of nearby aircraft (‘intruders’) using standard symbology.
- 1.4.6. Both ACAS II and TCAS I can generate a TA when a tracked intruder is diagnosed as being on a potential collision course. A TA is a cue for the flight crew to try to visually acquire the potential threat with the aid of the traffic display and, in the case of ACAS II only, to prepare for a possible RA.
- 1.4.7. Manoeuvres (whether vertical or horizontal) based on the traffic display alone (whether accompanied by a TA or not) are not permitted [26] [27]. The traffic display is designed to aid visual acquisition of an intruder: it is not designed nor certified for any other use. Limitations of the display and its interpretation mean that manoeuvres based on the traffic display can degrade flight safety (see EUROCONTROL’s ACAS Bulletin No. 6, ‘*Incorrect use of the TCAS traffic display*’ [28]).

2. Geometry of collisions

2.1. Mechanics of collision geometry

2.1.1. The area of interest is the last minute or so before a potential collision. A number of simplifying approximations allow the impending collision to be described by a simple mathematical model:

- The physical size of the aircraft is ignored – given a typical aircraft dimension of 50m and a not untypical closing speed of 360kt, the aircraft will be separated by 1NM when there is just 10s to go until the collision – the aircraft dimensions are then less than 3% of the distance scales of interest.
- The vertical speed of the aircraft is ignored – for civil aircraft the vertical speed will rarely be more than 10% of the forward speed (e.g. a climb-rate of 1500fpm is equal to a speed of just under 15kt). This means that the horizontal scale of a potential collision is generally much more significant than the vertical scale. From a pilot's point of view this is equivalent to saying that the threat will generally appear to approach close to the horizontal plane (typically within $\pm 6^\circ$).
- The aircraft are assumed to be travelling at constant speed and heading – this assumption errs on the side of caution when considering visual acquisition (*i.e.* it is a worst case scenario) since with unaccelerated motion each aircraft appears at a fixed position in the view as seen from the other aircraft. It is a feature of human vision that the targets that are most difficult to detect are those that do not to move across the field of view.

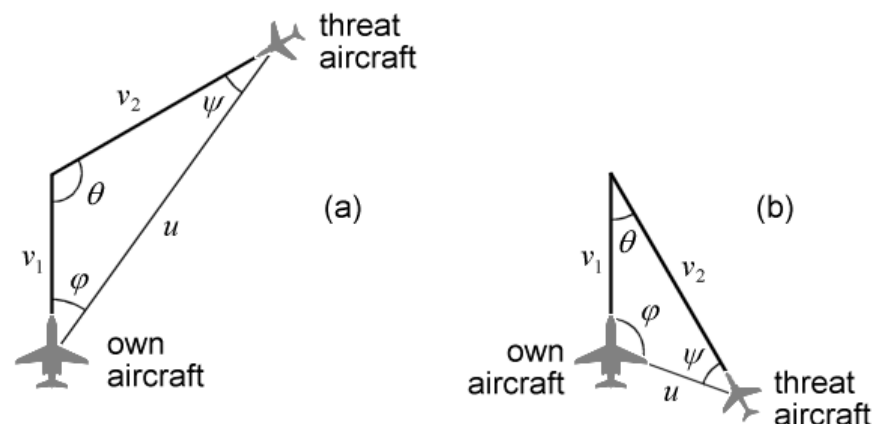


Figure 1: Plan view of collision geometries

2.1.2. These assumptions describe a 'rectilinear collision' and with them we can characterise the collision geometry by just three parameters (see Figure 1):

- the speed of own aircraft, v_1 ;
- the speed of the threat aircraft, v_2 ; and

- the collision angle, θ – the angle between the tracks of the two aircraft as they approach the collision.

2.1.3. Knowing these parameters we can solve the triangle to determine three other parameters:

- the closing speed (from the cosine rule), u ;

$$u = \sqrt{(v_1 - v_2)^2 + 2v_1v_2(1 - \cos \theta)} \quad (1)$$

- the apparent direction of approach of the threat, φ ;

$$\varphi = \cos^{-1} \left(\frac{v_1 - v_2 \cos \theta}{u} \right) \quad (2)$$

- the aspect angle from which the threat is viewed, ψ .⁴

$$\psi = 180^\circ - (\theta + \varphi) \quad (3)$$

2.1.4. The plan view of two illustrative collision geometries are shown in Figure 1:

- In encounter (a) the collision angle is $\theta = 135^\circ$. The apparent approach direction of the threat is $\varphi = 27^\circ$ and the threat is viewed from an aspect angle of $\psi = 18^\circ$. If own aircraft's speed is taken as $v_1 = 300\text{kt}$ then the threat's speed is $v_2 = 430\text{kt}$, and the closing speed is $u = 676\text{kt}$.
- In encounter (b) the collision angle is $\theta = 30^\circ$. The apparent approach direction of the threat is $\varphi = 110^\circ$ and the threat is viewed from an aspect angle of $\psi = 40^\circ$. Again if own aircraft's speed is taken as $v_1 = 300\text{kt}$ then the threat's speed is $v_2 = 430\text{kt}$, and the closing speed is $u = 227\text{kt}$.

2.1.5. The aircraft outlines in Figure 1 are intended only to indicate the aircraft headings, but if they are taken to be approximately to scale then the diagrams represent the situation about a quarter of a second before collision.

2.2. Diagrammatic representation

2.2.1. For a given value of own aircraft speed, the full range of encounter geometries can be represented on a single diagram: a polar plot of collision angle and the threat aircraft's speed.

2.2.2. Such a plot is shown in Figure 2. The aircraft symbol indicates the orientation of own aircraft and its position indicates the speed of own aircraft (in this case 300kt):

- the point (a) indicates the corresponding collision geometry illustrated in Figure 1 – collision angle of 135° and threat speed of 430kt;
- the point (b) indicates the corresponding collision geometry illustrated in Figure 1 – collision angle of 30° and threat speed of 430kt.

⁴ The viewing aspect of the threat from own aircraft is the same as the apparent direction of approach of own aircraft as seen by the threat (see Figure 1).

2.2.3. The same diagram can be used with a polar grid centred on own aircraft indicating the apparent direction of approach of the threat and the closing speed.

2.2.4. This representation is shown in Figure 3

- the point (a) again indicates the corresponding collision geometry illustrated in Figure 1 – approach direction of 27° and closing speed of 676kt;
- the point (b) again indicates the corresponding collision geometry illustrated in Figure 1 – approach direction of 110° and closing speed of 227kt.

2.2.5. Note that encounter geometries, such as (b), where the point lies below the horizontal line through the own aircraft symbol indicate encounter geometries where the threat aircraft approaches from behind own aircraft. In these geometries visual acquisition may be impossible due to limited visibility from the cockpit.

2.3. **TCAS warning times**

2.3.1. A TCAS system on-board an aircraft continuously tracks the range and altitude of nearby aircraft. Based on these tracked variables TCAS will generate alerts when certain internal tests indicate that there is a risk of impending collision. The tests use conflict detection thresholds which depend on the aircraft's altitude, being more sensitive at higher altitude.

2.3.2. In a collision geometry an alert will be generated at a time that depends on the closing speed, u (see paragraph 2.1.3), and the values of two detection threshold parameters:

- T , the nominal warning time; and
- D , a distance parameter known as “DMOD” – in slow closure collision geometries aircraft can not approach closer than D without an alert being generated.

altitude ⁵		TCAS I			TCAS II				
from	to	SL	T_{TA} (s)	D_{TA} (NM)	SL	T_{TA} (s)	D_{TA} (NM)	T_{RA} (s)	D_{RA} (NM)
	1000ft	A	20	0.20	2	20	0.30	no RAs	
1000ft	2000ft				3	25	0.33	15	0.20
2000ft	2500ft				4	30	0.48	20	0.35
2500ft	FL50	B	30	0.55	5	40	0.75	25	0.55
FL50	FL100				6	45	1.00	30	0.80
FL100	FL200				7	48	1.30	35	1.10
FL200									

Table 1: TCAS sensitivity levels (SL) and alert threshold parameters.

⁵ The values given are the nominal bounds of the altitude bands. In practice a hysteresis of typically 500ft is applied as an aircraft passes from one altitude band to another.

2.3.3. The altitude dependence of the values of the parameters for three types of alert (TCAS I TA, TCAS II TA, and TCAS II RA) are shown in Table 1.

2.3.4. The time remaining (until a potential collision) when a TCAS alert is generated in a rectilinear collision geometry can be derived (see Appendix A) and is given by the following relationship:

$$t_{alert} = \frac{T}{2} + \sqrt{\left(\frac{T}{2}\right)^2 + \left(\frac{D}{u}\right)^2} \quad (4)$$

2.3.5. At high closing speeds an alert is triggered close to the nominal warning time T . At low closing speeds an alert is triggered earlier, when the distance between the aircraft is close to D .⁶

2.3.6. Using the relationship in Eqn. (4) and the parameter values from Table 1 we can calculate the times at which various TCAS alerts would be generated in the example encounter geometries of Figure 1. Assuming the encounter occurred at FL150:

- In encounter (a) an aircraft equipped with TCAS I would receive a TA 30.3s before the potential collision – an aircraft equipped with TCAS II would receive a TA at 45.6s, and an RA at 30.6s before the potential collision. Note that these times are only slightly earlier than the nominal warning times given by the values of T (30s, 45s, and 30s, respectively).
- In encounter (b) an aircraft equipped with TCAS I would receive a TA 32.4s before the potential collision – an aircraft equipped with TCAS II would receive a TA at 50.0s, and an RA at 34.7s before the potential collision. Note that these times are noticeably earlier than the nominal warning times given by the values of T , due to the comparatively slow closing speed.

⁶ The result presented in Eqn. (4) is directly applicable only to the rectilinear collision geometries considered here. However, it serves to illustrate the fact that with a sufficiently low closing speeds an alert can be triggered an arbitrarily long time before a collision, regardless of the nominal warning time.

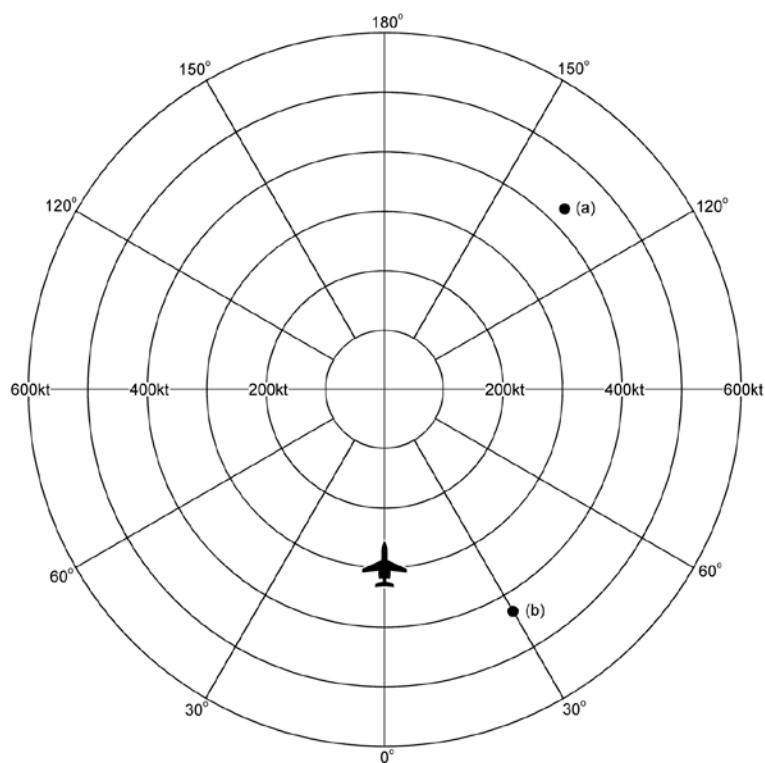


Figure 2: Encounter geometry plot – collision angle vs. threat speed.

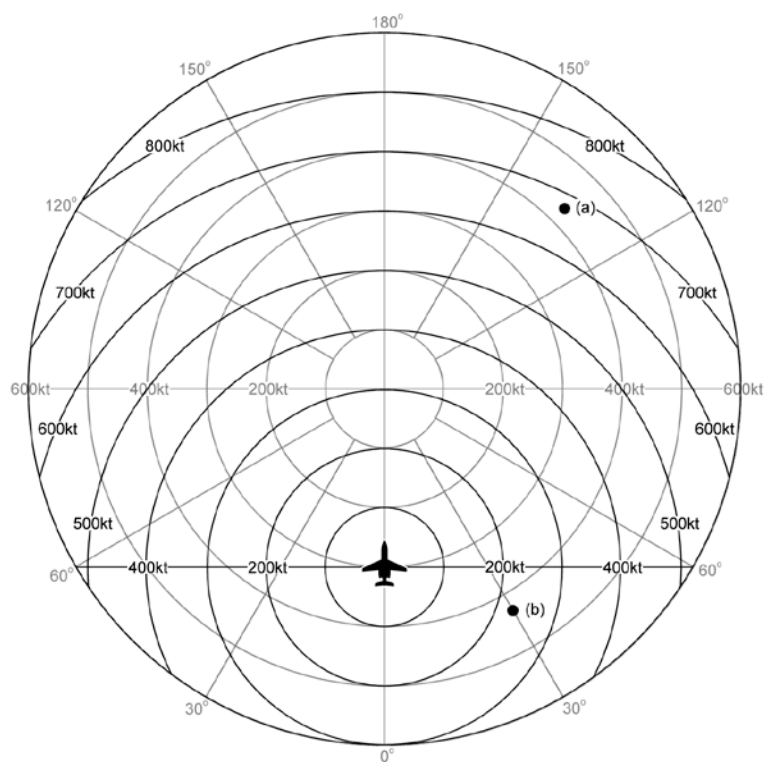


Figure 3: Encounter geometry plot – approach direction vs. closing speed.

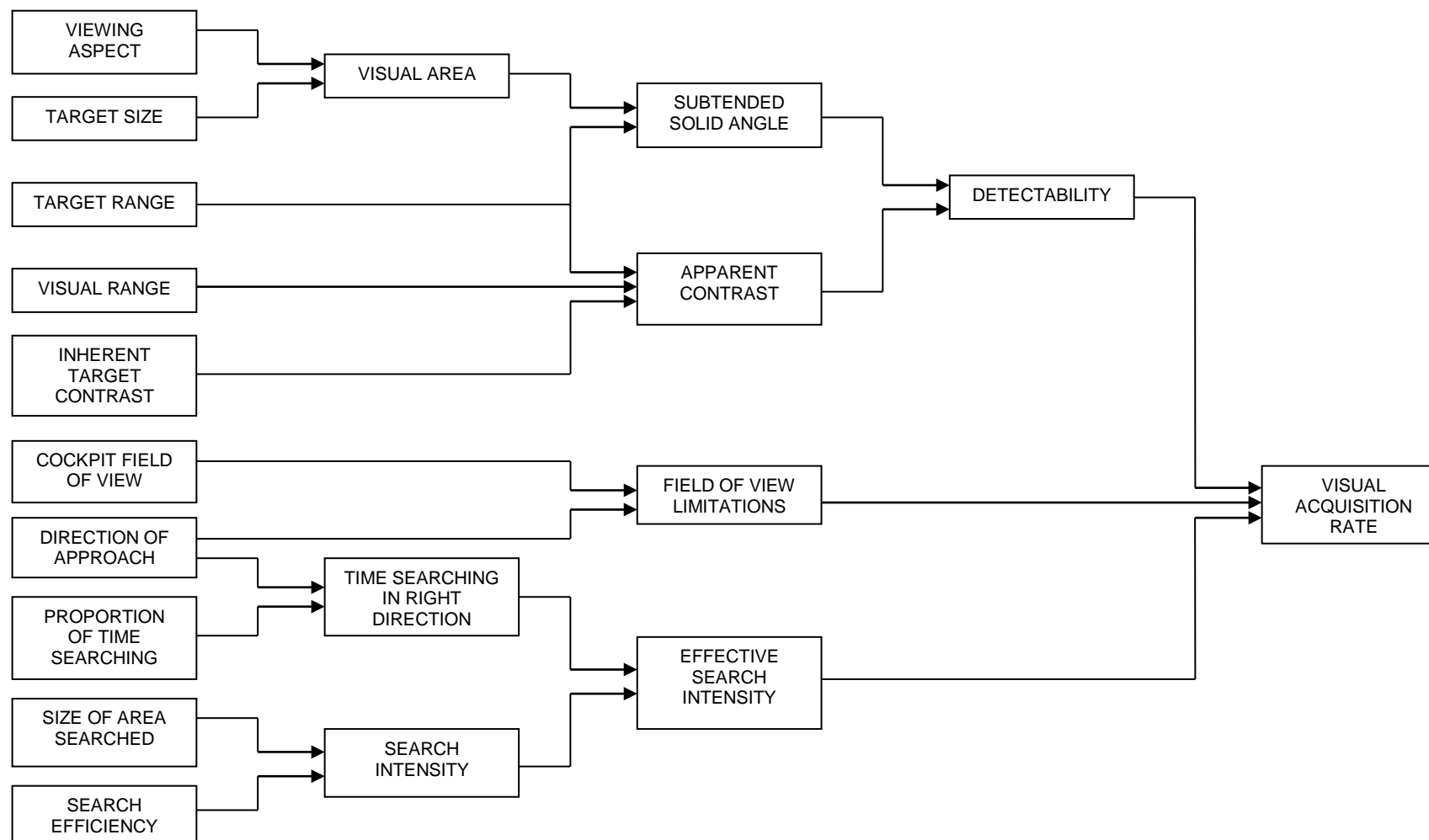


Figure 4: Functional relationship of factors determining instantaneous visual acquisition rate.

3. Quantifying visual acquisition

3.1. *Factors affecting visual acquisition rate*

3.1.1. Many factors affect the “visual acquisition rate”: the chance of visually acquiring a target in any given instant of time. The functional relationship between these factors is summarised in Figure 4 (adapted from a similar figure in [30]) and is outlined below – the terms in italics are to be found as specific elements in Figure 4.

3.1.2. The way in which these factors are quantified and combined is described later in this section.

3.1.3. Subtended solid angle⁷

3.1.3.1. Starting at the top left of Figure 4, the *viewing aspect* is the particular orientation of the target aircraft as seen from the host. This combined with the *target size* (i.e. the physical size of the target aircraft) gives the cross-sectional area of the target that is presented to the host: the *visual area* (see appendix B.1).

3.1.3.2. The target range is the distance to the target from the host and this together with the visual area determines the subtended solid angle: the apparent size of the target as seen from the host aircraft.

3.1.3.3. The way in which the apparent target size is quantitatively incorporated into the model is explained in section 3.2.

3.1.4. Apparent contrast

3.1.4.1. The seeing conditions are quantified by the *visual range*. When the visibility is less than ideal the *visual range* and the *target range* combine to determine to what extent the *inherent target contrast* (which depends on paint scheme, illumination, background etc.) is degraded. All three factors can therefore affect the *apparent contrast*: the contrast of the target as seen from the host.

3.1.4.2. The way in which the apparent contrast is quantitatively incorporated into the model is explained in section 3.3.

3.1.5. Detectability

3.1.5.1. The subtended solid angle and the apparent contrast together determine the detectability.

⁷ Solid angle is the three-dimensional analogue of the familiar two-dimensional plane angle. A length d viewed perpendicularly from a large distance, r , will subtend a plane angle of $\theta = d/r$ radians; an area A viewed perpendicularly from a large distance, r , will subtend a solid angle $\Omega = A/r^2$ steradians.

3.1.5.2. The detectability represents the best visual acquisition performance that could be achieved given an unlimited field of view and a continuous search. In practice these circumstances will not apply and this is taken into account by the factors considered in the lower half of Figure 4.

3.1.5.3. The way in which the detectability is incorporated into the model is described in section 3.4.

3.1.6. Field of view limitations

3.1.6.1. The *cockpit field of view* is constrained by the limits of the cockpit window and the airframe of the host aircraft. This and the *direction of approach* of the threat will determine whether *field of view limitations* will prevent the threat from being seen.

3.1.6.2. Field of view considerations in the model are discussed in section 3.5.

3.1.7. Effective search intensity

3.1.7.1. The *direction of approach* and the total *proportion of time searching* determine the fraction of *time searching in the right direction*.

3.1.7.2. The *size of the area searched* will generally be all of the field of view if the pilot is unalerted or some fraction of the field of view if the pilot is alerted to the presence of a threat and its general direction. It has generally been found that an alerted search is conducted more assiduously because it is known that there is a target to be seen. Also, it is found that in human vision several short periods of search can be more effective than a single longer period of search [14]. These factors are combined in the *search efficiency* which together with *size of area searched* determines the *search intensity*.

3.1.7.3. *Time searching in the right direction* and the *search intensity* determine the *effective search intensity*.

3.1.7.4. The way in which the effective search intensity is used within the model is described in section 3.6.

3.1.8. Visual acquisition rate

3.1.8.1. Finally the *detectability*, the *field of view limitations* and the *effective search intensity* combine to determine the *visual acquisition rate*.

3.1.8.2. The visual acquisition rate, as a function of time, is used to calculate the probability of a target being visually acquired by any given time. This calculation is described in more detail in section 3.7.

3.2. Apparent size of target

3.2.1. The apparent size of the target is the solid angle that it subtends, which is determined by the physical size of the target, the direction from which it is viewed (the aspect angle, ψ – see paragraph 2.1.3) and the distance from which it is

viewed (the range, r). If the cross-sectional area of the target viewed with a particular aspect angle is A then the solid angle, Ω , that it subtends is given by:

$$\Omega = \frac{A}{r^2} \quad (5)$$

- 3.2.2. Due to the irregular shape of real aircraft the cross-sectional area will in general be a complex function of the aspect angle. The cross-sectional area will be a minimum when the target is viewed head-on ($\psi = 0^\circ$ or 180°) and a maximum when the target is viewed broad-side ($\psi = 90^\circ$). An estimate of the cross-sectional area at other angles can be made based on these principal cross-sections as described in section B.1.
- 3.2.3. The cross-sectional areas of the aircraft types considered in this study are given in Table 3, together with silhouettes. The aircraft silhouettes are to scale and, if the printed page is held at arm's length (60cm), correspond to the apparent size of the real aircraft at a distance of 0.5NM.
- 3.2.4. A final factor in detectability is imposed by the optical resolution of human vision. Beyond a certain distance a threat aircraft will appear too small to be resolved by the eye. The details of the calculation of this limiting range, r_{lim} , is described in appendix B.2 and yields the rule of thumb indicated below – the limiting range in nautical miles is approximately twice the square-root of the cross-sectional area in metres-squared:

$$r_{\text{lim}} \text{ (in NM)} \approx 2 \times \sqrt{A \text{ (in m}^2\text{)}} \quad (6)$$

Take as an example the head-on silhouette of a Piper PA-23 (the first aircraft in Table 3). The cross-sectional area is $A = 6.2\text{m}^2$ giving a limiting range of $r_{\text{lim}} = 5\text{NM}$. At the scale of the illustrations this is equivalent to viewing the printed page from a distance of 6m (beyond which the silhouette should no longer be discernible).

- 3.2.5. In many encounters this limitation has little effect on visual acquisition because there is still plenty of time to detect the threat after it comes within the limiting range. However, in potential collisions with a small aircraft at a high closing speed it can be important. *E.g.* consider own aircraft travelling at 300kt on a head-on collision course with a fast jet travelling at 600kt (such as a Mirage F1 with a head-on cross-section of 4.5m^2 – see the second aircraft in Table 3). The rule of thumb in Eqn. (6) gives a limiting range of 4.2NM within which the threat can be seen. In this extreme example, the closing speed is $300\text{kt} + 600\text{kt} = 900\text{kt}$: at this rate the threat will become potentially visible to the pilot with only 17s to go until collision (regardless of any earlier traffic advisory).

3.3. **Apparent contrast**

- 3.3.1. The apparent contrast of the target is a complex function of the target itself (its shape and the reflectance of its paint scheme), the lighting conditions, the brightness of the background against which it is viewed and the clearness of the atmosphere.

- 3.3.2. If individual incidents are to be investigated a complex model can be used that takes account of these factors and includes such details as the time of day, season of the year, geographical latitude, and weather conditions (see [19]). If, as here, a more general analysis is required then a model that considers only the last of these (the clearness of the atmosphere) and averages over the other factors will suffice.
- 3.3.3. Under given daylight conditions the inherent contrast of the target is the contrast seen in a perfectly clear atmosphere or equivalently the contrast seen from very short range. The inherent contrast is designated C_0 .
- 3.3.4. Scattering in the atmosphere causes the apparent contrast to decrease from this inherent value as the range from which the target is viewed increases. Eventually at large ranges the target merges into the background and the contrast goes to zero. This relationship is described by Koschmieder's law which states that for a given level of visibility, the contrast falls off towards zero by a constant fraction for each equal increment in the range. This is an exponentially decreasing relationship:

$$\frac{C}{C_0} = \exp\left(-k \frac{r}{R}\right) \quad (7)$$

Where the apparent contrast, C , is a fraction (the exponential term) of the inherent contrast C_0 . The range of the target is r and the scattering in the atmosphere is described by the parameter R often termed the "visual range" or the "visibility".

- 3.3.5. In daylight conditions the ICAO definition of visibility [31] is effectively the meteorological optical range (MOR) – the distance at which atmospheric scattering causes the contrast decreases to 5% of its inherent value [32].⁸ This definition corresponds approximately to the limit of contrast discernible by human vision.
- 3.3.6. In perfect visibility the visual range is effectively infinite and Eqn. (7) becomes simply $C = C_0$: there is no degradation of contrast with distance. At the other extreme in thick cloud the visual range decreases to virtually zero and Eqn. (7) becomes $C = 0$: there is no contrast thus rendering the object invisible.
- 3.3.7. In normal conditions the response of human vision is proportional to both the apparent size of the target (in terms of angular area) and to the contrast of the target [20]. A larger target will be more easily detected than a small target and a contrasty target will be more easily detected than a less contrasty target. Two targets will be equally detectable if the target with less contrast is proportionately larger.

⁸ The percentage level adopted as the criterion determines the value of the constant k in Eqn. (7): for the 5% level of contrast $k = -\ln(5\%) = 3.0$. Other criteria occasionally encountered are: 5.5% giving $k = -\ln(5.5\%) = 2.9$; and 2% giving $k = -\ln(2\%) = 3.9$.

3.4. Detectability

- 3.4.1. The detectability is proportional to both the apparent size of the target and the apparent contrast of the target. The detectability is therefore proportional to the product of the terms in Eqns. (5) and (7), thus:

$$\text{detectability} \propto \frac{A}{r^2} \exp\left(\frac{-3r}{R}\right) \quad (8)$$

- 3.4.2. The constant of proportionality is the inherent contrast of the threat. In the current study an average value is applicable covering a range of aircraft types and livery. Rather than calculate this directly the average inherent contrast factor is absorbed into the search intensity parameter (see section 3.6) which is derived from an analysis of flight trials involving a range target aircraft.

3.5. Field of view limitations

- 3.5.1. Limitations to the field of view can have a profound effect on the possibility of visual acquisition – in the extreme case of a threat overtaking own aircraft from behind there is no prospect of seeing this aircraft from the cockpit of a civil jet.
- 3.5.2. The precise field of view is complex and aircraft type dependent. It is limited by the windscreen surround, the pillars separating windscreen panels, and even the nose wings and engines of the aircraft. As well as rendering visual acquisition impossible in certain encounter geometries, these obstacles will also determine the limits of binocular vision in general.
- 3.5.3. The position of the pilot in the cockpit (*i.e.* generally not on the centreline of the aircraft) means that the field of view limitations will not necessary be the same for an aircraft approaching from the left and an aircraft approaching from the right in what would otherwise be symmetrical encounters.
- 3.5.4. However, field of view limitations are taken into account in a simplistic way in the current study. It is assumed that the pilot has an unobstructed view ahead and can see 105° to port and starboard of the dead-ahead direction. Beyond this angle it is assumed that the window surround precludes any prospect of visual acquisition.

3.6. Effective search intensity

- 3.6.1. The effective search intensity is a combination of the time searching in the right direction and the search intensity with which that search is conducted. Both of these factors will depend on whether the pilot has been alerted to the presence of the threat by a TCAS alert or not.
- 3.6.2. In the model the effective search intensity is expressed as a single parameter, β , which has units of 'per unit solid angle per unit time' (/sr.s). The parameter can take on two values: a default value corresponding to the normal scanning procedure of an unalerted pilot; or a higher value corresponding to a search conducted in response to a TCAS traffic advisory with the aid of a traffic display.

3.6.3. To derive values for the search intensity from first principles is a formidable task since it depends upon the characteristics of the search strategy conducted by the pilot and also on the physiological and psychological factors governing human vision. In practice, values for the search intensity are derived from experiment.⁹

3.6.4. An analysis of flight trials in [29] and [30] derived a range of values for typical pilots. These, together with the review of visual acquisition performance in [34], suggest the following representative values (which are used in the current model):

- for a pilot's normal visual scan, $\beta_0 = 17,000/\text{sr.s}$;
- for a search in response to an alert, $\beta_1 = 140,000/\text{sr.s}$.

These values indicate that a traffic alert and use of the traffic display increases the efficiency of a visual search by just over a factor of eight.¹⁰

3.6.5. The values adopted in the current study are necessarily average values and can be expected to show variation between individual pilots. One effect noted in [25] was that (all other things being equal) search effectiveness tended to decrease with age but increase with experience to the extent that a pilot would need to fly at least 90 hours per year to maintain his search effectiveness throughout his flying career.

3.6.6. If two flight-crew conduct the visual search then the total search intensity parameter value will be the sum of the individual values. However, this does not necessarily imply a doubling of the search intensity: the value for the pilot not flying will generally be much lower than that for the pilot flying. The tasks of the pilot not flying are different to those of the pilot flying and do not necessarily include the conduct of a visual scan outside the cockpit.¹¹

3.7. ***Instantaneous visual acquisition rate***

3.7.1. The probability of detecting a target in an instant of time dt , between a given time t and time $t + dt$, is proportional to the length of time dt , where the parameter of proportionality is the "visual acquisition rate" $\lambda(t)$:

$$\text{prob}(\text{visual acquisition between } t \text{ and } t + dt) = \lambda(t).dt \quad (9)$$

(the visual acquisition rate is the quantity whose functional dependence on other factors is shown in Figure 4).

⁹ This approach also has the advantage that the average inherent contrast of the threat aircraft can be absorbed into this parameter as described in paragraph 3.4.2.

¹⁰ If two flight crew are conducting independent visual searches then the combined value of search intensity will be the sum of the individual search intensities: *i.e.* the search intensity will generally be doubled if two flight crew conduct the search. However, this is not relevant in the scenarios considered here.

¹¹ A further complication arises if the pilot not flying visually acquires a threat. He must convey this information to the pilot flying who must then visually acquire the threat before visual acquisition is of use in see-and-avoid.

- 3.7.2. We saw in section 3.1 that the visual acquisition rate is determined by the detectability, the field of view, and the search intensity. As explained in section 3.5 the field of view limitations are not explicitly included in the model and so the visual acquisition rate becomes simply the product of the detectability (see Eqn. (8)) and the search intensity β (see section 3.4), giving:

$$\lambda(t) = \beta \frac{A}{r^2} \exp\left(\frac{-3r}{R}\right) \quad (10)$$

This represents the general case of the instantaneous visual acquisition rate.

- 3.7.3. Taking the instant of the potential collision as time zero, the range r in the rectilinear collision geometries considered in this study is given by $-ut$, where u is the closing speed. The visual acquisition rate in the moments leading up to the potential collision (*i.e.* when the time t is negative) is therefore given by the following expression

$$\lambda(t) = \beta \frac{A}{u^2 t^2} \exp\left(\frac{3u}{R} t\right) \quad (11)$$

in which time is the only variable and the other parameters are known. This represents the specific case of the instantaneous visual acquisition rate for the rectilinear collision geometries considered in this report.

- 3.7.4. A simulation based study would calculate the generic instantaneous visual acquisition rate, as defined in Eqn. (9) and specified in Eqn. (10), on each cycle and from this stochastically determine whether visual acquisition occurred. Such an approach would be suitable where the effectiveness of see-and-avoid was assessed by directly modelling avoidance manoeuvres. In the current study, only visual acquisition is being assessed and so the approach is to integrate the instantaneous visual acquisition rate to provide an algebraic expression for the visual acquisition probability, as described in the next section.

3.8. **Visual acquisition probability**

- 3.8.1. Visual acquisition is an inhomogeneous Poisson process. This simply means that the visual acquisition rate varies with time (it is inhomogeneous) and that in any period of time there are only a discrete number of possible outcomes (it is a Poisson process): the target is either detected; or it is not detected.
- 3.8.2. Given the nature of the process, the probability, p , of a given target being visually acquired by some time t_0 can be shown to be given by the expression

$$p(t_0) = 1 - \exp\left(-\int_{-\infty}^{t_0} \lambda(t).dt\right) \quad (12)$$

where $\lambda(t)$ is the visual acquisition rate.

- 3.8.3. Using the expression for the visual acquisition rate in the rectilinear collision geometries considered in this study (given in Eqn. (11)) we can express the probability of Eqn. (12) as

$$p(t_0) = 1 - \exp\left(-\beta(t) \frac{A}{u^2} \int_{-\infty}^{t_0} \frac{1}{t^2} \exp\left(\frac{3u}{R} t\right) dt\right) \quad (13)$$

where:

- β is the search intensity of the pilot (which, depending on the time, will correspond to an 'alerted' or 'unalerted' value);
- A is the apparent cross-sectional area of the threat;
- u is the closing speed; and
- R is the visual range.

3.8.4. Knowing each of the parameters above, the expression in Eqn. (13) can be integrated to give the probability of visual acquisition for a particular encounter geometry. The mathematical details of the calculation are provided in Appendix C, and an example is provided in the next section.

3.9. ***A practical example***

3.9.1. To illustrate the use of the model, this section shows the probability of visual acquisition as a function of time in a specific illustrative collision geometry.

3.9.2. A TCAS I equipped aircraft is assumed to be on a head-on collision course with a Piper PA-23 (cross-sectional area of 6.2m², see Table 3) at a closing speed of 350kt. The encounter occurs at altitude and so the TCAS I nominal TA warning time is 30s (see Table 1). The visibility is assumed to be unlimited ($R = \infty$), *i.e.* the example represents a best case – in poorer visibility the visual acquisition probabilities, for the same encounter geometry, will be lower.

3.9.3. Figure 5 shows probability of visual acquisition as a function of time.

3.9.4. The encounter starts with the aircraft well separated but on a collision course:

- Until 53s before the collision the pilot is unable to visually resolve the threat aircraft.
- At 53s before the collision the threat is at a range of 5.2NM and becomes visually resolvable – there is now some prospect of the pilot visually acquiring the aircraft.
- The pilot has not been alerted to the presence of the threat and so the search intensity is low (the unalerted value of $\beta = 17,000/\text{sr.s}$).

3.9.5. A TCAS I TA is triggered at 31s before the collision when the aircraft are 3NM apart – there is a 4.4% chance that in such a collision geometry the pilot will have visually acquired the threat before the TA is triggered.

- The pilot has now been alerted to the presence of the threat. A delay will occur while the pilot comprehends the aural alert, consults the traffic display, and assimilates the information displayed (2s is allowed for this process in the current study). The search will now be concentrated in a smaller area and with a higher intensity encapsulated in the alerted value of

$\beta = 140,000/\text{sr.s}$). This results in an abrupt change in the probability curve 2s after the traffic alert.

- By the time there is only 15s to collision there is a 60% chance that in such a collision geometry the pilot will have visually acquired the intruder – were the aircraft unequipped this probability would be 14%.
- With less than 15s to collision there is little prospect of the threat being successfully avoided even if it is seen (see paragraph 4.6.2.2) – the grey zone on the right of Figure 5. The probability of visual acquisition rises to certainty at the moment of impact when the threat would fill the field of view.¹²

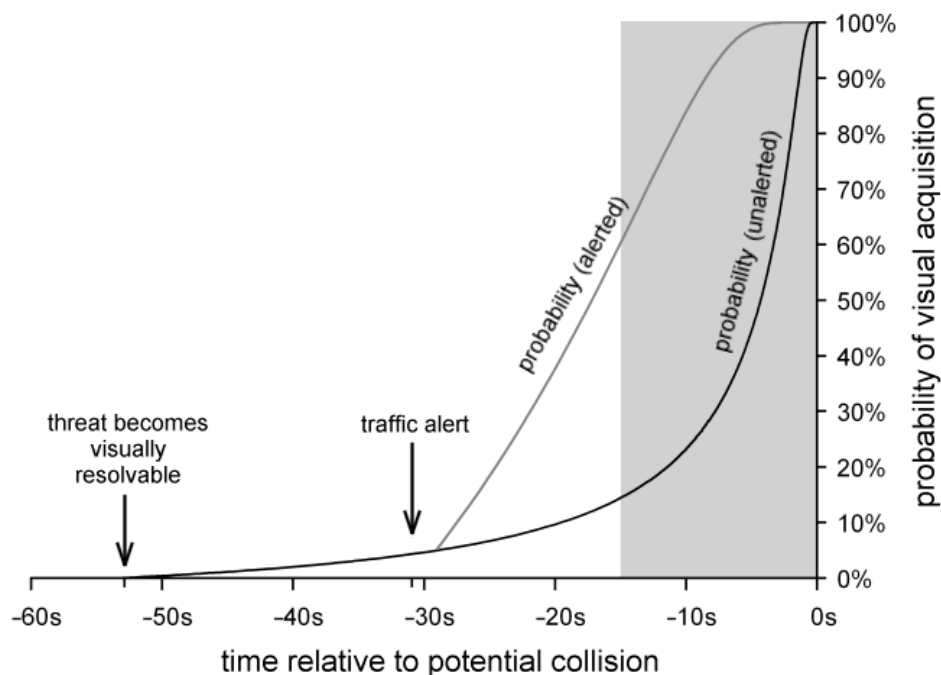


Figure 5: Probability of visual acquisition with time.

3.9.6. For the results presented in section 4.6, the complete curve of Figure 5 is effectively calculated (using appropriate parameters) for each point on the polar plot of encounter geometries. Each curve is then analysed to determine the value of the variable of interest at that point on the plot. The value then determines the colour-coding of that point in the figures.

¹² This is strictly only true when the threat aircraft is headed directly towards the cockpit of own aircraft. In practice some lateral offset (less than the dimensions of the aircraft involved) can exist and a collision can still occur, as with the collision in Brazilian airspace between a Boeing 737 and an Embraer Legacy on 29th September 2006. In these circumstances the threat aircraft will appear large but will not entirely fill the field of view and the threat may go undetected as in the Brazilian collision. This consideration only becomes important when the distance to go until collision is of a similar magnitude to the lateral offset, *i.e.* in the last second or so before collision, when there is virtually no prospect of averting the collision regardless of whether the threat is sighted or not. At earlier times in the encounter the model used here remains valid.

3.10. *Limitations of the model*

- 3.10.1. A number of assumptions and inherent limitations should be borne in mind when considering probabilities calculated by the current model. These are listed below.
- 3.10.2. The model considers rectilinear encounter geometries in which the threat does not appear to move across the field of view. The movement of targets that do appear to move across the field of view makes them easier to detect but these are generally not on a collision course except in the case of aircraft that turn into a collision.
- 3.10.3. The model is only applicable to visual acquisition during daylight (but could be adapted to consider visual acquisition during night time).
- 3.10.4. The model considers detectability of the threat based on its size and contrast only. No account is taken of other factors such as exhaust smoke, contrails, sound, nor glint or glare from the sun.
- 3.10.5. The model assumes that visibility is homogenous and isotropic. It does not allow for scattered cloud or patches of poor visibility.
- 3.10.6. The model considers only a single intruder aircraft, *i.e.* it does not allow for the possibility that the pilot will visually acquire another aircraft (that may not be a threat) and the effect that this will have on the probability of visually acquiring the collision threat.

4. Scenarios

4.1. Introduction

- 4.1.1. The Lincoln Laboratory visual acquisition model, described in section 3, has been implemented and used to calculate visual acquisition probabilities in a number of encounter scenarios.
- 4.1.2. Five illustrative scenarios have been chosen to cover a range of encounter altitudes, own aircraft speeds, threat aircraft types, and equipage. The scenarios are deliberately diverse, with different parameters chosen in each, so that in a limited number of scenarios the effectiveness (or otherwise) of visual acquisition in a wide range of conditions can be illustrated.
- 4.1.3. The parameters of the scenarios are described in the following sections and are summarised in Table 2.
- 4.1.4. Use of the model in a formal safety study would consider all relevant combinations of these parameters and weight these according to their prevalence in the airspace of interest. The results would then be combined with the appropriate weightings to give overall values for the effectiveness of visual acquisition.

scenario		1	2	3	4	5
altitude		1000ft – 2000ft	2500ft – FL50	FL50 – FL100	FL100 – FL200	above FL200
TCAS I	SL	A	B	B	B	B
	T_{TA}	20s	30s	30s	30s	30s
	D_{TA}	0.20NM	0.55NM	0.55NM	0.55NM	0.55NM
TCAS II	SL	3	4	5	6	7
	T_{RA}	15s	20s	25s	30s	35s
	D_{RA}	0.20NM	0.35NM	0.55NM	0.80NM	1.10NM
VFR visibility limit		5km	5km	5km	8km	8km
own speed		150kt	200kt	250kt	300kt	350kt
threat type		Piper PA23	Dassault Mirage F1	Embraer Phenom 100	Airbus A320	Boeing 747
cross-sectional area	A_x	6.2m ²	4.5m ²	8.1m ²	48.4m ²	175.2m ²
	A_y	13.6m ²	23.8m ²	20.6m ²	163.3m ²	579.1m ²
speed range		100kt – 225kt	150kt – 600kt	100kt – 350kt	200kt – 500kt	300kt – 550kt
likely equipage		unequipped, TCAS I	unequipped	unequipped, TCAS I, TCAS II	TCAS II	TCAS II

Table 2: Summary of scenarios.

4.2. Altitude of encounters

4.2.1. Encounters at altitudes in five different altitude bands (one in each of the ACAS II sensitivity levels (SL) have been chosen):

1. 1,000ft – 2,000ft AGL, TCAS I SL A, TCAS II SL 3;
2. 2,500ft AGL – FL50, TCAS I SL B, TCAS II SL 4;
3. FL50 – FL100, TCAS I SL B, TCAS II SL 5;
4. FL100 – FL200, TCAS I SL B, TCAS II SL 6;
5. above FL200, TCAS I SL B, TCAS II SL 7.

4.2.2. The corresponding alert parameters for TCAS I and TCAS II are shown in the summary of the scenarios in Table 2.

4.3. Own aircraft speed

4.3.1. The speed of own aircraft (the VLJ) has been chosen to range from 150kt in the encounters at the lowest altitude (1,000ft – 2,000ft AGL) to 350kt in the encounters at the highest altitude (above FL200):

1. 1,000ft – 2,000ft AGL, own aircraft speed 150kt;
2. 2,500ft AGL – FL50, own aircraft speed 200kt;
3. FL50 – FL100, own aircraft speed 250kt;
4. FL100 – FL200, own aircraft speed 300kt;
5. above FL200, own aircraft speed 350kt.

4.4. Visibility

4.4.1. For each scenario two visual ranges are considered, corresponding to clear skies with unlimited visibility ($R = \infty$) and the lower limit of visibility for VFR flights.

4.4.2. The lower limit of visibility for flight under VFR rules are [21]:

- below 10,000ft AMSL (scenarios 1, 2, and 3), $R = 5\text{km}$ (2.7NM);
- above 10,000ft AMSL (scenarios 4 and 5), $R = 8\text{km}$ (4.3NM).

4.5. Threat aircraft types

4.5.1. A range of aircraft types have been chosen with a different aircraft type as the threat aircraft in each scenario:

1. Piper PA23, twin-engined piston aircraft, pilot + 3–5 seats;
2. Dassault Mirage F1, single seat military fighter jet;
3. Embraer Phenom 100, very light jet, pilot + 4–6 seats;
4. Airbus A320, medium passenger jet, 2 crew + 150–200 seats;
5. Boeing 747, large passenger jet, 2–3 crew + 360–520 seats.

- 4.5.2. The range of speeds of these aircraft types (for the altitude of the scenario in which they are taken to be the threat aircraft) is shown in Table 2.
- 4.5.3. The dimensions, cross-sectional area, and scale silhouettes of these aircraft types are shown in Table 3.






Piper PA23 Aztec	span: 11.3m length: 9.5m height: 3.1m	$A_x=6.2\text{m}^2$ $A_y=13.6\text{m}^2$	
Dassault Mirage F1	span: 8.4m length: 15.3m height: 4.5m	$A_x=4.5\text{m}^2$ $A_y=23.8\text{m}^2$	
Embraer Phenom 100	span: 12.3m length: 12.8m height: 4.4m	$A_x=8.1\text{m}^2$ $A_y=20.6\text{m}^2$	
Airbus A320	span: 34.1m length: 37.6m height: 11.8m	$A_x=48.4\text{m}^2$ $A_y=163.3\text{m}^2$	
Boeing 747	span: 64.3m length: 70.7m height: 19.3m	$A_x=175.2\text{m}^2$ $A_y=579.1\text{m}^2$	

Table 3: Aircraft dimensions, cross-sections, and silhouettes.

The aircraft silhouettes are to scale and, if the printed page is held at arm's length (60cm), correspond to the apparent size of the real aircraft at a distance of 0.5NM.

4.6. *Equipage cases*

- 4.6.1.1. Within each scenario the consequences of a number of equipage combinations have been calculated. Within each combination the probability of the event of interest is calculated for each encounter geometry and the results plotted on a single polar encounter geometry diagram for that combination.

4.6.1.2. Calculations have been performed for a range of cases which fall into two groups:

- simple visual acquisition – the likelihood of the pilot of own aircraft visually acquiring the threat aircraft by some particular time for the particular scenario and case; and
- potentially incompatible manoeuvres – the likelihood of the pilot of own aircraft visually acquiring the threat aircraft at about the same time as the threat aircraft makes a manoeuvre.

These groups are described in more detail below.

4.6.2. Simple visual acquisition

4.6.2.1. The probability of simple visual acquisition of the threat aircraft by the pilot of a VLJ has been calculated for two cases of equipage:

- the VLJ is not equipped with TCAS – the pilot will not be alerted by an onboard system as to the presence of the threat; and
- the VLJ is equipped with TCAS I – the pilot will be alerted at the time of the traffic advisory and after a short delay (in this study 2s) the visual search will be conducted with increased intensity.

4.6.2.2. The probability that visual acquisition occurs before each of two crucial times has been calculated:

- The latest time by which visual acquisition is useful – *i.e.* the latest time before a potential collision at which there is still a prospect of an avoidance manoeuvre, based on visual acquisition, averting a collision. Estimates of this time vary greatly and the precise value will depend on the individual pilot and aircraft type. The time of 12.5s quoted in [23] (and elsewhere) is ultimately derived from a study of US naval aviation (*i.e.* trained military pilots in highly manoeuvrable aircraft). For VLJs a longer time is more appropriate: in the current study the value of 15s has been adopted (the NTSB has used 15s as the absolute minimum time for detection, evaluation, and evasive action if the collision is to be avoided [18] and this is consistent with the smallest RA warning time provided by ACAS¹³).
- The time at which the pilot would have received an RA had his aircraft been ACAS II equipped – if visual acquisition on a TCAS I equipped aircraft occurs does not occur before this instant then the aircraft is afforded less protection than if it were equipped with ACAS II.

4.6.2.3. The combination of two equipage possibilities (own aircraft unequipped or own aircraft equipped with TCAS I) and two crucial times (by 15s before collision, or by the time that an RA would have been generated had the aircraft been ACAS II equipped) leads to four cases which are labelled (a), (b), (c), and (d) and are summarised in Table 4.

¹³ ACAS II uses larger time thresholds at higher altitudes but this is to provide greater separation, in turn to allow for greater pressure-altimetry error – not a factor in visual avoidance manoeuvres.

case	own aircraft equipage	probability of visual acquisition...
a	unequipped	...by 15s before collision
b		...by time of ACAS II RA
c	TCAS I	...by 15s before collision
d		...by time of ACAS II RA

Table 4: Cases of simple visual acquisition of the threat.

- 4.6.2.4. Within a particular scenario the effect of equipage with TCAS I in prompting visual acquisition can be assessed by comparing case (a) with case (c), and by comparing case (b) with case (d).

4.6.3. Potentially incompatible manoeuvres

- 4.6.3.1. Manoeuvres by own aircraft based on visual acquisition cannot be coordinated with any manoeuvre by the threat aircraft regardless of the threat aircraft's equipage. That is not to say that the manoeuvres will necessarily be incompatible, but any compatibility will not be the result of coordination.
- 4.6.3.2. With uncoordinated manoeuvres there exists the possibility that a manoeuvre by own aircraft will thwart a manoeuvre to which the threat is already committed, or conversely that a manoeuvre to which own aircraft is already committed will be thwarted by a manoeuvre by the threat.
- 4.6.3.3. These undesirable circumstance can come about if one aircraft initiates a manoeuvre when the other aircraft is already committed to a manoeuvre but which has not yet become apparent to the first aircraft (either visually or through transponder altitude replies).
- 4.6.3.4. When a pilot commits to a manoeuvre (either in response to an ACAS II RA or, if his aircraft is not equipped with ACAS II, because he visually acquires the collision threat) there will be a delay until the aircraft starts to manoeuvre and then a further delay until any deviation becomes sufficiently large to be apparent to the other aircraft. The combined delay is taken to be 10s in the current study.
- 4.6.3.5. Consequently, manoeuvres initiated within 10s of each other are likely to be uncoordinated and potentially incompatible. For a TCAS I equipped VLJ this circumstance can come about: when the pilot visually acquires the threat within 10s of the threat visually acquiring the VLJ when the threat is not equipped with ACAS II (cases (e) and (f) in Table 5); or when the pilot visually acquires the threat within 10s of an RA being generated in an ACAS II equipped threat (case (g) in Table 5).

case	threat aircraft equipage	probability of visual acquisition...
e	unequipped	...in both aircraft within 10s of each other
f	TCAS I	
g	ACAS II	...in VLJ within 10s of RA in threat aircraft

Table 5: Cases of potentially incompatible manoeuvres.

4.6.3.6. These cases are applicable in the following scenarios:

- case (e) – unequipped threat. Possible in scenarios 1 (GA aircraft), 2 (military fast jet), and 3 (another VLJ).
- case (f) – TCAS I equipped threat. Possible in scenarios 1 (GA aircraft), and 3 (another VLJ);
- case (g) – TCAS II equipped threat. Possible in scenario 3 (another VLJ), and to be expected in scenarios 4 (medium passenger jet), and 5 (large passenger jet)

5. Results and discussion

5.1. Interpretation of the diagrams

- 5.1.1. The probabilities of visual acquisition have been calculated for the scenarios and cases of section 4. These probabilities are plotted on the polar encounter geometry diagrams described in section 2.2. The diagrams are colour coded so that blue represents a probability of 0% to 5% (*i.e.* in 100 encounters with the given geometry the event of interest will on average occur in 5 or less) through the spectrum to red which represents a probability of 95% to 100% (*i.e.* in 100 encounters the event of interest will on average occur in 95 or more).
- In cases (a), (b), (c), and (d) – simple visual acquisition by a given time – colours towards the red end of the spectrum (*i.e.* a high probability of visual acquisition) are generally desirable.
 - However, in cases (e), (f), (g) – visual acquisition within 10s of a potential manoeuvre by the threat – colours towards the red end of the spectrum (*i.e.* a high probability of uncoordinated manoeuvres by both aircraft at about the same time) are generally undesirable.
- 5.1.2. Encounter geometries corresponding to speeds of the threat aircraft that are unlikely to occur operationally are left blank (*i.e.* coloured white) on the diagrams. Consequently there is a blank circular area at the centre of each diagram corresponding to threat speeds that are unrealistically low, and generally a blank annular area around the outside of the diagram corresponding to threat speeds that are unrealistically high.
- 5.1.3. The aircraft symbol below the centre of the diagram represents the speed and heading of own aircraft. Extending below the own aircraft symbol is a V-shaped area with 0% probability of visual acquisition (therefore coloured blue) corresponding to encounter geometries in which the threat approaches from behind own aircraft in a region that is obscured from the cockpit of own aircraft (see paragraph 3.5.4).
- 5.1.4. The simple model of cockpit visibility means that the probability plots would normally be symmetrical with the left and right halves of the plot being mirror images of each other. Rather than duplicate information, each diagram is used to plot the results for two values of visibility: on the left-hand side of each diagram are plotted the probabilities corresponding to unlimited visibility ($R = \infty$); on the right-hand side of each diagram are plotted the probabilities corresponding to the visibility limit allowed for VFR ($R = 5\text{km}$ or 8km depending on altitude).
- 5.1.5. In diagrams showing the probability of simple visual acquisition (*e.g.* Figure 17) the encounter geometries close to the own aircraft symbol correspond to encounters with a low closing speed. In these encounters the threat has a high detectability for a relatively long time and so the probability of visual acquisition is high (red, orange, and yellow tints).
- 5.1.6. As the angle of approach becomes less acute the closing speed increases and the probability of visual acquisition is lower (green and blue tints).

- 5.1.7. The effect of the meteorological visibility can be seen by comparing the size of the area of high probability of visual acquisition on left-hand side of the diagrams (unlimited visibility) with the similar but smaller area on the right-hand side of the diagrams (visibility at the limit of VFR rules).
- 5.1.8. In diagrams showing the probability of potentially incompatible manoeuvres (e.g. Figure 23) the probability in encounter geometries with a low closing speed is generally small – in these encounters visual acquisition of the threat by own aircraft has a high probability and tends to occur before a manoeuvre by the threat (be it prompted by visual acquisition or an RA). At moderate closing speeds the probability of potentially incompatible manoeuvres rises to a maximum before falling off at high closing speeds where visual acquisition by own aircraft tends to occur (if it occurs at all) after a manoeuvre by the threat.

5.2. Scenario 1

5.2.1. Description

- 5.2.1.1. In scenario 1 own aircraft is travelling at a speed of 150kt at an altitude between 1,000ft and 2,000ft AGL.
- 5.2.1.2. At these altitudes the nominal TCAS I TA warning time is 20s and the nominal ACAS II RA warning time is 15s. The limit of visibility for flying VFR is 5km.
- 5.2.1.3. The threat aircraft is taken to be a Piper PA23: a twin-engined piston GA aircraft flying at a speed in the range 100kt to 225kt. The threat aircraft is likely to be unequipped or equipped with TCAS I.

5.2.2. Simple visual acquisition

- 5.2.2.1. The probability of visual acquisition of the threat is shown in Figure 6 (scenario 1a) and Figure 7 (scenario 1b) for own aircraft unequipped, and in Figure 8 (scenario 1c) and Figure 9 (scenario 1d) for own aircraft equipped with TCAS I.
- 5.2.2.2. At the altitude of this scenario (1,000ft – 2,000ft AGL) the nominal RA warning time is 15s and so cases (b) and (d) (visual acquisition by 15s before collision) are effectively the same as cases (a) and (c) (visual acquisition by the time of an ACAS II RA) respectively.

5.2.3. Potentially incompatible manoeuvres

- 5.2.3.1. The probability of potentially incompatible manoeuvres is shown in Figure 10 for an unequipped threat, and in Figure 11 for the threat equipped with TCAS I.

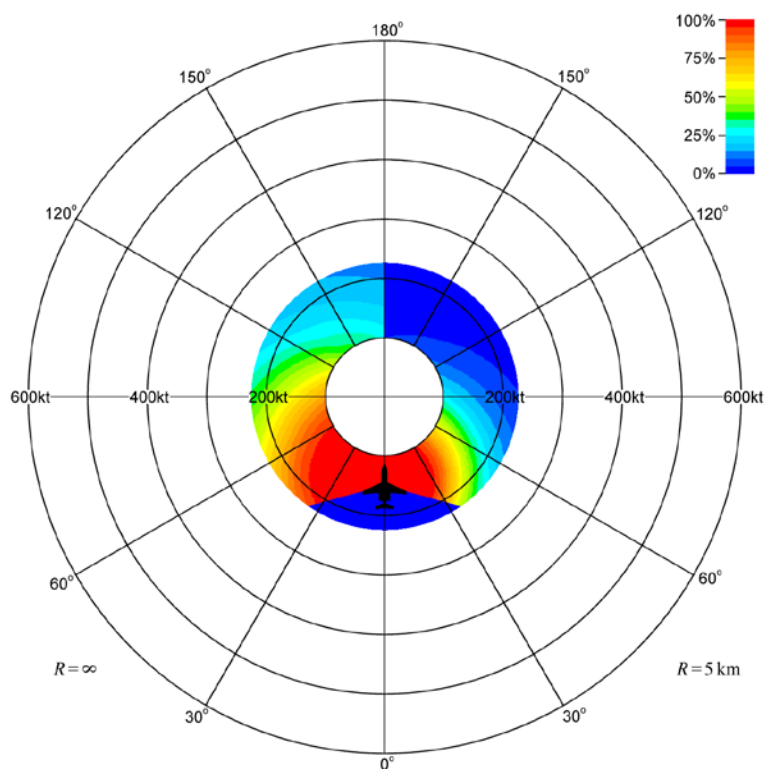


Figure 6: Scenario 1a – probability of visual acquisition of GA aircraft by unequipped VLJ, by 15s before collision.

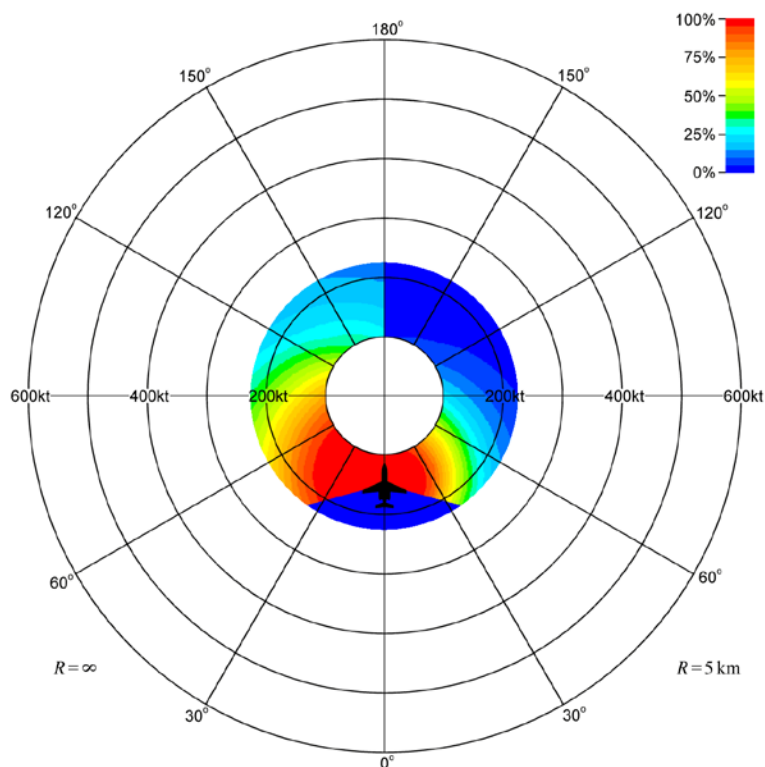


Figure 7: Scenario 1b – probability of visual acquisition of GA aircraft by unequipped VLJ, by time ACAS II RA would be issued.

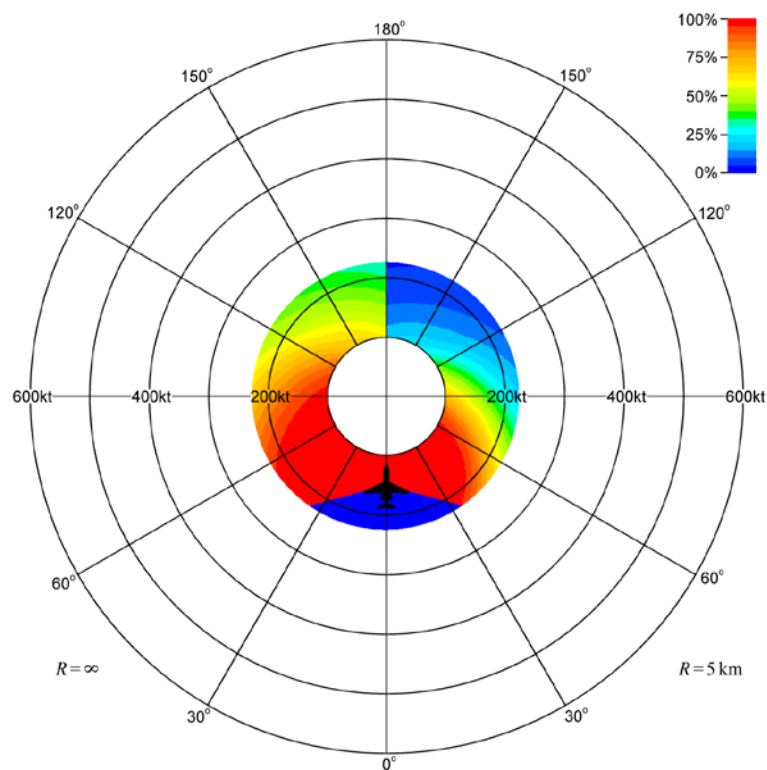


Figure 8: Scenario 1c – probability of visual acquisition of GA aircraft by TCAS I equipped VLJ, by 15s before collision.

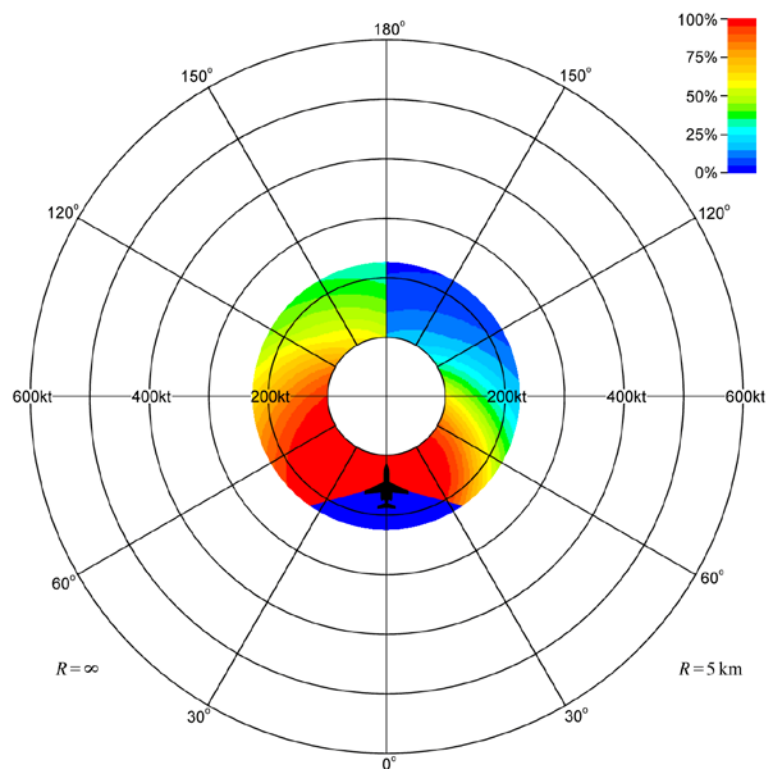


Figure 9: Scenario 1d – probability of visual acquisition of GA aircraft by TCAS I equipped VLJ, by time ACAS II RA would be issued.

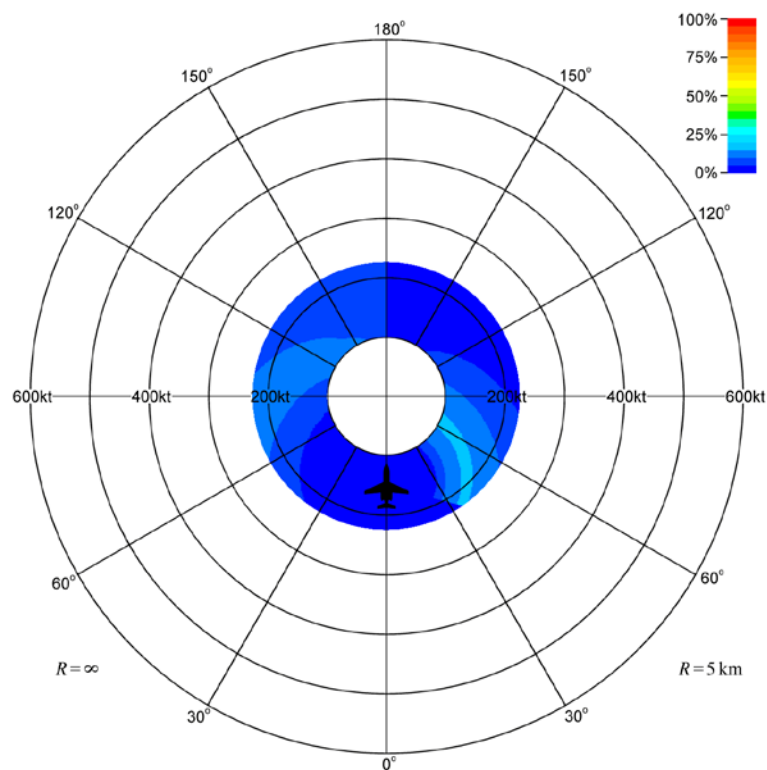


Figure 10: Scenario 1e – probability of visual acquisition by TCAS I equipped VLJ and unequipped GA, within 10s of each other.

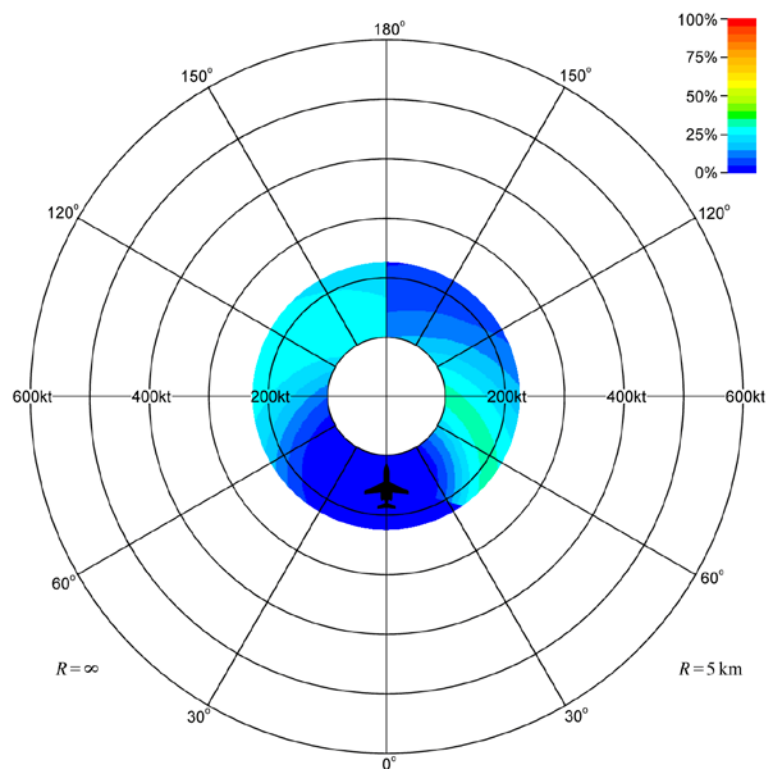


Figure 11: Scenario 1f – probability of visual acquisition by TCAS I equipped VLJ and TCAS I equipped GA, within 10s of each other.

5.3. Scenario 2

5.3.1. Description

- 5.3.1.1. In scenario 2 own aircraft is travelling at a speed of 200kt at an altitude between 2,500ft AGL and FL50.
- 5.3.1.2. At these altitudes the nominal TCAS I TA warning time is 30s and the nominal ACAS II RA warning time is 20s. The limit of visibility for flying VFR is 5km.
- 5.3.1.3. The threat aircraft is taken to be a Dassault Mirage F1 (a single-seat military fast jet) flying at a speed in the range 150kt to 600kt. The threat aircraft is likely to be unequipped.

5.3.2. Simple visual acquisition

- 5.3.2.1. The probability of visual acquisition of the threat is shown in Figure 12 (scenario 2a) and Figure 13 (scenario 2b) for own aircraft unequipped, and in Figure 14 (scenario 2c) and Figure 15 (scenario 2d) for own aircraft equipped with TCAS I.

5.3.3. Potentially incompatible manoeuvres

- 5.3.3.1. The probability of potentially incompatible manoeuvres is shown in Figure 16 for an unequipped threat.

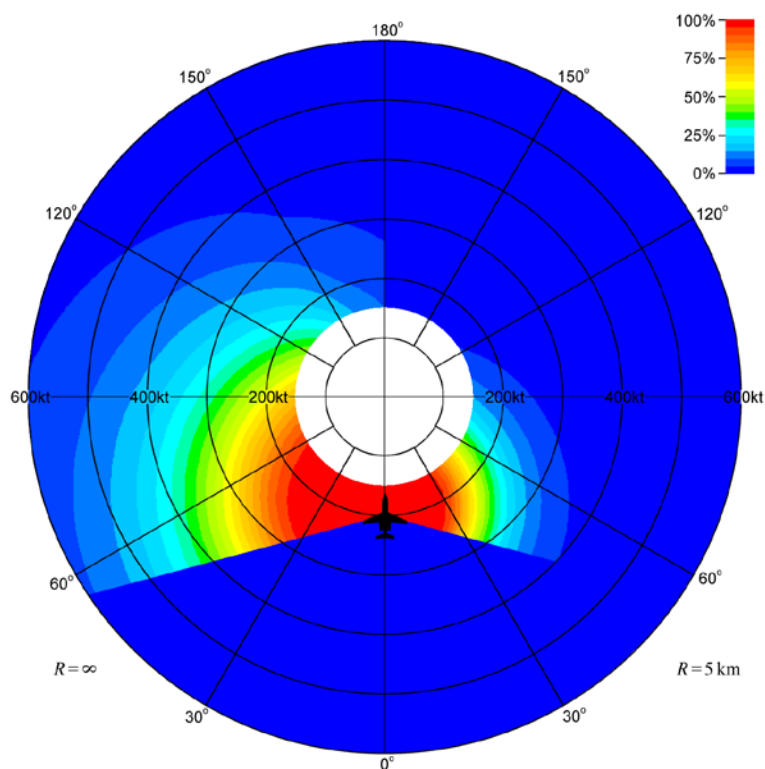


Figure 12: Scenario 2a – probability of visual acquisition of military fast jet by unequipped VLJ, by 15s before collision.

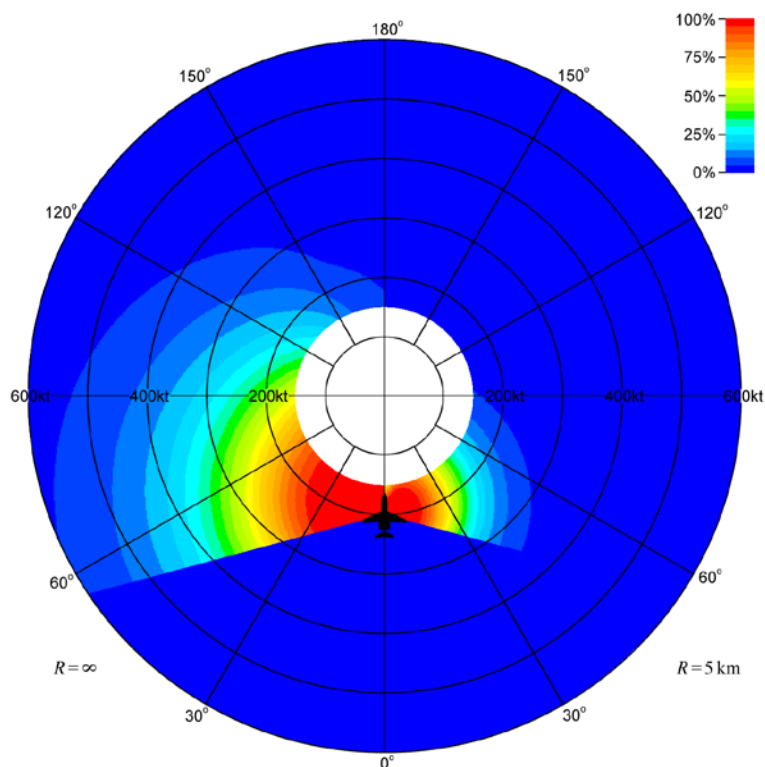


Figure 13: Scenario 2b – probability of visual acquisition of military fast jet by unequipped VLJ, by time ACAS II RA would be issued.

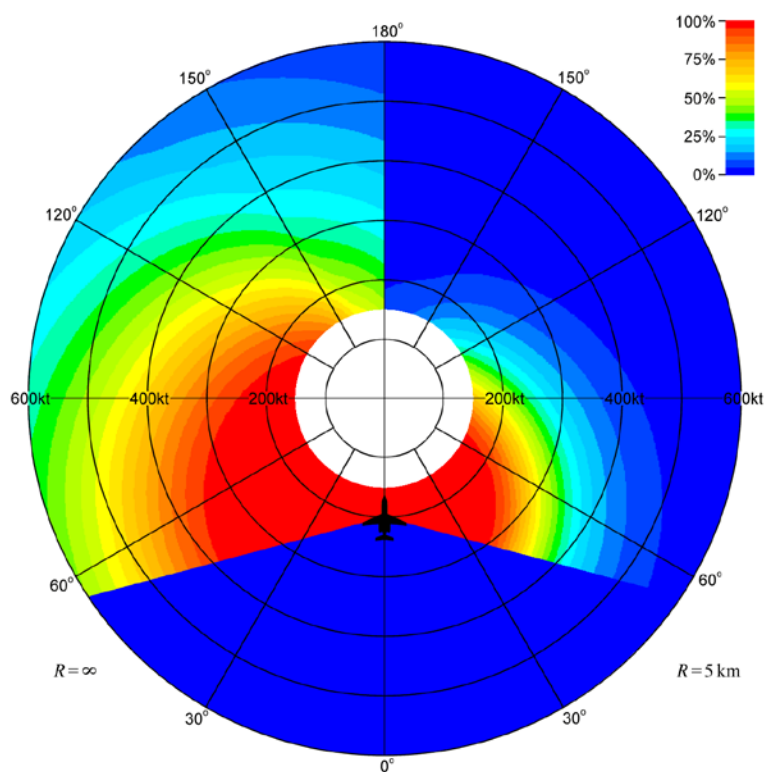


Figure 14: Scenario 2c – probability of visual acquisition of military fast jet by TCAS I equipped VLJ, by 15s before collision.

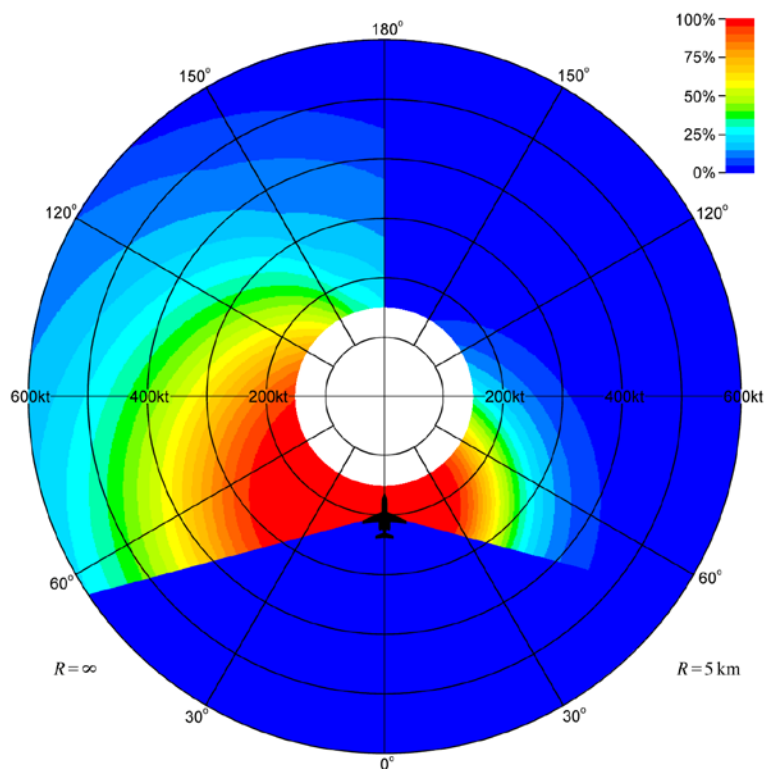


Figure 15: Scenario 2d – probability of visual acquisition of military fast jet by TCAS I equipped VLJ, by time ACAS II RA would be issued.

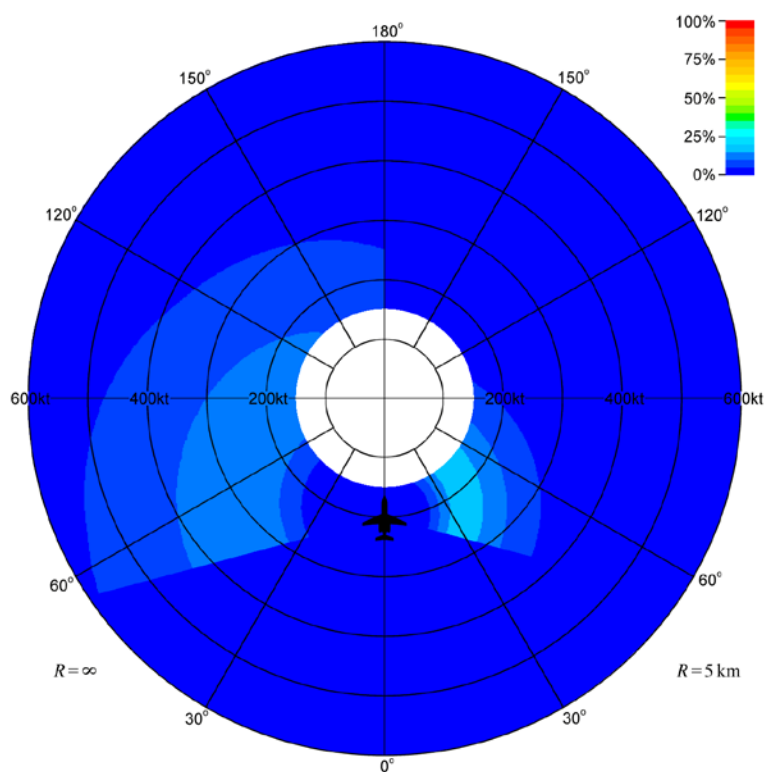


Figure 16: Scenario 2e – probability of visual acquisition by TCAS I equipped VLJ and unequipped military fast jet, within 10s of each other.

5.4. Scenario 3

5.4.1. Description

- 5.4.1.1. In scenario 3 own aircraft is travelling at a speed of 250kt at an altitude between FL50 and FL100.
- 5.4.1.2. At these altitudes the nominal TCAS I TA warning time is 30s and the nominal ACAS II RA warning time is 25s. The limit of visibility for flying VFR is 5km.
- 5.4.1.3. The threat aircraft is taken to be a Embraer Phenom 100 (another VLJ) flying at a speed in the range 100kt to 350kt. The threat aircraft is likely to be unequipped, equipped with TCAS I, or equipped with ACAS II.

5.4.2. Simple visual acquisition

- 5.4.2.1. The probability of visual acquisition of the threat is shown in Figure 17 (scenario 3a) and Figure 18 (scenario 3b) for own aircraft unequipped, and in Figure 19 (scenario 3c) and Figure 20 (scenario 3d) for own aircraft equipped with TCAS I.

5.4.3. Potentially incompatible manoeuvres

- 5.4.3.1. The probability of potentially incompatible manoeuvres is shown in Figure 21 for an unequipped threat, and in Figure 22 for the threat equipped with TCAS I.
- 5.4.3.2. The probability of potentially incompatible manoeuvres is shown in Figure 23 for the threat equipped with ACAS II.

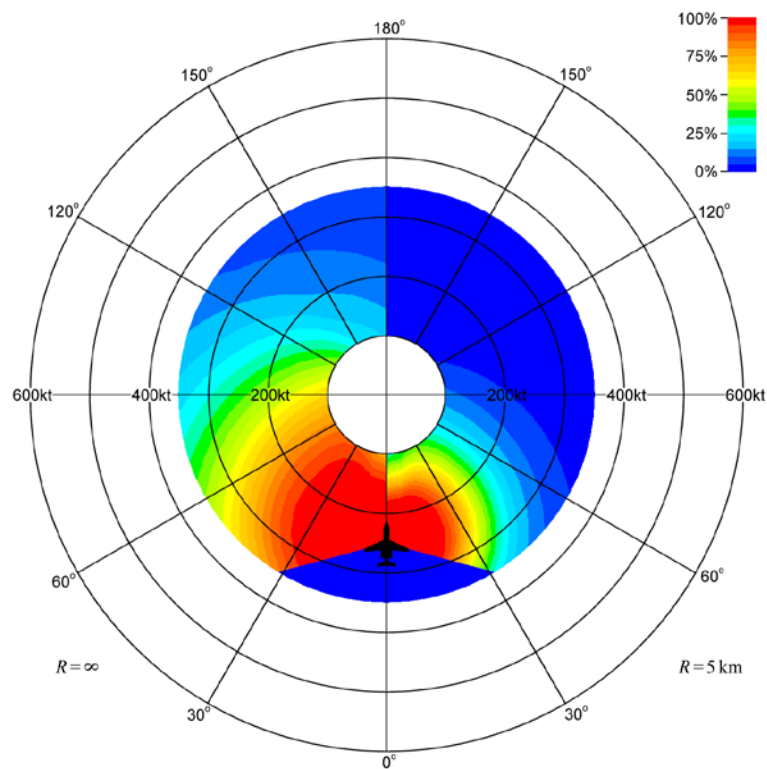


Figure 17: Scenario 3a – probability of visual acquisition of another VLJ by unequipped VLJ, by 15s before collision.

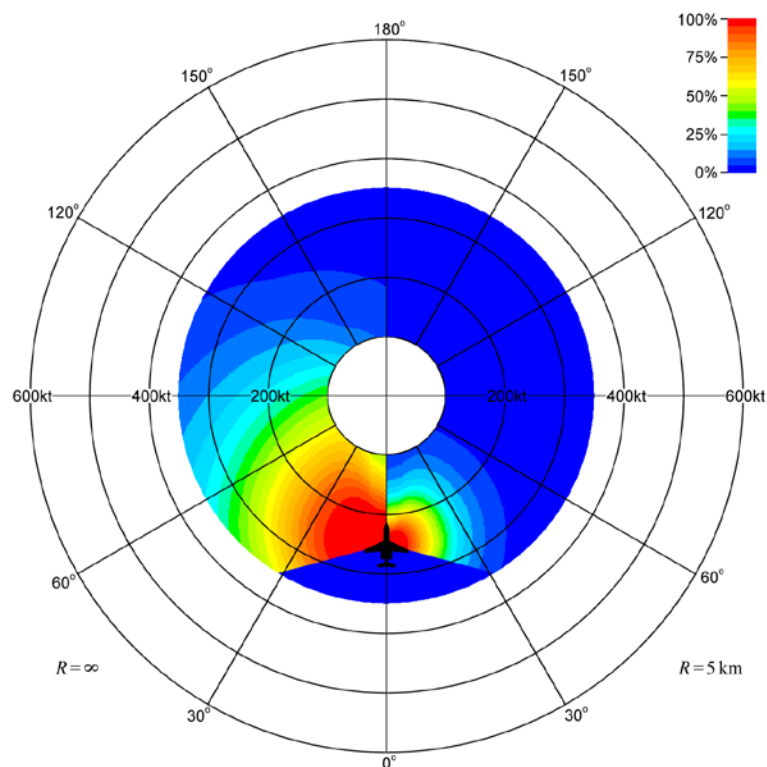


Figure 18: Scenario 3b – probability of visual acquisition of another VLJ by unequipped VLJ, by time ACAS II RA would be issued.

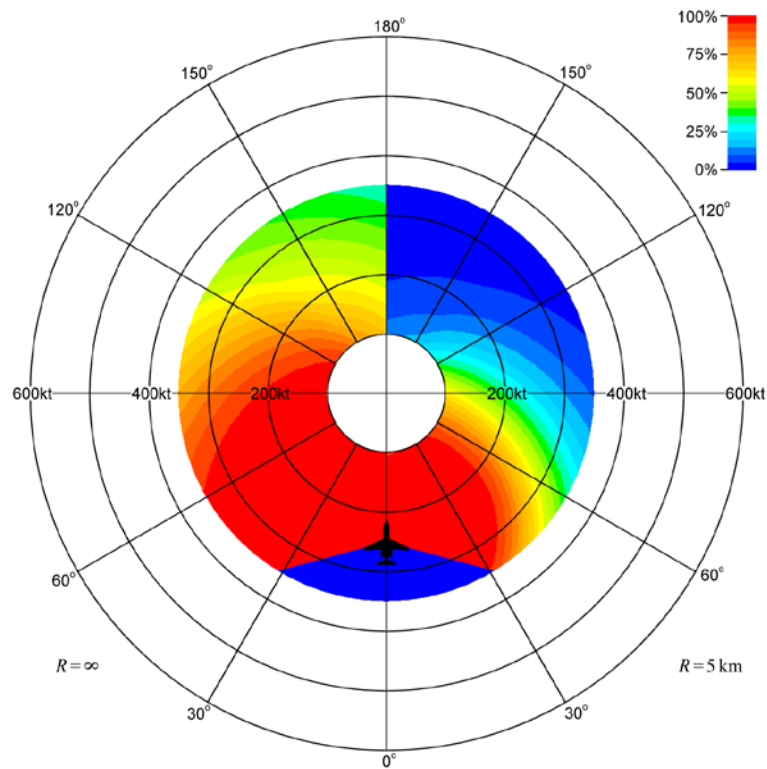


Figure 19: Scenario 3c – probability of visual acquisition of another VLJ by TCAS I equipped VLJ, by 15s before collision.

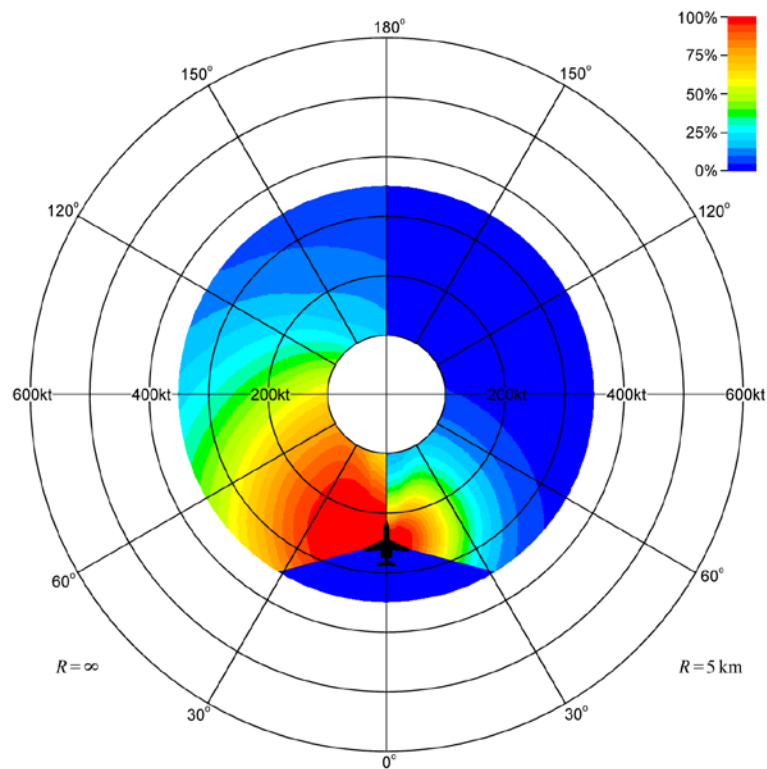


Figure 20: Scenario 3d – probability of visual acquisition of another VLJ by TCAS I equipped VLJ, by time ACAS II RA would be issued.

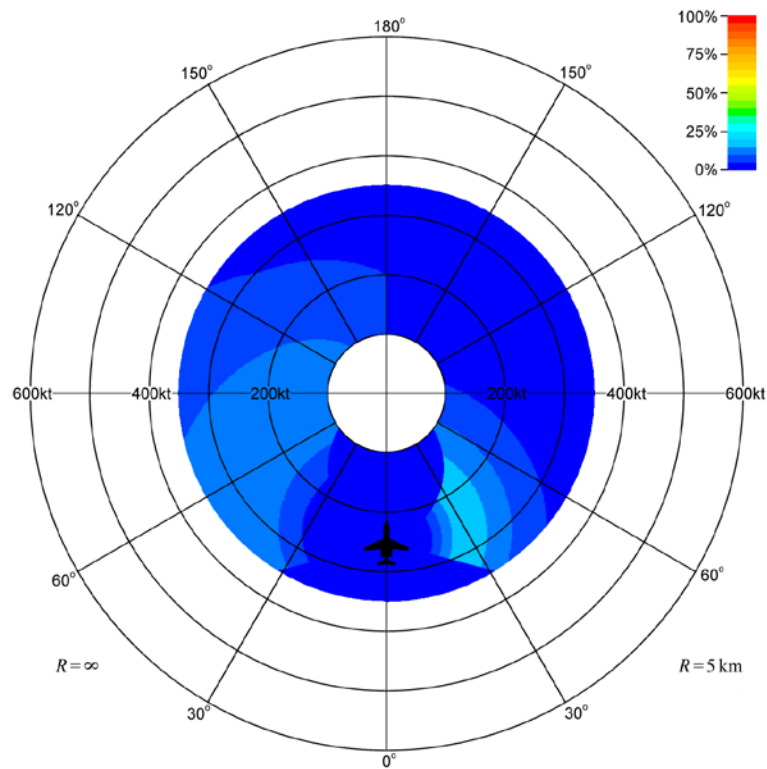


Figure 21: Scenario 3e – probability of visual acquisition by TCAS I equipped VLJ and unequipped VLJ, within 10s of each other.

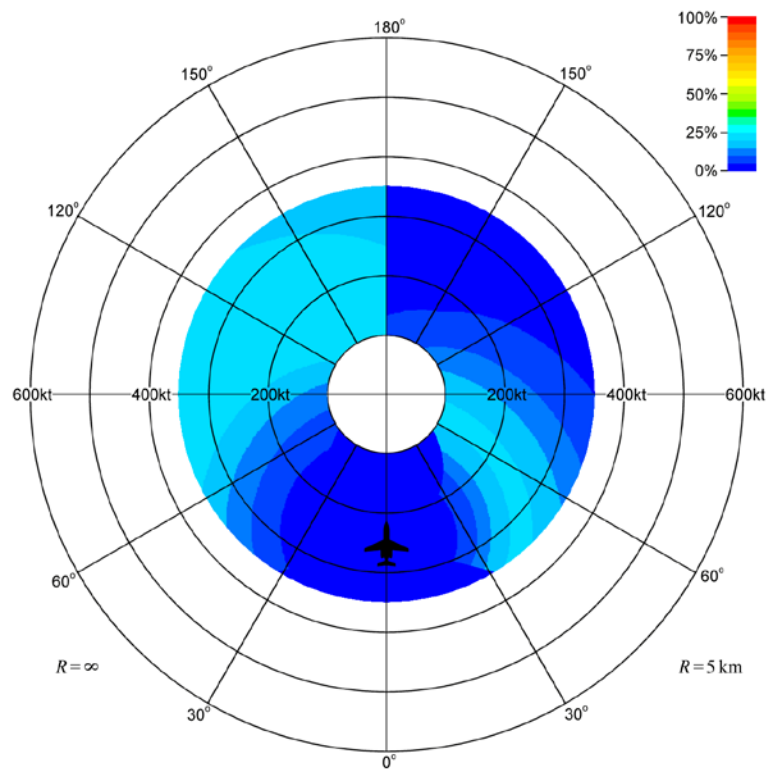


Figure 22: Scenario 3f – probability of visual acquisition by TCAS I equipped VLJ and another TCAS I equipped VLJ, within 10s of each other.

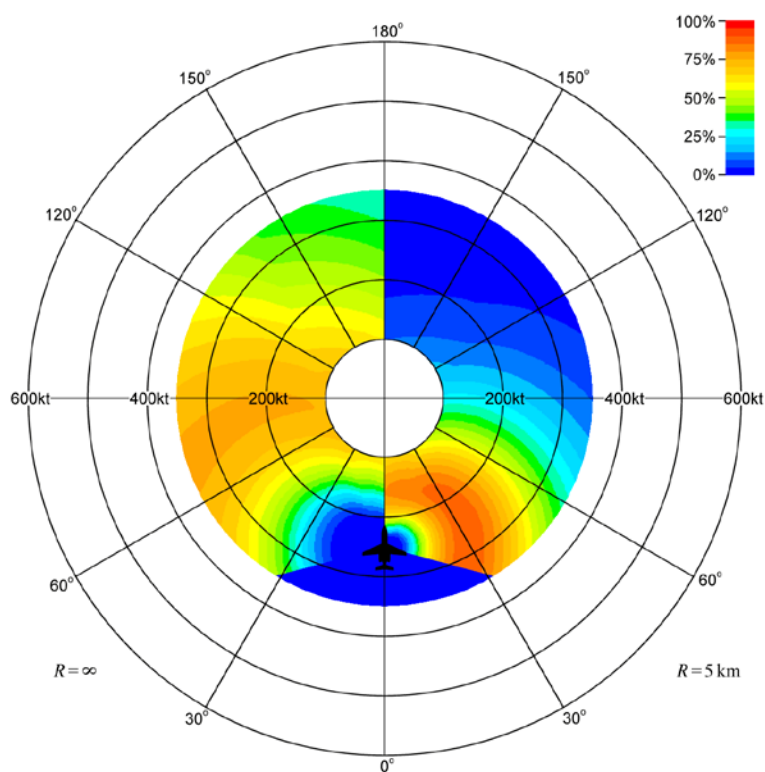


Figure 23: Scenario 3g – probability of visual acquisition by TCAS I equipped VLJ and RA in TCAS II equipped VLJ, within 10s of each other.

5.5. Scenario 4

5.5.1. Description

- 5.5.1.1. In scenario 4 own aircraft is travelling at a speed of 300kt at an altitude between FL100 and FL200.
- 5.5.1.2. At these altitudes the nominal TCAS I TA warning time is 30s and the nominal ACAS II RA warning time is 30s. The limit of visibility for flying VFR is 8km.
- 5.5.1.3. The threat aircraft is taken to be an Airbus A320 (a medium-sized passenger aircraft) flying at a speed in the range 200kt to 500kt. The threat aircraft falls within the ACAS mandate and will therefore be equipped with ACAS II.

5.5.2. Simple visual acquisition

- 5.5.2.1. The probability of visual acquisition of the threat is shown in Figure 24 (scenario 4a) and Figure 25 (scenario 4b) for own aircraft unequipped, and in Figure 26 (scenario 4c) and Figure 25 (scenario 4d) for own aircraft equipped with TCAS I.
- 5.5.2.2. Scenarios 4b and 4d (visual acquisition by the time of an ACAS RA) are covered by a single diagram because at the altitude of the scenario (FL100 to FL200) the ACAS II RA parameters exceed the TCAS I TA parameters. Consequently, an ACAS II RA would always be issued before the TCAS I TA and so equipage with TCAS I does not alter the probability of visual acquisition.

5.5.3. Potentially incompatible manoeuvres

- 5.5.3.1. The probability of potentially incompatible manoeuvres is shown in Figure 27 for the threat equipped with ACAS II.

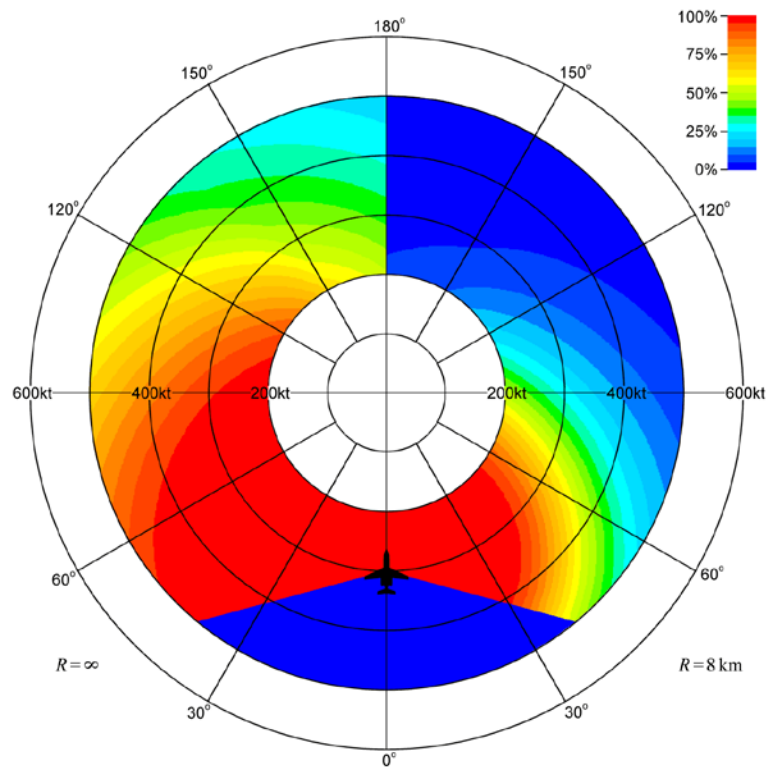


Figure 24: Scenario 4a – probability of visual acquisition of medium passenger jet, by unequipped VLJ, by 15s before collision.

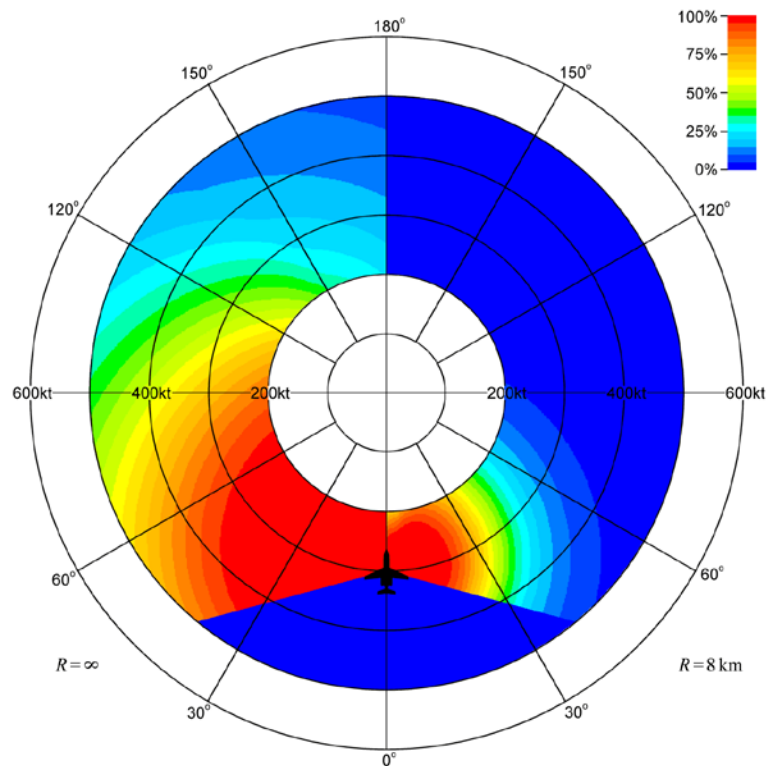


Figure 25: Scenarios 4b and 4d – probability of visual acquisition of medium passenger jet by VLJ, by time ACAS II RA would be issued.

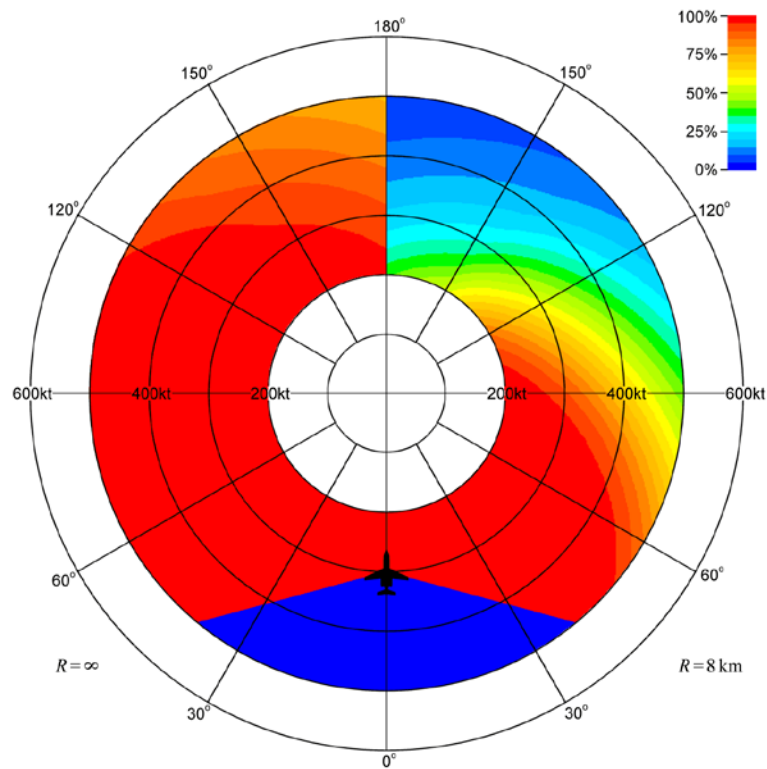


Figure 26: Scenario 4c – probability of visual acquisition of medium passenger jet by TCAS I equipped VLJ, by 15s before collision.

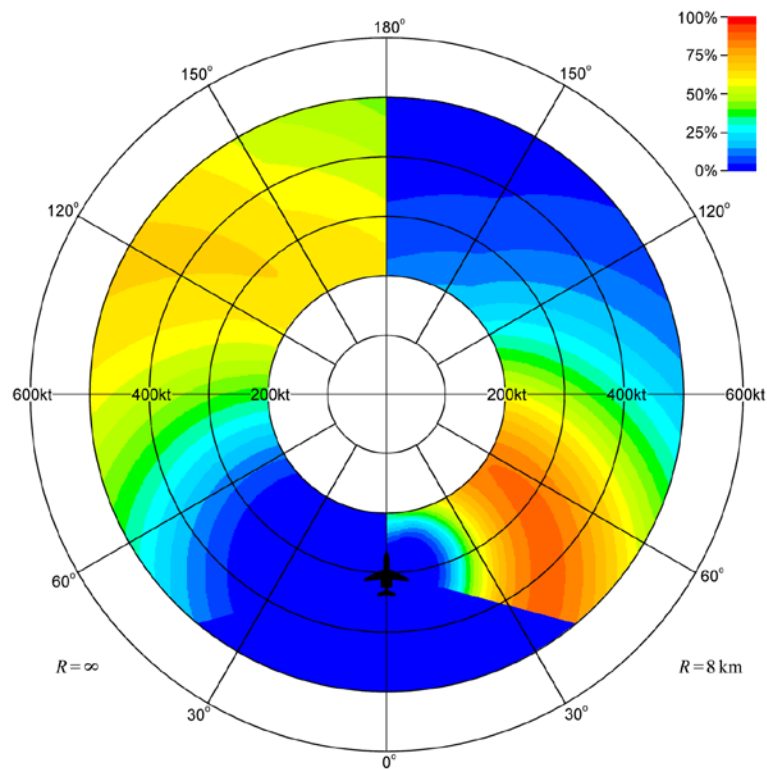


Figure 27: Scenario 4g – probability of visual acquisition by TCAS I equipped VLJ and RA in TCAS II equipped medium passenger jet, within 10s of each other.

5.6. Scenario 5

5.6.1. Description

- 5.6.1.1. In scenario 5 own aircraft is travelling at a speed of 350kt at an altitude above FL200.
- 5.6.1.2. At these altitudes the nominal TCAS I TA warning time is 30s and the nominal ACAS II RA warning time is 35s. The limit of visibility for flying VFR is 8km.
- 5.6.1.3. The threat aircraft is taken to be a Boeing 747 (a long-haul passenger aircraft) flying at a speed in the range 300kt to 550kt. The threat aircraft falls within the ACAS mandate and will therefore be equipped with ACAS II.

5.6.2. Simple visual acquisition

- 5.6.2.1. The probability of visual acquisition of the threat is shown in Figure 28 (scenario 5a) and Figure 29 (scenario 5b) for own aircraft unequipped, and in Figure 30 (scenario 5c) and Figure 29 (scenario 5d) for own aircraft equipped with TCAS I.
- 5.6.2.2. Scenarios 5b and 5d (visual acquisition by the time of an ACAS RA) are covered by a single diagram because at the altitude of the scenario (above FL200) the ACAS II RA parameters exceed the TCAS I TA parameters. Consequently, an ACAS II RA would always be issued before the TCAS I TA and so equipage with TCAS I does not alter the probability of visual acquisition.

5.6.3. Potentially incompatible manoeuvres

- 5.6.3.1. The probability of potentially incompatible manoeuvres is shown in Figure 31 for the threat equipped with ACAS II.

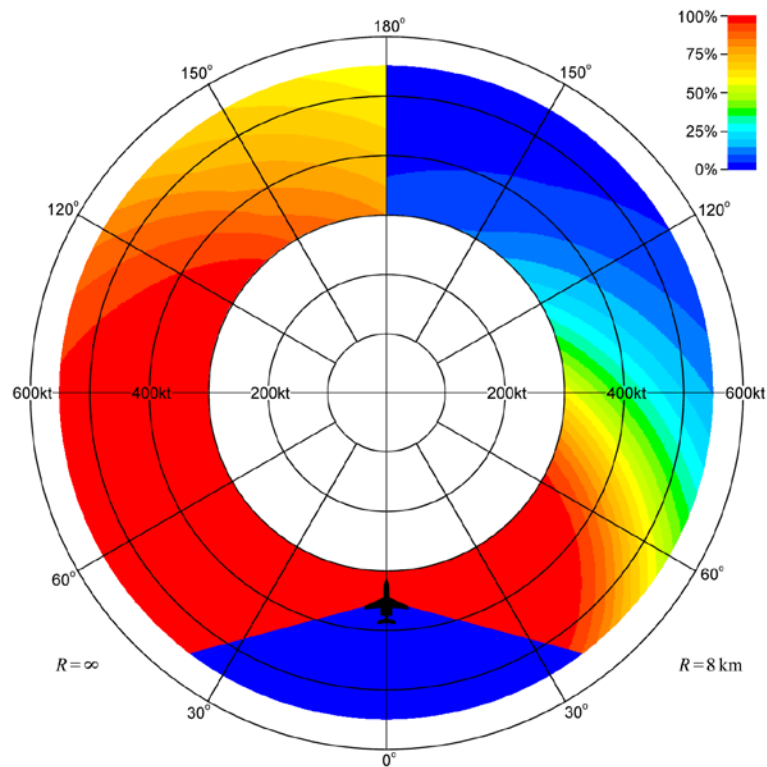


Figure 28: Scenario 5a – probability of visual acquisition of large passenger jet by unequipped VLJ, by 15s before collision.

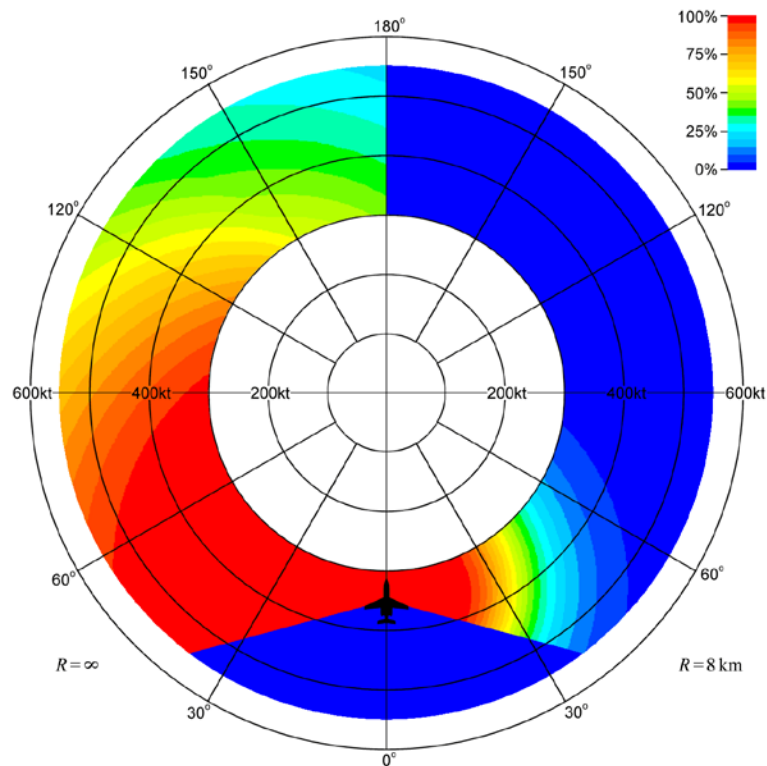


Figure 29: Scenarios 5b and 5d – probability of visual acquisition of large passenger jet by VLJ, by time ACAS II RA would be issued.

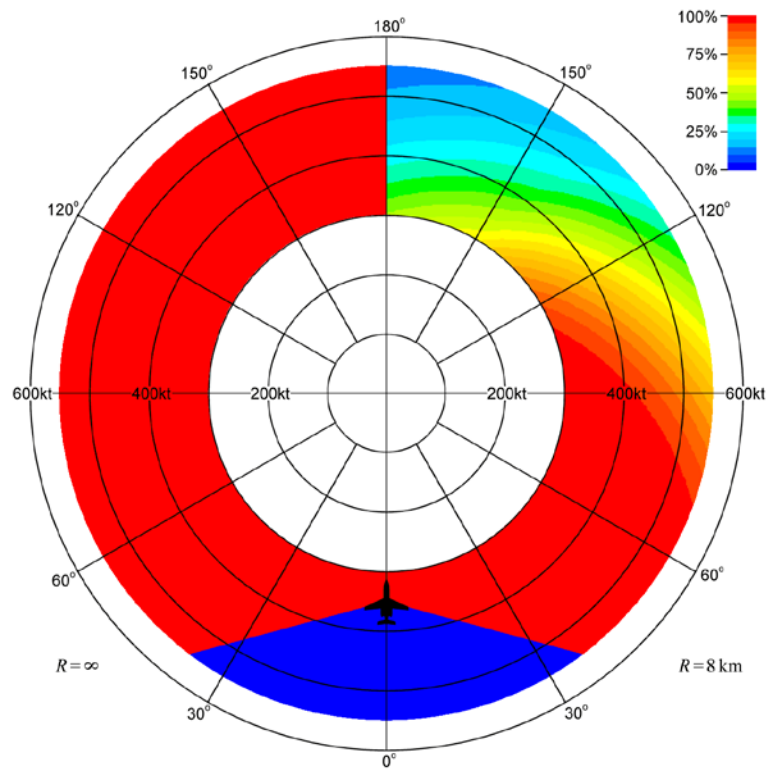


Figure 30: Scenario 5c – probability of visual acquisition of large passenger jet by TCAS I equipped VLJ, by 15s before collision.

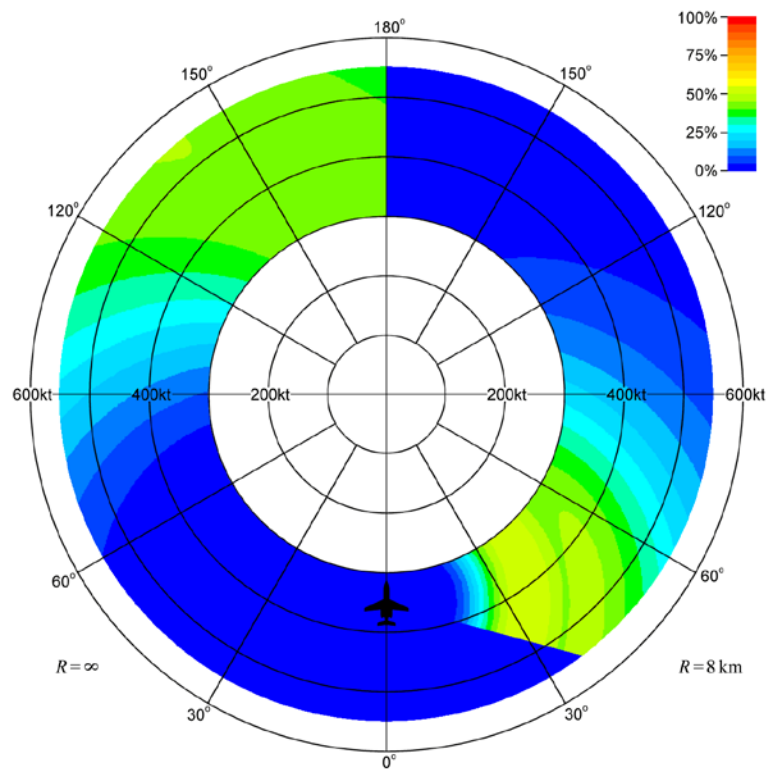


Figure 31: Scenario 5g – probability of visual acquisition by TCAS I equipped VLJ and RA in TCAS II equipped large passenger jet, within 10s of each other.

5.7. Discussion

5.7.1. Simple visual acquisition

- 5.7.1.1. When the meteorological visibility is unlimited TCAS I provides a definite enhancement to the probability of visual acquiring a collision threat. This can be seen, for example, by comparing the left-hand side of Figure 17 with the left-hand side of Figure 19. Figure 17 shows that, with unlimited visibility, a pilot of an unequipped aircraft travelling at 250kt has a less than 50% chance of usefully (*i.e.* by the time that 15s remain until the potential collision) visually acquiring another VLJ on a collision course if the closing speed exceeds 350kt. Figure 19 shows the same scenario but with TCAS I deployed – here the pilot has a 50% chance of usefully visually acquiring the threat with closing speeds up to 550kt (except, of course, when the collision threat is a faster aircraft approaching from behind – this caveat applies to all the comments made here).
- 5.7.1.2. The benefits of TCAS I (in terms of enhanced visual acquisition) are most noticeable against larger threats such as the medium-sized passenger aircraft considered in scenario 4 (compare Figure 24 with Figure 26) and the large passenger aircraft considered in scenario 5 (compare Figure 28 with Figure 30). In these scenarios the probability of useful visual acquisition at the highest closing speeds (with unlimited visibility) rise from 25% to 75% and from 55% to 95% respectively.
- 5.7.1.3. Against smaller sized threats (such as the GA aircraft in scenario 1, the military fast jet in scenario 2, and the VLJ in scenario 3) the benefits of TCAS I equipage are less marked. Against the slower aircraft (GA and VLJs) the probability of useful visual acquisition in unlimited visibility with TCAS I is no higher than 35% at the highest closing speeds (see Figure 8 and Figure 19), and against a military jet can be as low as 10% (see Figure 14).
- 5.7.1.4. The benefits of TCAS I (in terms of enhanced visual acquisition) are highly dependent on the meteorological visibility. As the visibility approaches the limit for flying VFR the probability of visual acquisition (as shown on the right-hand side of the diagrams) is noticeably reduced in all scenarios as described below.
- 5.7.1.5. Against the smaller sized threats of scenarios 1, 2, and 3 the probability of useful visual acquisition by a TCAS I equipped aircraft in visibility at the VFR limit of 5km is less than 50% for closing speeds over 300kt (see the right-hand sides of Figure 8, Figure 14, and Figure 19).
- 5.7.1.6. Even against the larger-sized threats of scenarios 4 and 5 there is a marked reduction in the probability of useful visual acquisition by a TCAS I equipped aircraft in visibility at the VFR limit of 8km:
- against a medium-sized passenger aircraft the probability of useful visual acquisition is less than 50% for closing speeds over 600kt and is as low as 10% for the highest closing speeds (see right-hand side of Figure 26);
 - against a large passenger aircraft the probability of useful visual acquisition is less than 50% for closing speeds over 750kt and is as low as 15% for the highest closing speeds (see right-hand side of Figure 30).

5.7.2. Potentially incompatible manoeuvres

- 5.7.2.1. The probability of an unequipped threat usefully visually acquiring own aircraft (a VLJ) is comparatively low except at the lowest closing speeds (see, for example, Figure 17). Consequently when both the threat and own aircraft are unequipped the probability of each visually acquiring the other within a time span of 10s is also low – less than 20% (see Figure 10, Figure 16, and Figure 21).
- 5.7.2.2. When the threat is equipped with TCAS I the probability of its usefully visually acquiring own aircraft is increased (see, for example, Figure 19). This increase in the probability of useful visual acquisition also brings with it an increase in the probability of potentially incompatible manoeuvres. Against a threat equipped with TCAS I the probability of each visually acquiring the other within a time span of 10s is higher: up to 35% for GA equipped with TCAS I in scenario 1 (see Figure 11); up to 25% for another VLJ equipped with TCAS I in scenario 3 (see Figure 22).
- 5.7.2.3. When the threat is equipped with ACAS II the time interval in which potentially incompatible manoeuvres might occur is constrained (to the time of the RA ± 10 s). During this interval the probability of visual acquisition of the ACAS II equipped threat by a TCAS I equipped VLJ will be comparatively high and so the probability of potentially incompatible manoeuvres is also high.
- 5.7.2.4. When the meteorological visibility is unlimited the time at which visual acquisition is likely to occur is spread-out and so there is a moderately high probability of potentially incompatible manoeuvres at a range of closing speeds:
- up to 80% probability at closing speeds of 350kt against a VLJ in scenario 3 (see left-hand side of Figure 23);
 - up to 70% probability at closing speeds of 650kt against a medium-sized passenger aircraft in scenario 4 (see left-hand side of Figure 27);
 - up to 45% probability at closing speeds of 850kt against a large passenger aircraft in scenario 5 (see left-hand side of Figure 31);
- 5.7.2.5. When the meteorological visibility is reduced the time at which visual acquisition is likely to occur becomes compressed towards the time of collision. There is consequently a greater overlap of the likely time of visual acquisition and the interval of time of the around the RA. This in turn leads to a higher peak probability of potentially incompatible manoeuvres concentrated in a narrower band of closing speeds:
- up to 90% probability at closing speeds of 150kt against a VLJ in scenario 3 (see right-hand side of Figure 23);
 - up to 90% probability at closing speeds of 250kt against a medium-sized passenger aircraft in scenario 4 (see right-hand side of Figure 27);
 - up to 50% probability at closing speeds of 250kt against a large passenger aircraft in scenario 5 (see right-hand side of Figure 31);

6. Conclusions

6.1. *Visual acquisition model*

- 6.1.1. The comparatively simple Lincoln Laboratory model of visual acquisition has been implemented and successfully used to illustrate the probability of visual acquisition, both with and without TCAS I, in a number of illustrative scenarios.
- 6.1.2. The scenarios could easily be extended to include the full range and combination of parameters, which if suitably weighted, could provide average values of visual acquisition to be used in safety analyses.
- 6.1.3. The instantaneous visual acquisition rate used in the model could be used stochastically to determine the instant of visual acquisition in a simulation based study of the effectiveness of ACAS equipage. Such a study could also include avoidance manoeuvres prompted by visual acquisition.

6.2. *Simple visual acquisition*

- 6.2.1. Equipage with TCAS I can undoubtedly enhance the prospect of visually acquiring a collision threat in certain scenarios:
 - it is most effective against the larger aircraft types (medium and large passenger aircraft) considered in scenarios 4 and 5;
 - it is less effective against the smaller aircraft types (GA, military fast jets, and VLJs) considered in scenarios 1, 2, and 3;
 - it is particularly ineffective against small-sized threats with high closing speeds (scenario 2) in which there is virtually no prospect of visual acquisition, even when equipped with TCAS I, at the highest closing speeds.
- 6.2.2. TCAS I is naturally of no benefit in visually acquiring collision threats which approach from behind.
- 6.2.3. Although effective in certain scenarios when the meteorological visibility is unlimited, this effectiveness is markedly decreased when the visibility decreases. Even at the limit of visibility for VFR the usefulness of TCAS I as an aid to visual acquisition is severely curtailed, even against the larger-sized threats. This effectiveness will obviously be further reduced (ultimately to nil) in IMC.

6.3. *Potentially incompatible manoeuvres*

- 6.3.1. The enhancement of the probability of usefully visually acquiring a collision threat ironically brings with it an increase in the probability that the two aircraft will potentially employ incompatible avoidance manoeuvres. This in turn may decrease or even negate the effectiveness of these manoeuvres.

- 6.3.2. The effect is most marked against threats which are equipped with ACAS II since the interval around the time at which an RA will be generated corresponds to times at which the occurrence of visual acquisition is high.

6.4. *Further work*

- 6.4.1. The work reported has shown that TCAS I equipage can enhance the prospect of visual acquisition in suitable conditions. However, this enhanced visual acquisition carries with it the possibility of an increased probability of incompatible manoeuvres being selected by the two aircraft in a collision geometry. The selection of incompatible manoeuvres could negate the benefits of TCAS I equipage and could conceivably even increase the risk of mid-air collision in certain encounter geometries by compromising the effectiveness of ACAS RAs.
- 6.4.2. To fully assess the consequence of these competing effects and determine what safety benefit, if any, results from TCAS I equipage (and how it compares to the expected safety benefit resulting from ACAS II equipage), it is necessary to model not only visual acquisition but also the avoidance manoeuvres that a pilot might employ in response to visual acquisition. The method by which the current visual acquisition model, and subsequent avoidance manoeuvres, could be incorporated into safety study simulations of the effectiveness of ACAS II was described in paragraph 3.7.4.

7. References

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A. Derivation of TCAS warning times

A.1. The TCAS system on-board an aircraft continuously (once per second) measures the range of potential threats, r , and from the sequence of range measurements derives the range rate, \dot{r} . These measurements are used to estimate the time to any collision.

A.2. In a collision geometry an alert is generated when the estimated time to collision falls below a time threshold, T , which depends on altitude (being larger, *i.e.* more sensitive, at higher altitude).

A.3. A simple estimate of the time, τ , remaining to any collision with the threat assumes that the aircraft are on a collision course and calculates the time needed to erode a separation of, r , given a closing rate, \dot{r} , thus:

$$\tau = \frac{-r}{\dot{r}} \quad (14)$$

(The minus sign reflects the fact that the range rate is negative when the range is decreasing.)

A.4. A refinement to this estimated time to collision introduces the Bramson criterion to ensure that there is sufficient warning time to allow for late manoeuvres in slow closure encounters (when both aircraft have similar speeds and headings). This refinement decrements the measured range by a quantity D^2/r where D is a distance modifier (known as “DMOD”) which depends on altitude (being larger, *i.e.* more sensitive, at higher altitude):

$$\tau = \frac{-\left| r - \frac{D^2}{r} \right|}{\dot{r}} \quad (15)$$

This can be rearranged as:

$$\tau = \left| \frac{D^2 - r^2}{r\dot{r}} \right| \quad (16)$$

A.5. In a rectilinear collision geometry the range rate is the closing speed u , and with time t remaining until collision the range is ut . A TCAS alert will be triggered at time t_{alert} when the estimated time to collision, τ , falls below the nominal warning time T . Substituting these expressions into Eqn. (16) gives the relationship

$$T = \frac{D^2 - u^2 t_{alert}^2}{u^2 t_{alert}} \quad (17)$$

- A.6. Eqn. (17) can be solved to give the time t_{alert} at which a TCAS alert is generated (relative to the time of the potential collision) as a function of the alert parameters D and T , and the closing speed u :

$$t_{alert} = -\left(\frac{T}{2} + \sqrt{\left(\frac{T}{2}\right)^2 + \left(\frac{D}{u}\right)^2}\right) \quad (18)$$

- A.7. At high closing speeds an alert is triggered close to the nominal warning time T . At low closing speeds an alert is triggered earlier, when the distance between the aircraft is close to D .

B. Cross-sectional area

B.1. Visual area

B.1.1. An aircraft presents a cross-sectional area, A , when viewed at an aspect angle of ψ . Due to the irregular shape of real aircraft the cross-sectional area will in general be a complex function of the aspect angle.

B.1.2. The cross-sectional area can be estimated from the head-on cross-section A_x and the broad-side cross-section A_y . These principal visual areas are projected onto a plane normal to the line-of-sight between the two aircraft to give the projected areas A'_x and A'_y :

$$A'_x = |A_x \cos \psi| \quad (19)$$

$$A'_y = |A_y \sin \psi| \quad (20)$$

B.1.3. If aircraft were not irregular in shape then the visual area would simply be the sum of the projected areas. However, in practice when an aircraft is viewed at an oblique angle some parts of the airframe will be masked by nearer parts. An approximate correction for masking is applied by assuming that the actual visual area is the larger of the projected areas plus one third of the smaller projected area:

$$A = \max(A'_x, A'_y) + \frac{1}{3} \min(A'_x, A'_y) \quad (21)$$

B.1.4. This approximation is without error when the aircraft is viewed along one of its principal axes.

B.2. Resolution

B.2.1. A physical limitation on the visibility of an aircraft (or indeed any object) is imposed by the optics of the eye. Beyond a limiting range the visual area of the threat aircraft will be too small to be discernible by human vision.

B.2.2. Calling the angular resolution capability of the eye d we can estimate the range r_{lim} , at which a target of area A is just resolvable, by assuming that the diameter of a disc of area A subtends the angle d . This gives the following expression:

$$r_{\text{lim}} = \frac{2}{d} \sqrt{\frac{A}{\pi}} \quad (22)$$

B.2.3. The time, t_{lim} (measured relative to the time of the potential collision), at which the aircraft comes within the resolution limit in a rectilinear collision geometry can be found from r_{lim} and the closing speed u :

$$t_{\text{lim}} = \frac{-r_{\text{lim}}}{u} \quad (23)$$

- B.2.4. The point-to-point angular resolution capability of the eye is typically about 1 arc-minute¹⁴ – it is reported in [20] that it is unusual for any subject to achieve better than 0.5 arc-min in the laboratory and that in flight-tests target aircraft are almost never seen until they exceed 2 arc-min.¹⁵ The value of $d = 1$ arc-min has therefore been adopted in this study and substituting this into Eqn. (22) yields the relationship:

$$r_{\text{lim}} \text{ (in NM)} = 2.09 \times \sqrt{A \text{ (in m}^2\text{)}} \quad (24)$$

¹⁴ An arc-minute is one sixtieth of a degree, which is about one thirtieth of the diameter of the full Moon. With normal viewing the full stop at the end of this sentence will be about 3 arc-minutes in diameter.

¹⁵ Some sources suggest that an even larger value should be adopted. The NISTB state that "...as a minimum, targets should subtend 0.2 degrees (12 minutes) of arc to insure reasonably accurate recognition" [7]. This value is twelve times larger than the value adopted in the current study but corresponds to a value required "to insure ... recognition" rather than simply the prospect of detection with a low probability as in current study.

C. Calculation of visual acquisition probability

C.1. Evaluating the integral

- C.1.1. In section 3.8 it was shown that the probability of visual acquisition by a time t_0 , in a rectilinear collision geometry, can be found by evaluating the equation below.

$$p(t_0) = 1 - \exp\left(-\beta \frac{A}{u^2} \int_{-\infty}^{t_0} \frac{1}{t^2} \exp\left(\frac{3u}{R}t\right) dt\right) \quad (25)$$

- C.1.2. Time is measured relative to the instant of the potential collision and so the time of interest will be negative (*i.e.* before the potential collision).

- C.1.3. When the visibility is unlimited ($R = \infty$) the integral in Eqn. (25) can be evaluated straightforwardly; when the visibility is not unlimited the integral can be evaluated using the exponential integral function. So:

$$p(t_0) = 1 - \exp(-\beta \cdot Q(t_0)) \quad (26)$$

where

$$Q(t) = \begin{cases} -\frac{A}{u^2 t} : R = \infty \\ -\frac{A}{u^2 t} (\exp(x) - x \cdot \text{Ei}(x)) : R \neq \infty \end{cases} \quad (27)$$

$x = 3ut/R$ and the function Ei is the exponential integral.

C.2. Changes in search intensity

- C.2.1. The equations in appendix C.1 enable the probability of visual acquisition to be determined when the search intensity, β , remains constant. We also need to be able to calculate the probability when there is a change (or changes) in the search intensity from one fixed value to another at a particular time.

- C.2.2. Specifically this study considers the case where the search intensity changes from an unalerted value of β_0 to an alerted value of β_1 at (or soon after) the time of a TCAS alert, t_{alert} . Furthermore we wish to take into account that before a time t_{lim} the threat will be smaller than the limit of resolution of human vision – in this case the search intensity is effectively zero: no matter how intently the pilot searches he will not acquire the threat.

C.2.3. The probability of visual acquisition by time t_0 can be calculated by considering a piecewise decomposition of integral in Eqn. (25). Two cases need to be considered (assuming that t_{lim} and t_{alert} are both earlier than t_0) depending on whether t_{lim} is earlier than t_{alert} or not.

- when t_{lim} is earlier: $t_{lim} < t_{alert}$:

$$p(t_0) = 1 - \exp(\beta_0 Q(t_{lim}) + (\beta_1 - \beta_0) Q(t_{alert}) - \beta_1 Q(t_0)) \quad (28)$$

- when t_{alert} is earlier: $t_{alert} \leq t_{lim}$:

$$p(t_0) = 1 - \exp(\beta_1 (Q(t_{lim}) - Q(t_0))) \quad (29)$$

C.3. *Probability of visual acquisition in a given interval*

C.3.1. If the probability of visual acquisition occurring by time t_1 is p_1 , and if the probability of visual acquisition occurring by a subsequent time t_2 is p_2 , then the probability that visual acquisition occurs between times t_1 and t_2 is simply the difference in probabilities: $p_2 - p_1$.

D. Acronyms

ACAS	airborne collision avoidance system
ATC	air traffic control
AVAL	ACAS on VLJs and LJs – Assessment of safety Level
CAA	UK Civil Aviation Authority
CDTI	cockpit display of traffic information
ECAC	European Civil Air Conference
FAA	US Federal Aviation Administration
ICAO	International Civil Aviation Organization
IMC	instrument meteorological conditions
LJ	light jet
MOPS	minimum operational performance standard
MOR	meteorological optical range
MTOM	maximum take-off mass
NTSB	US National Transportation Safety Board
RA	resolution advisory
SARPs	standards and recommended practices
SL	sensitivity level
TA	traffic advisory
TCAS	Traffic alert and Collision Avoidance System
USA	United States of America
VLJ	very light jet
VFR	visual flight rules
WP	work package

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