Development of an Integrated Anti-collision System

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In this research it is given an analysis of current and in development anti-collision systems, with the main purpose of finding insufficiencies. It is introduced a new and more integrated architecture that covers the lacks in current anti-collision systems. In order to demonstrate the functionality of this new model, several simulations are performed in some of the most significant scenarios.

I. Nomenclature

ATC:	Air Traffic Tontrol.
ICAO:	International Civil Aviation Organization.
FAA:	Federal Aviation Administration.
ACAS:	Airbone Collision Avoidance System.
TCAS:	Traffic alert and Collision Avoidance System.
MTOW:	Maximun Take Off Weight.
TAWS:	Terrain Awareness and Warning System.
FCC:	Fight Control Computer.
FD:	Flight Director.
EFIS:	Electronic Flight Instrument System.
ADS-B:	Automatic Dependent Surveillance-Broadcast.
UAV:	Unmanned Aerial Vehicle.
SL:	Sensitive Level.
TA:	Traffic Advisory.
RA:	Resolution Advisory.
HTA:	Horizontal Traffic Advisory.
HRA:	Horizontal Resolution Advisory.
VTA:	Vertical Traffic Advisory.
VRA:	Vertical Resolution Advisory.
$\mathbf{S_o}$:	Current horizontal component of ownship's position.
S_{oz}:	Current ownship's altitude.
$\mathbf{v_o}$:	Current horizontal component of ownship's velocity.
v_{oz}:	Current ownship's vertical speed.
$\mathbf{a_o}$:	Current ownship's acceleration.
$\mathbf{s_i}$:	Current horizontal component of intruder's position.
s_{iz}:	Current intruder's altitude.
$\mathbf{v_i}$:	Current horizontal component of intruder's velocity.
v_{iz}:	Current intruder's vertical speed.
$\mathbf{a_i}$:	Current intruder's acceleration.
t_{coa}:	Time for co-altitude.
t_{cpa}:	Time for closest point of approach.
t_{react}:	Reaction time.
$DMOD_l$:	Range threshold for SL l.
$ZTHR_l$:	Vertical threshold for SL l.
TAU_l:	Time threshold for SL l.
$\tau_{mod\ l}$:	Current ownship's modified tau for SL l.
H:	Initial altitude.
γ:	Slope angle.
β:	Angle of intersection of the trajectories as projected on the horizontal plane.

II. Introduction

THERE is a huge amount of space in the sky.

That is what firsts aviators thought and, since there were very few planes, the only anti-collision system these pioneers needed was their sight and reflexes.

Time passed and the number of planes flying multiplied. The 1956 Grand Canyon mid-air collision represented a turning point in the air traffic control technologies[1] and, among others, initiated the idea of a last resource boarded system that helped prevent mid-air collisions, acting independently of ATC. However, technical difficulties led to the postponement of the development of such system.

Other similar accidents occurred in the following decades, which finally forced ICAO to develop standards for Airborne collision avoidance systems (ACAS) and FAA to develop a Trafic collision avoidance system (TCAS). The carriage of an ACAS II system has become mandatory according to aircraft size[2].

Almost 40 years have passed since the development of TCAS technologies and, even if there have been new versions, there have not been deep changes in the system. Technology has advanced greatly while leaving TCAS behind, hence the need of the development and proof of concept of a new design.

Before developing a new idea, it is essential to be aware of the state of the art. It will be focused on two systems, TCAS II and ACAS X.

A. TCAS II:

It is the only available system that fulfills ACAS II requirements, therefore it is mandatory for aircrafts exceeding MTOW of 5.700 Kg or 19 seats[2].

It will emit a Traffic advisory when certain conditions are encountered, informing the pilot of the proximity of an aircraft. When stricter conditions are met, it will develop a Resolution Advisory, indicating the pilot how to change vertical speed in order to avoid collision[3].

It is important to note that only VRA is calculated, there is no horizontal maneuver to avoid the intruder aircraft.

The integration of TCAS into the aircraft systems has a complicated architecture, which it is summarised in the following image.

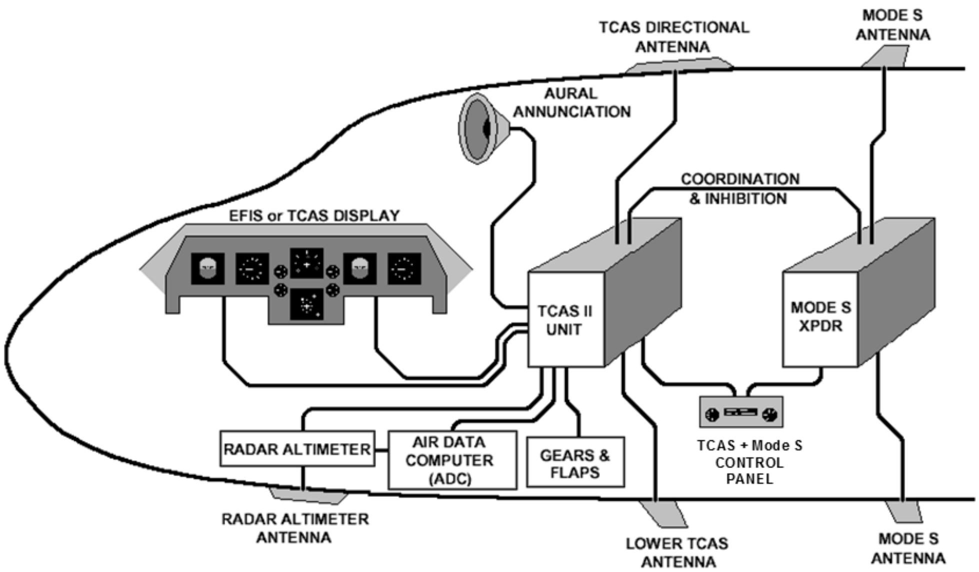


Figure 1. TCAS II architecture image extracted from [2]. *It may be appreciated different inputs and outputs to and from TCAS II Unit. Note that there is no communication with other systems such as TAWS or FCC.*

To summarize, TCAS II unit receives information from numerous sensors, from which it is highlighted the TCAS directional antenna that interrogates surrounding aircrafts acting as a secondary radar.

TCAS II unit uses all this information to perform surveillance, detect threats, determine avoidance maneuvers and generate advisories. For this functions, TCAS II propagates current trajectories (simplified as a straight line) and, if they would lead to reduced safety distance, it calculates numerous avoidance maneuvers and selects the least altering one that accomplishes enough safety distance.

These advisories are communicated to the pilot through EFIS or TCAS display and aural annunciation. TCAS II unit also harmonizes maneuvers with the other aircraft (if it is equipped with TCAS II) through mode S antenna, for which it needs to coordinate with Mode S XPDR.

As of today, TCAS II has several defects. It is emphasized the following ones:

1) Expensive system, hence small aircrafts would not have TCAS II equipped.
2) Lacks of horizontal avoidance maneuver.
3) May contradict alerts from other systems (such as terrain awareness and warning systems), since it does not communicate with them.
4) Lacks of coordination with ATC.
5) False warnings, especially in the proximity of airports, as it assumes straight trajectories instead of using the trajectories in the director plan loaded into the FCC.

Given room for improvement, FAA has funded research and development of a new system, ACAS X.

B. ACAS X[4]:

There are two main differences from ACAS X to TCAS II.

The first one is the sources of information. Instead of relying only on TCAS antenna interrogations, ACAS X is intended to be compatible with any surveillance source (or a combination of surveillance sources) that meet specified performance criteria (plug and play concept).

Secondly, alert logic is not based on propagation of trajectories, but upon a numeric lookup table optimized with respect to probabilistic models and other safety and operational considerations. Consequently, ACAS X has a greatly reduced computing need since instead of numerous calculations it only looks for the current situation on the lookup table in order to find out the advisories. In addition to that, numeric lookup table is easier to certify than hard-code rules used in TCAS II.

The most important variant is ACAS X, which is not a new system that replaces TCAS II, but an addition to it that helps optimizing avoidance and reduce false alerts.

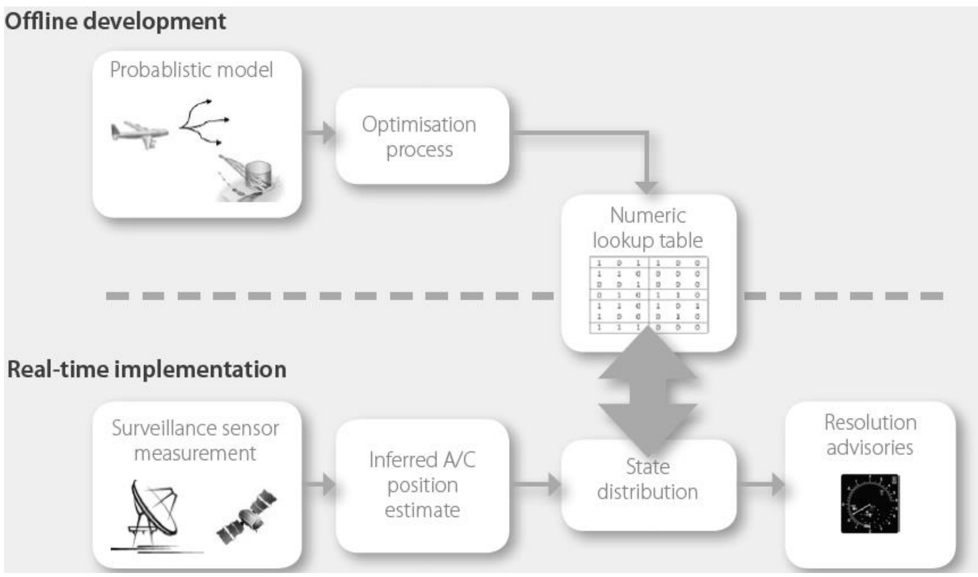


Figure 2. Functioning of ACAS X system, image extracted from [4]. *Offline development generates the numeric lookup table that is employed during real time implementation. The sources are "plug and play", not only transponder based.*

III. A new concept

Technology development leads the way to new horizons where aircrafts would flight *pilot-less*. Thus, it would be fundamental to develop anti-collision systems which may supply the deficiencies in current ones. In those systems realibility, integrity, precision, continuity, functionality and alert are the main priorities. In this paper it is introduced a new starting point for the development of an entire new system, in which aircrafts have the capability to avoiding other aircrafts or the terrain in order to evade collision.

A. Objectives

The main objectives that are desired to fulfill with this new architecture are the following ones:

1) Lower costs and weight.
2) Satisfy ACAS II, ACAS III and ACAS X requirements.
3) Communicate with ADS-B.
4) Coordinate with TAWS.
5) Include Flight Director.
6) Harmonize with multiple intruder aircrafts, mainly smalls ones that may not carry ACAS system on board.
7) Coordinate with ATC.

This new concept is focused on last generation commercial aircrafts. However, this concept could be spread to smaller aircrafts and UAVs since technology is being developed at huge steps.

B. New Architechture

It is proposed an architecture that involves a radically new point of view, a completely different proposal in which TCAS II and its antennas are suppressed as an independent system. This step would lead to a new fully integration based architecture.

Currently, when risk of collision is detected, TCAS II provides a RA where a vertical maneuver is set. Furthermore, TCAS II also grants the pilot the possibility to do or not to do. With this design it is sought that the decision to perform the resolution would fall to the aircraft's FCC. Nevertheless, this will not be a reality until autonomous commercial flights are fully developed.

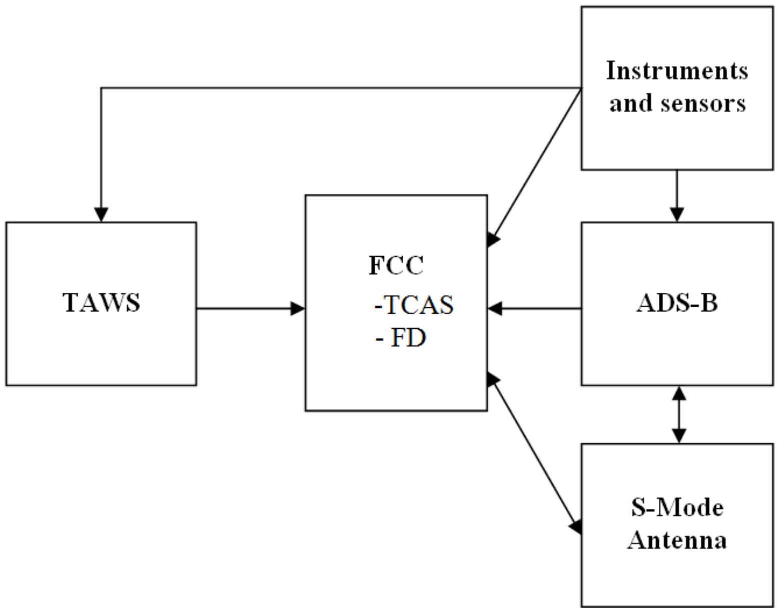


Figure 3. New Architecture. *It is shown the interaction between systems, with TCAS technology integrated in FCC along with FD.*

FCC would be a key element in this new architecture development, since it would absorb the functions of TCAS system. Moreover, it would be in charge of managing all information that comes from every source and providing a performance answer before a collision risk. Considering that FD is integrated on FCC in modern commercial aircrafts, it would be possible to return to the original trajectory once the aircrafts involved in the RA were out of risk.

On board sensors provide the FCC with data related to inertial measurements, position, altitude and heading.

Communication with ADS-B would be fundamental since this system is the one in charge of transmiting, throught the S-Mode Antenna, the data that may be required for FCC to evaluate a possible conflict. Communication with ATC would also be permited by the S-Mode Antenna.

Coordination between FCC and TAWS would allow the FCC to consider whether it is possible or not to perform a descending maneuver, and in case this would not be possible, to perform an alternative horizontal maneuver.

Finally, the introduced idea would fit in the proposed objectives. It would also reduce weight as a result of elimination of TCAS hardware. It is assumed that costs are lowered due to this fact.

C. Advantages and disadvantages

This new architecture offers many advantages, such as: the possibility to take advantage from the full potencial of the capabilities of the systems on board, an integrated architecture with all the advantages granted by the objectives fulfilled. This configuration bets on more autonomous flights, seeking to reduce to a minimum the pilot's interventions and as a result, the reduction of human factors as a direct cause in catastrophic conflicts.

There are some disadvantages that may be extracted from this idea, such as: this proposal is contrary to the current tendency of developing isolated systems with specific functions, and integrated systems would require higher reliability due to the responsibility involved. Nevertheless, at the rhythm technology advances this levels of realibility, integrity, precision, continuity and functionality may be reached.

IV. Simulation

With the main objective of performing a concept test on the new proposed anti-collision system, it has been done a simulation in which the previous developed architecture is implemented.

In order to develope a simulation it has been used the tool MATLAB-Simulink. Hypothesis have been made to enclose the problem to a realistic scenario. The process followed by the simulation is based on: on one hand risk detection included on TCAS II[3], and on the other hand in decision algorithm stablished on ACAS II and ACAS X[4].

A. Simplifications:

Due to the great complexity in the real architecture of aircrafts as well as in air traffic management, the following simplifications have been assumed in the simulation:

1) Inside the airspace where the simulation takes place there would only be two aircrafts.
2) Aircrafts would be modelled only in the view of cinematics, not being considered flight mechanics or dynamics since they are assumed to be satisfied.
3) Cinematics would be modelled as an uniformly accelerated rectilinear motion or balanced turn.
4) Changes in balance angle would be considered as instantaneous.
5) TAWS system has been simulated such as it would emit an alert in case the trajectory would surpass the limits stablished in time to ground collision and descent speed.
6) Communication between aircrafts an ATC would not be considered.
7) Simulation will be calculated until the time of conflict resolution.

B. Risk determination[3]:

In order to stablish the risk determination method, it has been followed an algorithm implemented by TCAS II. This algorithm stablishes two protection domains. The first one, which is the biggest, enclosures a region that activates the TA alert and send a warning to the cockpit. The second one, contained inside the first one, stablishes the limit where the RA is activated and the moment in which a maneouver is mandatory to avoid the conflict.

These domains are stablished as a minimum distance that would allow enough time to ensure the possibility of performing evasive actions. These are built with the own aircraft and intruder's speed, as well as with the trajectory followed by both of them. The size of this regions will also be dependant of the parameter known as Sensitivity Level, which is subject to flight level in which the aircrafts are flying (conflicts between aircrafts located in regions with different SL it will be considered the most restrictive, which corresponds to the aircraft at a higher flight level) .

Furthermore, it may be checked how the dimensions are stablished in ways of time. These times are: time to co-altitude t_{coa} or, if the trajectory is not strictly in heading of collision, time to the closest horizontal point approach t_{cpa}. These values are compared with a limits given by SL: τ and the security domains are created when the previous times are equal to the limit given.

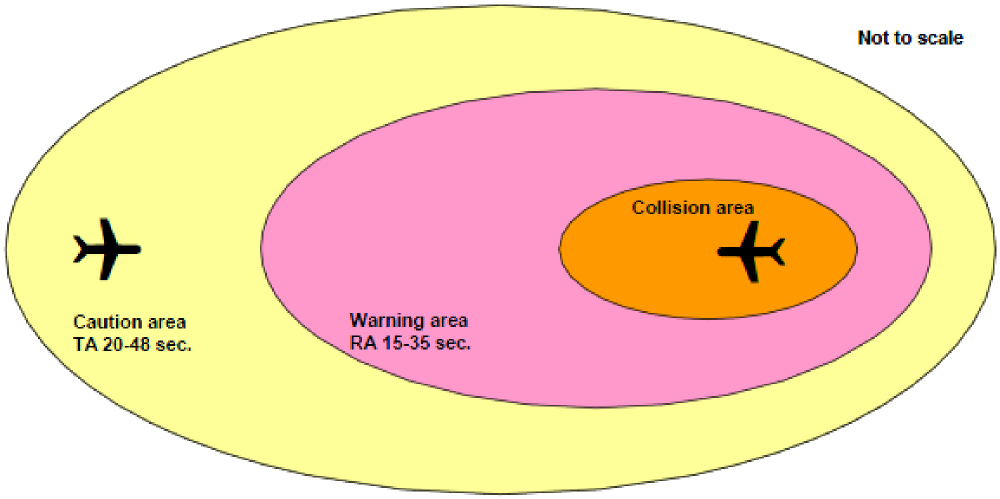
Thus, the criteria used to determine the domains are distinguished in horizontal and vertical planes and are described as it follows:

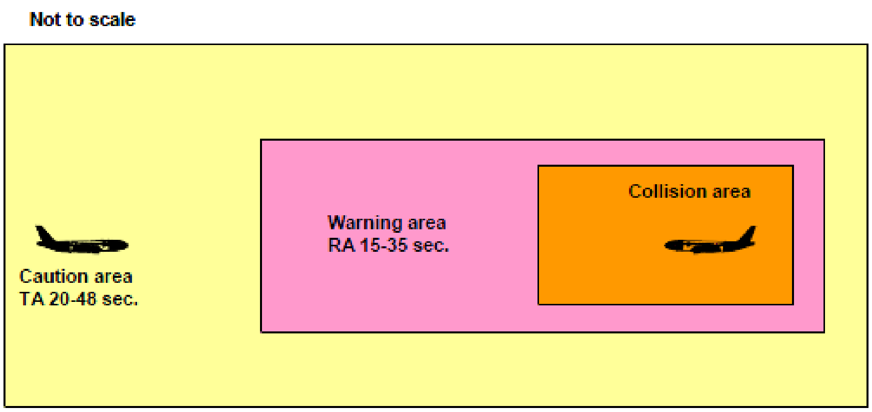
$$Horizontal_{RA_l}(\boldsymbol{s},\boldsymbol{v}) \equiv \|\boldsymbol{s}\| \leq DMOD_l \; or \left(\boldsymbol{s}\cdot\boldsymbol{v} < 0 \;\; and \;\; \tau_{mod_l}(\boldsymbol{s},\boldsymbol{v}) \leq TAU_l\right)$$
$$Vertical_{RA_l}(s_z, v_z) \equiv |s_z| \leq ZTHR_l \; or \; (s_z v_z < 0 \;\; and \;\; t_{coa}(s_z, v_z) \leq TAU_l)$$

Where,

$$\boldsymbol{s} = \boldsymbol{s}_o - \boldsymbol{s}_i \;\; ; \;\; \boldsymbol{v} = \boldsymbol{v}_o - \boldsymbol{v}_i \;\; ; \;\; s_z = s_{oz} - s_{iz} \;\; ; \;\; v_z = v_{oz} - v_{iz}$$
$$\tau_{mod_l}(\boldsymbol{s},\boldsymbol{v}) \equiv \frac{DMOD_l^2 - \|\boldsymbol{s}\|^2}{\boldsymbol{s}\cdot\boldsymbol{v}} \;\; ; \;\; t_{cpa}(\boldsymbol{s},\boldsymbol{v}) \equiv -\frac{\boldsymbol{s}\cdot\boldsymbol{v}}{\|\boldsymbol{v}\|^2} \;\; ; \;\; t_{coa}(s_z, v_z) \equiv -\frac{s_z}{v_z}$$

The relations used to TA warning are analogous, differing only in the values $DMOD_l$, $ZTHR_l$ and TAU_l, as they may be seen detailed in the table below.





Own Altitude	*SL*	*tau* values (sec)		*TVTHR* (sec)	*DMOD* values (NM)		*ZTHR* (feet) Alt. Threshold		*ALIM* (feet)
		TA	RA	RA	TA	RA	TA	RA	RA
0 – 1000 ft AGL	2	20	no RA	no RA	0.30	no RA	850	no RA	no RA
1000 – 2350 ft AGL	3	25	15	15	0.33	0.20	850	600	300
2350 ft AGL – FL50	4	30	20	18	0.48	0.35	850	600	300
FL50 – FL100	5	40	25	20	0.75	0.55	850	600	350
FL100 – FL200	6	45	30	22	1.00	0.80	850	600	400
FL200 – FL420	7	48	35	25	1.30	1.10	850	700	600
Above FL420	7	48	35	25	1.30	1.10	1200	800	700

Figure 4. TCAS-II protected volume, image extracted from [3]. *It may be noted the shape of these volumes and the parameters on which they are based***.**

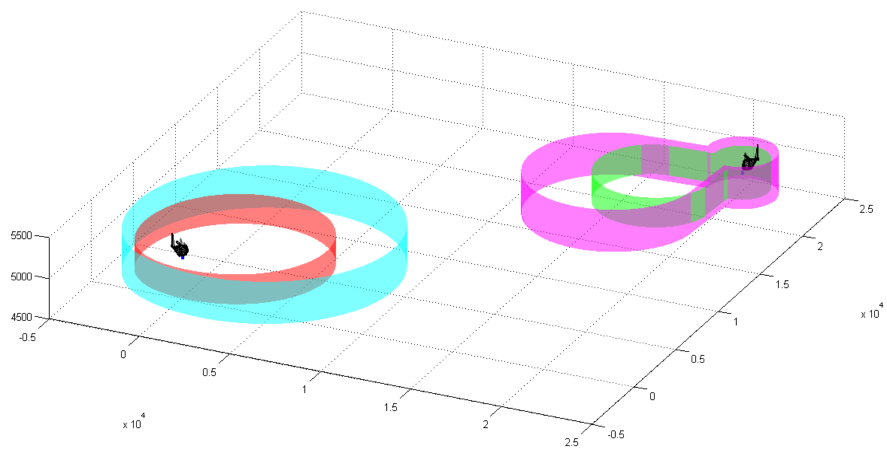


Figure 5. Protection domains. *It may be seen the protection domains in a scenario where two aircrafts at same altitud are in heading to collide. The aircraft in the left is moving slowlier that the aircraft in the right.*

C. Vertical Resolution Advisory:

Once that it has been stablished an RA alert, the algorithm used to calculate risk is followed and it will be determined the maneuver that the aircraft will follow in order to avoid the obstacle.

In every circumstance, firstly a vertical maneuver will be attempted (ascending or descending), defining a vertical speed such as, after a time t_{coa} (or t_{cpa}), it will be reached, at least, the minimum separation stablished by the protection volume of the RA alert (defined in the risk calculation algorithm).

Following this approach, the algorithm for vertical resolution of conflicts will be based on a series of cases according to the speed and trajectory of both aircrafts, and for each of these cases it will reach the value of vertical speed increment Δv_{oz} that will be required to successfully solve the conflict.

This algorithm will also guarantee that, even if only one of the aircrafts involved in the conflict performs the avoidance maneuver, it will be solved in the stablished time, meaning that it has flexibility for different intruder obstacles (which could be an aircraft with or without anti-collision system, or a fix or moving obstacle as long as the aircraft equipped with the TCAS system is able to detect it), and it could open the way to airspace management optimization.

In the calculation of this increase in vertical speed it will also introduce the parameter t_{react} associated to the reaction time of the aircraft to perform the maneuver (or the pilot, in case it is not autopiloted).

Thus, the algorithm is as follows:

$$if\ (s_z = 0\ \ and\ v_z = 0) \quad then \quad \Delta v_{oz} = \pm \frac{ZTHR}{t_{cpa} - t_{react}}$$

$$if\ (s_z > 0\ \ and\ s_z v_z \geq 0) \quad then \quad \Delta v_{oz} = \frac{ZTHR}{t_{cpa} - t_{react}}$$

$$if\ (s_z < 0\ \ and\ s_z v_z \geq 0) \quad then \quad \Delta v_{oz} = -\frac{ZTHR}{t_{cpa} - t_{react}}$$

$$if\ (s_z > 0\ \ and\ s_z v_z < 0) \quad then \quad \Delta v_{oz} = max\left\{\frac{ZTHR}{t_{cpa} - t_{react}} \middle| -\frac{TAU \cdot v_z}{t_{coa} + TAU}\right\}$$

$$if\ (s_z < 0\ \ and\ s_z v_z < 0) \quad then \quad \Delta v_{oz} = min\left\{-\frac{ZTHR}{t_{cpa} - t_{react}} \middle| -\frac{TAU \cdot v_z}{t_{coa} + TAU}\right\}$$

Every other parameter used in the algorithm have been previously stablished in the risk determination, defined in the preceding section.

It may be noticed that the design of the algorithm allows, since it refers to relative position and speed between the aircrafts, that if both of them possess the anti-collision system, they will perform resolutions in opposite directions whichever the situation might be.

This, however, is not inmediate in the case of both aircraft being at the same flight level and having the same vertical speed (case of resolution with $s_z = 0\ \ and\ v_z = 0$). In this situation the aircraft with a higher FCC serial number will be the one having a positive increment of vertical speed and viceversa (this is an arbitrary decision, other alternative differenciation method could be imposed).

Once the aircraft takes the decision of the vertical maneouver it would perform, it will be analysed if it is feasible, according to:

1) Evaluation by the TAWS, which will determine if it encounters a terrain conflict, according to ground collision time or excessive descendant speed.
2) Technical capability of performing the maneuver.
3) Existence of other RA with different obstacles.
4) In case of having flight trajectories included in the FCC, it could be possible to analyse if the trajectory itself would avoid the obstacle without the need of alteration.

If it were not possible to perform the avoidance maneuver in the vertical plane, for any of the previous reasons, a horizontal maneuver will be held.

D. Horizontal Resolution Advisory:

The HRA is a method that is not currently implemented on any anti-collision on board system. The need of an HRA emerges when a VRA results unfeasible due to safety criteria: during take off and landig maneuvers, terrain warning or forbidding given by ATC.

The risk determination method is the same as the one for VRA. The main differences are related to the criteria stablished to perform an horizontal methodology, and to determine whether a HRA is required are the following:

1) Time to terrain collision, given a speed, less than 60 s.
2) Descendant speed higher than an upper limit.

Before any of the previous situations, it has been considered that it is not posible to perform VRA since it would compromise aircraft safety.

The methodology that has been proposed is based on: relative position, aircrafts speed vector and RA time to collision. It has been stablished the aircraft in the minor speed as a reference. The reference aircraft would perform a balanced turn towards the semi-space, defined by the plane constructed with the speed vector and the vertical direction, not occupied by the intruder aircraft. To determine the new trajectory of the intruder aircraft it has to be considered the plane surface with normal vector the speed vector of the reference aircraft. Using this plane as a reference, the intruder aircraft would perform a balanced turn towards the semi-space which its speed vector heads.

$$\boldsymbol{if}\ \left((\vec{s} \times \vec{v}_O) \cdot \vec{k} \geq 0 \ \right), \quad \vec{a}_O = \|\vec{a}_O\| \vec{u}_O$$
$$\| \quad \boldsymbol{if}\ (\vec{v}_O \cdot \vec{v}_I) \geq 0, \quad \boldsymbol{then} \quad \vec{a}_I = -\|\vec{a}_I\| \vec{u}_I, \quad \boldsymbol{else}\ \vec{a}_I = \|\vec{a}_I\| \vec{u}_I$$

$$\boldsymbol{if}\ \left((\vec{s} \times \vec{v}_O) \cdot \vec{k} < 0 \ \right), \quad \vec{a}_O = -\|\vec{a}_O\| \vec{u}_O$$
$$\| \quad \boldsymbol{if}\ (\vec{v}_O \cdot \vec{v}_I) \geq 0, \quad \boldsymbol{then} \quad \vec{a}_I = \|\vec{a}_I\| \vec{u}_I, \quad \boldsymbol{else}\ \vec{a}_I = -\|\vec{a}_I\| \vec{u}_I$$

Where:

$$\boldsymbol{u} = \frac{\boldsymbol{k} \times \boldsymbol{v}}{\|\boldsymbol{k} \times \boldsymbol{v}\|} \qquad \|\boldsymbol{a}\| = \frac{\|\boldsymbol{v}\|^2}{\boldsymbol{r}}$$

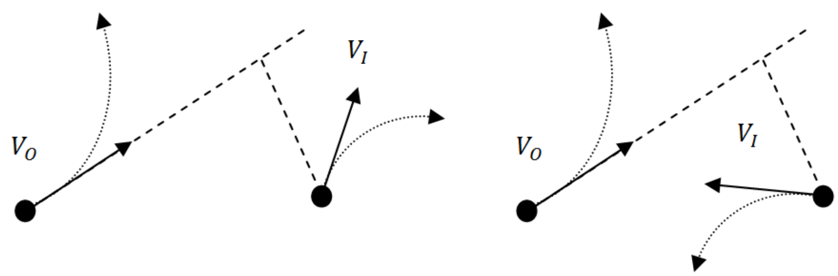


Figure 6. Horizontal Resolution Advisory model. *It may be seen the two possible cases of HRA.*

E. Scenarios:

In this part it will be presented the analyzed scenarios under the hypothesis and methodologies previously described. Four cases have been considered with constant speed (without accelerations):

1) Conflict at identical altitude.
2) Conflict with 2 ascending aircrafts.
    a. Climb with 2.3º slope.
    b. Climb with 1º slope.
3) Conflict in ascent-descent.
4) Conflict with TAWS alert.

In this table we consolidate the most significant data of this series of simulations.

Scenario	$V_O\ [m/s]$	$V_I\ [m/s]$	$H_O\ [m]$	$H_I\ [m]$	γ_O [°]	γ_I [°]	β [°]
Conflict 1	200	250	10000	10000	0	0	180
Conflict 2.a	200	250	10000	10000	2.3	2.3	45
Conflict 2.b	200	250	10000	10000	1	1	45
Conflict 3	200	250	10000	10200	1	1	45
Conflict 4	100	150	750	750	0	0	45

Table 1. Simulation scenarios data 1

With this casuistry it has been attempted to obtain the most frequent situations in which there could be a conflict sensitive to result in collision. To illustrate the results of the simulations, different images will be presented for each scenario where it is possible to verify that the trajectories divert according to the methodology specified in previous sections.

In conflict 1 it may be observed how the aircrafts maintain cruise at constant altitude and, after RA, one ascends and the other descends until a minimum safety distance between them is reached.

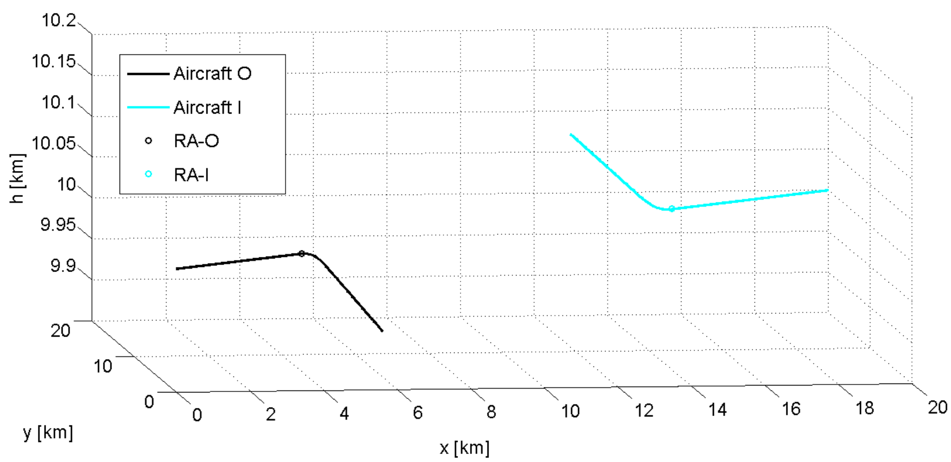


Figure 7. Conflict 1

In conflict 2.1 it may be seen both aircraft ascending with slope of 2.3º, holding heading that will result in intersection of 45º in the horizontal plane. After RA it may be observed that both continue on an ascending path, but one of them with smaller ascending speed while the other increments its vertical speed, until they are cleared from risk.

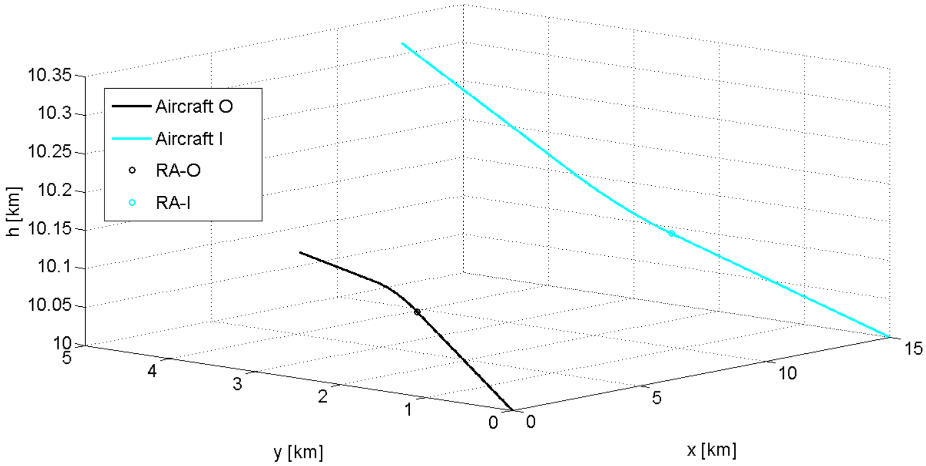


Figure 8. Conflict 2.1

In conflict 2.2 it may be noticed both aircraft ascending with slope of 1º, holding headings that, identically to conflict 2.1, will intersect with an angle of 45º on the horizontal plane. After RA it may be identified that one of them continues with smaller vertical rate while the other with higher vertical rate until they are cleared of risk.

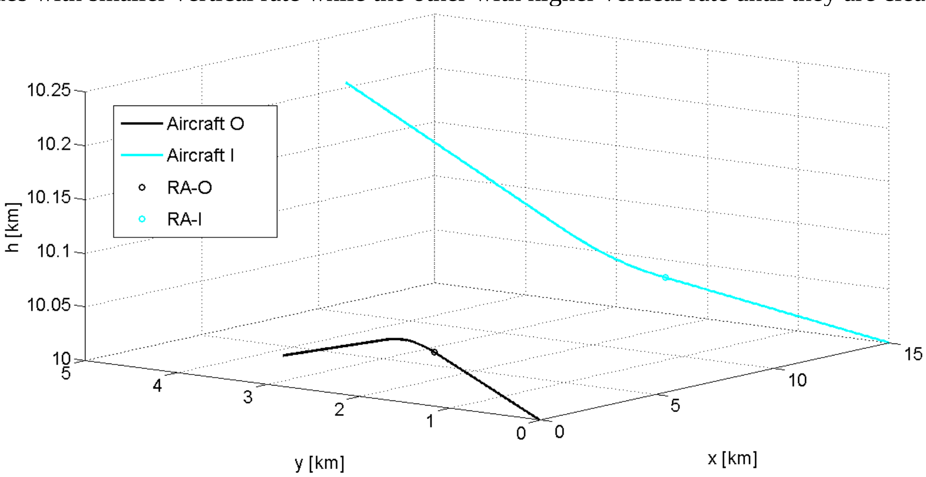


Figure 9. Conflict 2.2

In conflict 3, two aircraft may be observed, one ascending with slope of 1º from an altitude of 10000 m and the other descending with 1º from an altitude of 10200 m, holding headings that will intersect with a 45º angle on the horizontal plane. After RA it may be noticed how the descending aircraft ascends while the ascending aircraft descends.

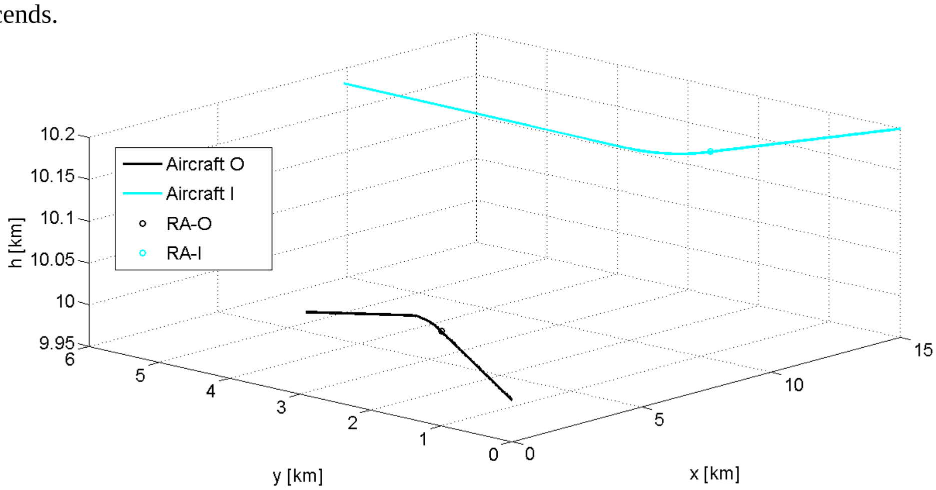


Figure 10. Conflict 3

In conflict 4, two aircraft may be observed at low altitude flight, with heading intersecting 45 degrees as previous scenarios. Since they are close to the ground, TAWS issues an alert for the descend rate that the vertical maneuver would require and, therefore, the aircraft that should have descended performs a symmetrical turn while the other performs the ascending vertical resolution maneuver.

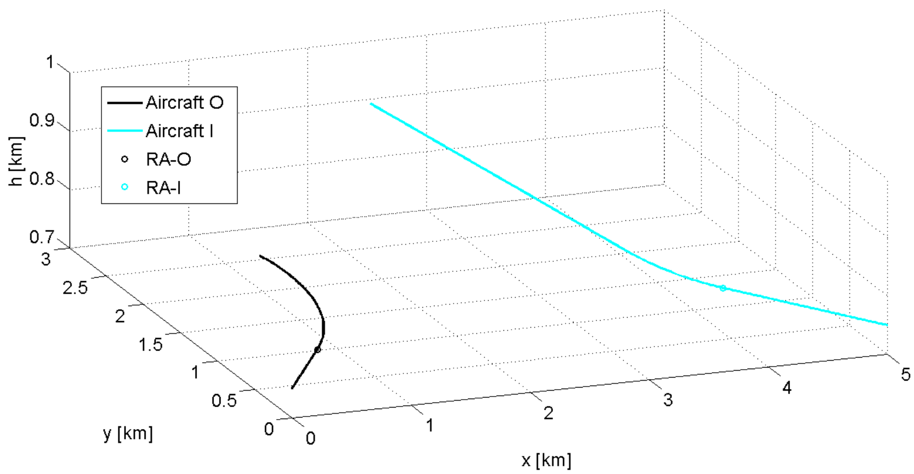


Figure 11. Conflict 4

These modelling and simulations put into perspective how it is possible to develop a methodology that allows to address all the casuistry of possible collisions and integrate it with the published information of trajectories and ATC to improve efficiency. With a better development, it would be possible to stablish resolution between a higher number of aircrafts and perform more complex maneuvers. As it is presented, the main objective of proposing the possibility of integrating a vertical and horizontal resolutions with preprogrammed laws included in the FCC is achieved.

V. Conclusion

It has been successfully developed a new arquitechture, which has been validated by a series of simulations. Objectives have been reached, although further development could be attained by stating less restrictive simplifications in the modelling.

It is essential to highlight that our purposes are not the simulations themselves, but the concept of an integrated FCC-TCAS system which is validated by them.

This system would allow to perform a *safer and more efficient* avoidance that will be critical in the near future, when airspace is even more congested and UAVs become widespread.

References

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