Discussion on Complexity and TCAS Indicators for Coherent Safety Net Transitions

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Abstract— **Transition between Separation Management in ATM and Collision Avoidance constitutes a source of potential risks due to non-coherent detection and resolution clearances between them. To explore an operational integration between these two safety nets, a complexity metric tailored for both Separation Management and Collision Avoidance, based on the intrinsic complexity, is proposed.**

To establish the framework to compare the complexity metric with current Collision Avoidance detection metrics, a basic pair-wise encounter model has been considered. Then, main indicators for horizontal detection of TCAS, i.e. tau and tau_mod, have been contrasted with the complexity metric.

A simple method for determining the range locus for specific TCAS *tau* values, depending on relative speeds and encounter angles, was defined. In addition, range values when detection thresholds were infringed have been found to be similar, as well as its sensitivity to relative angles.

Further work should be conducted for establishing a framework for the evaluation and validation of this complexity metric. This paper defines basic principles for an extended evaluation, including multi-encounter scenarios and longer look ahead times.

Keywords: ATM; Separation Management; Collision Avoidance TCAS; complexity; tau;

I. INTRODUCTION

ACAS (*Airborne Collision Avoidance System)* is the last technical decision support tool for crews to prevent a Near Mid Air Collision (NMAC) [1]. In the case that previous Air Traffic Management (ATM) safety nets have failed, the system provides resolution advisories to involved aircraft to remove the threat.

Currently, the technical implementation of ACAS is the Traffic Collision and Avoidance System (TCAS). TCAS II [2], last TCAS version, is mandatory within the ECAC airspace for civil aircraft exceeding 5700 kg or authorised to carry out more than 19 passengers.

TCAS II is a transponder-based system, independent from ground systems, which analyses relative dynamics between pairs of aircraft, and then, issues resolution advisories if required. The system operational capabilities are limited by the traffic density, up to 0.30 (aircraft/NM^2), and by relative speeds for different relative headings [1].

In regard to TCAS II limitations, SESAR and NextGen forecasts predict higher traffic densities for future ATM scenarios [3]. In addition, it has been proven that TCAS logic failures may occur in multi-encounter scenarios [4]. Nonetheless, TCAS II has provided an excellent performance for pair-wise encounters, with an outstanding impact on reducing the risk of potential collisions.

AGENT (Adaptive self-Governed aerial Ecosystem by Negotiated Traffic) is a SESAR 2020 Exploratory Research granted project, which aims to develop a flight efficient, safe collaborative and supervised separation management, operationally integrated to trajectory management and collision avoidance layers within a Trajectory Based-Operations concept. AGENT is exploring solutions which will reduce or remove main drawbacks of current TCAS II implementations.

A high-level Concept of Operations was defined [5] for AGENT, in which new metrics were proposed for evaluating the complexity of given scenarios. One of them is a revisited version of the Intrinsic Complexity (IC) [6].

The purpose of this paper is to compare the performance of TCAS horizontal detection indicator and the IC for a pair-wise encounter at the transition zone between separation management and collision avoidance layers, and it is organised as follows. Section II establishes the background and states the problem. Section III defines the methodology, while results are presented in Section IV. Finally, conclusions are contained in Section V.

II. OVERVIEW AND PROBLEM STATEMENT

A. TCAS II Overview

TCAS II is the only certified implementation of the ACAS function. The system works independently from ground, conducting surveillance, tracking, threat detection and advisory resolution.

TCAS II threat detection is partially based on an estimation of the remaining time to the Closest Point of Approach (CPA) between the *ownship* and an *intruder* [7]. This estimation is based on the computation of the ratio, τ (tau), between the TCAS

observable, the slant range r, and the range variation, or closure rate $\dot{r}$ (1).

$$\tau \equiv -\frac{r}{\dot{r}} \qquad (1)$$

Tau is complemented with a *vertical tau,* given by the ratio between vertical separation and the vertical closure rate. Then, TCAS detection is activated when both tau and vertical tau are less than a certain threshold, which depends on a fixed Sensitivity Level (SL). A SL is required to find a compromise between essential and pointless advisories. As a consequence, the SL characterises the protection volume around the ownship, which also depends on the relative dynamics between both aircraft.

Two main problems of the tau definition arise when the range closure rate or the vertical closure rate are very low. In these cases, aircraft could be in a short range but the indicator will not exceed the alert threshold. In addition, similar problems may arise when there exist high closure rates but large miss distances. For removing those, tau is slightly modified to incorporate the DMOD (Distance MODification) (2).

$$\tau_{mod} \equiv -\frac{r^2 - DMOD^2}{r\dot{r}} \qquad (2)$$

TCAS II presents two main limitations. Firstly, it was designed for densities up to 0.30 (aircraft/NM^2). Secondly, it has been proven that under certain circumstances, TCAS logic may fail due to multi-encounter situations [8]. In addition, there may arise critical scenarios due to non-coherent interaction with other safety nets, as ATC, e.g. the Überlingen accident [9]. Although now is mandatory for crews to follow TCAS clearances, there have been several researches highlighting that interacting safe independent systems may become into a unsafe one [10], [11].

AGENT seeks for an enhanced TCAS operationally integrated with the separation management layer. A multi-agent approach is followed for determining negotiated trajectories to solve complex scenarios. AGENT aims at identifying not only pair-wise encounters but cluster of aircraft which are interdependent, to conduct a simultaneous resolution for all aircraft, as it has been previously studied that consecutive conflict resolution may result in unsafe situations [12].

Cluster detection, tracking and resolution would be managed based on complexity criteria. Although several studies have undertaken the subject, such as [12]-[13], there is no strict definition of air traffic complexity. Additionally, scenarios evolving from separation management towards collision avoidance should ideally be solved with compatible actions for all aircraft, independent at which safety net aircraft are. To this end, an equivalent metric for threat identification is required, in order to establish the state of the aircraft relative to the different safety nets.

B. Proposed Complexity Metric

AGENT preliminary proposed complexity metric is based on the Intrinsic Complexity indicator, presented in [14]–[16], in which air traffic is modelled as a Dynamical System, defined by the following equation:

$$\dot{X} = f(X) \qquad (3)$$

Where X and $\dot{X}$ are position and velocities for the set of aircraft. In the surrounding area of an aircraft m, located at X_m, (3) can be rewritten as:

$$\dot{X} - \dot{X}_m = J_f \cdot (X - X_m) + HOT \approx J_f \cdot (X - X_m) \qquad (4)$$

Where J_f represent the Jacobian matrix for $f(X)$ at point X_m if smooth behaviour is assumed. X denotes aircraft coordinates in the vicinity of the aircraft m, and $\dot{X}$ the speed of the *flow of aircraft* at point X_m. Thus, if an analogy with a linear dynamic system is done, $A = J_f$ and $B = X_m$, the homogeneous part of (4) reflects the impact of velocity upon aircraft position, whereas the independent part represents the drift of the aircraft flow at X_m.

The analysis of **A** matrix facilitates the visualization of traffic relative dynamics. Thus, real parts of eigenvalues associated with A at X_m determine the convergence or divergence of the traffic flow at that location. When the eigenvalue is negative, the traffic is considered to be contracting. Further details could be found in [5] and [16].

Within the scope of this paper, pair-wise encounters are considered. Figure 1 represents a typical pair-wise encounter geometry, where $[(\cos(\alpha), \cos(\beta), \cos(\gamma)]$ is a unitary vector pointing from the ownship (aircraft m) to the intruder. Then, if **V,** [Vx Vy Vz], indicates their relative speed, the closure rate $\dot{d}$ could be expressed as:

$$\dot{d} = V_x \cdot \cos(\alpha) + V_y \cdot \cos(\beta) + V_z \cdot \cos(\gamma) \qquad (5)$$

In these conditions, and for a pair-wise encounter, (4) could be expressed as follows:

$$[\dot{X} - \dot{X}_m] = \frac{V_x \cdot \cos(\alpha) + V_y \cdot \cos(\beta) + V_z \cdot \cos(\gamma)}{d} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot [X - X_m] \qquad (6)$$
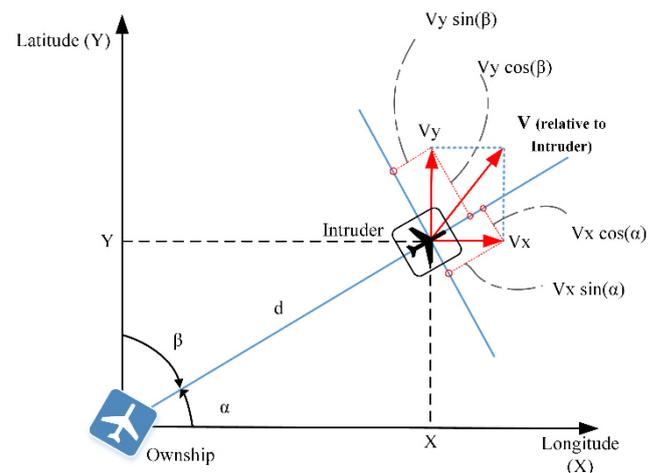

Figure 1. Typical pair-wise encounter geometry

Therefore, **A** has a triple eigenvalue, and consequently, solution for equation (4) is:

$$X = X_0 \cdot e^{\frac{V_x \cdot \cos(\alpha) + V_y \cdot \cos(\beta) + V_z \cdot \cos(\gamma)}{d} \cdot t}$$

It could be observed that in the case where aircraft are converging, the eigenvalue equals to $\frac{1}{\tau}$.

Now, the metric is based in two considerations. On the one hand, it reflects the rate of convergence of the traffic flows. On the other hand, it is complemented with a measurement of the traffic density. Further explanation can be found on [5]. Thus, the metric for aircraft m is defined as follows:

$$CM_m = \left[\frac{R^2 H}{8} \sum_{n=1}^{N} \frac{1}{\max(d_{mn}, R/2)^2 \cdot \max(h_{mn}, H/2)} \right] \cdot$$
$$\left[\sum_{k=1}^{3} e^{-T_{SM} \cdot real(eig(k))} \right]$$

(7)

The first part of the formula retains the notion of "air traffic density" in terms of volumetric density. R and H are characteristic horizontal and vertical distances respectively, and d_{mn} and h_{mn} represent the lateral and vertical distances to aircraft n.

The second part reflects the degree of convergence for a particular traffic flow in a point of the airspace. T_{SM} denotes a characteristic reaction time for the Separation Management layer whereas $eig(k)$ represent the eigenvalue k of A matrix. The multiplication between the eigenvalues and T_{SM} embodies the severity of the situation. If a scenario is close to a NMAC, then this value have an exponential increase.

If now we consider only a pairwise encounter and the closure rate in its scalar form, the horizontal component of (7) is transformed to:

$$CM_H \cong \left[1 + \frac{R^2}{4} \cdot \frac{1}{(\max(\frac{R}{2}, r))^2} \right] \left[e^{-T_{SM} \cdot \lambda_H} \right]$$

$$\lambda_H = \frac{V_H \cdot X_H}{d^2}$$

(8)

III. METHODOLOGY

A. Comparison Method

TCAS II and IC-based indicators are compared analysing their response under different initial conditions for ownship and intruder. The model will consider constant speeds for both ownship and intruder, and also, the vertical component of the slant range is ignored.

For conducting the evaluations, an "ideal" encounter model is formulated in which threat indicators will be reflected. Then, as both indicators will trigger events-based alerts, magnitudes associated with each of them will be computed when thresholds are reached, such as aircraft range or the time-to-go to the CPA, depending on the relative speeds and track angles.

B. Encounter model

The present work uses a simple model for an aircraft encounter scenario (see Figure 2). Relative positioning of both aircraft, the ownship position at Closest Point of Approach (CPA) has been considered as the reference for the coordinates of a Cartesian system, where distances are given in NM, and X axis is oriented in the direction of the ownship velocity.

In this system, initial positions for both aircraft depends on their velocities, assumed as constant, and on the time to CPA (t_{CPA}) as well. Thus, initial states of the ownship and the intruder are given by:

$$\vec{r_1}(t_0) = -v_1 \cdot t_{CPA} \cdot \vec{\imath}$$
$$\vec{v_1}(t_0) = v_1 \cdot \vec{\imath}$$
$$\vec{r_2}(t_0) = v_2 \cdot t_{CPA} \cdot (\cos(\theta) \cdot \vec{\imath} + \sin(\theta) \cdot \vec{\jmath})$$
$$\vec{v_2}(t_0) = -v_2(\cos(\theta) \cdot \vec{\imath} + \sin(\theta) \cdot \vec{\jmath})$$

(9)

Where indexes 1 and 2 refer to *ownship* and *intruder* respectively. Velocities are ground speeds given by their modules (v_1 and v_2 correspondingly). Finally, the angle θ stands for the incidence angle for the intruder regarding the X axis (ownship speed direction). Unitary vectors $\vec{\imath}$ and $\vec{\jmath}$ are oriented in X and Y directions respectively.

Both aircraft follow then a linear motion, in which their positions are given by:

$$\vec{r_1}(t) = \vec{r_1}(t_0) + \vec{v_1}(t_0) \cdot t$$
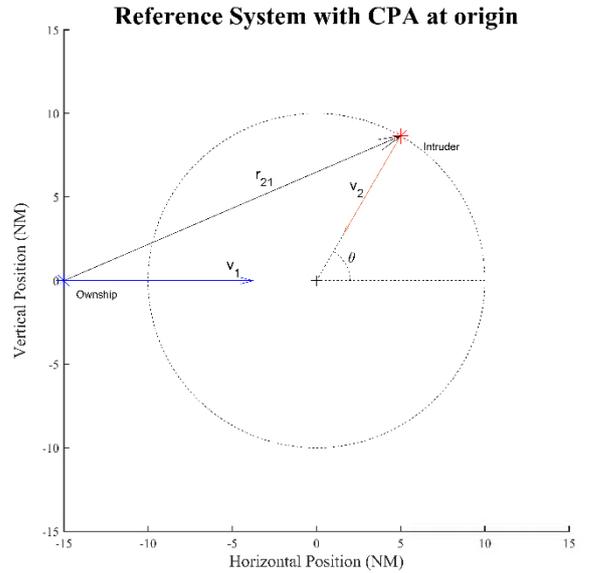$$\vec{r_2}(t) = \vec{r_2}(t_0) + \vec{v_2}(t_0) \cdot t$$

(10)

Figure 2. Reference System for a pair-wise encounter with CPA at Origin

C. TCAS Detection Model in the CPA reference model

TCAS conducts different functions, and among them, threat detection. To present a Traffic Advisory (TA), or issue a Resolution Advisory (RA), the TCAS detection function analyses, among others, the parameter τ (tau) defined in (1).

Tau is given by the rate between aircraft slant range and the closure rate between both aircraft. In other words, it estimates the remaining time to the CPA.

Previous studies ([17], [18]) examined TCAS indicators by analysing the relative motion between both aircraft. Following the same approach, and taking into account previous definitions (9), (10), the horizontal range and its closure rate could be expressed as follows:

$$\vec{r_{21}}(t) = \vec{r_{21}}(t_0) + \vec{v_{21}}(t_0) \cdot t$$

$$\vec{r_{21}}(t_0) = \vec{r_{21}^0} = t_{CPA} \cdot (v_2 \cdot \cos(\theta) + v_1) \cdot \vec{\imath} + t_{CPA} \cdot v_2 \cdot \sin(\theta) \cdot \vec{\jmath}$$

$$\vec{v_{21}}(t_0) = \vec{v_{21}^0} = -(v_2 \cdot \cos(\theta) + v_1) \cdot \vec{\imath} - v_2 \cdot \sin(\theta) \cdot \vec{\jmath}$$

$$(11)$$

Where $\vec{r_{21}}(t)$ and $\vec{v_{21}}(t_0)$ stand respectively for the relative position and relative speed of the intruder with respect to the ownship. Note that $\vec{v_{21}}$ is also constant. Now, range and closure rate are given by:

$$\|\vec{r_{21}}(t)\| = \sqrt{(\vec{r_{21}^0} \cdot \vec{r_{21}^0}) + 2t \cdot (\vec{r_{21}^0} \cdot \vec{v_{21}^0}) + t^2 \cdot (\vec{v_{21}^0} \cdot \vec{v_{21}^0})}$$

$$\|\dot{\vec{r_{21}}}(t)\| = \frac{(\vec{r_{21}^0} \cdot \vec{v_{21}^0}) + t \cdot (\vec{v_{21}^0} \cdot \vec{v_{21}^0})}{\|\vec{r_{21}}(t)\|}$$

$$(12)$$

If now (1) and (12) are combined, tau could be expressed as follows:

$$\tau = \frac{(v_1^2 + v_2^2 - 2 \cdot v_1 \cdot v_2 \cdot \cos(\theta)) \cdot (t_{CPA} - t)^2}{(v_1^2 + v_2^2 - 2 \cdot v_1 \cdot v_2 \cdot \cos(\theta)) \cdot (t_{CPA} - t)}$$
$$= t_{CPA} - t$$

$$(13)$$

Then, for a given tau, the range between both aircraft for a given τ could be expressed as follows:

$$\|\vec{r_{21}}(t)\| = \sqrt{(v_1^2 + v_2^2 - 2 \cdot v_1 \cdot v_2 \cdot \cos(\theta)) \cdot (t - t_{CPA})^2}$$
$$= \sqrt{V(v_1, v_2, \theta)} \cdot (t_{CPA} - t_{tau})$$
$$= \sqrt{V(v_1, v_2, \theta)} \cdot \tau$$

$$V(v_1, v_2, \theta) = (v_1^2 + v_2^2 - 2 \cdot v_1 \cdot v_2 \cdot \cos(\theta))$$

$$(14)$$

Equation (14) determines the locus of the range of an intruder triggering an alert / resolution advisory for different levels of sensitivity of TCAS.

Now, modified tau$_{mod}$ can be expressed following a similar approach. Thus, (2) is transformed to:

$$\tau_{mod} = \frac{V(v_1, v_2, \theta) \cdot (t - t_{CPA})^2 - DMOD^2}{V(v_1, v_2, \theta) \cdot (t_{CPA} - t)} \quad (15)$$
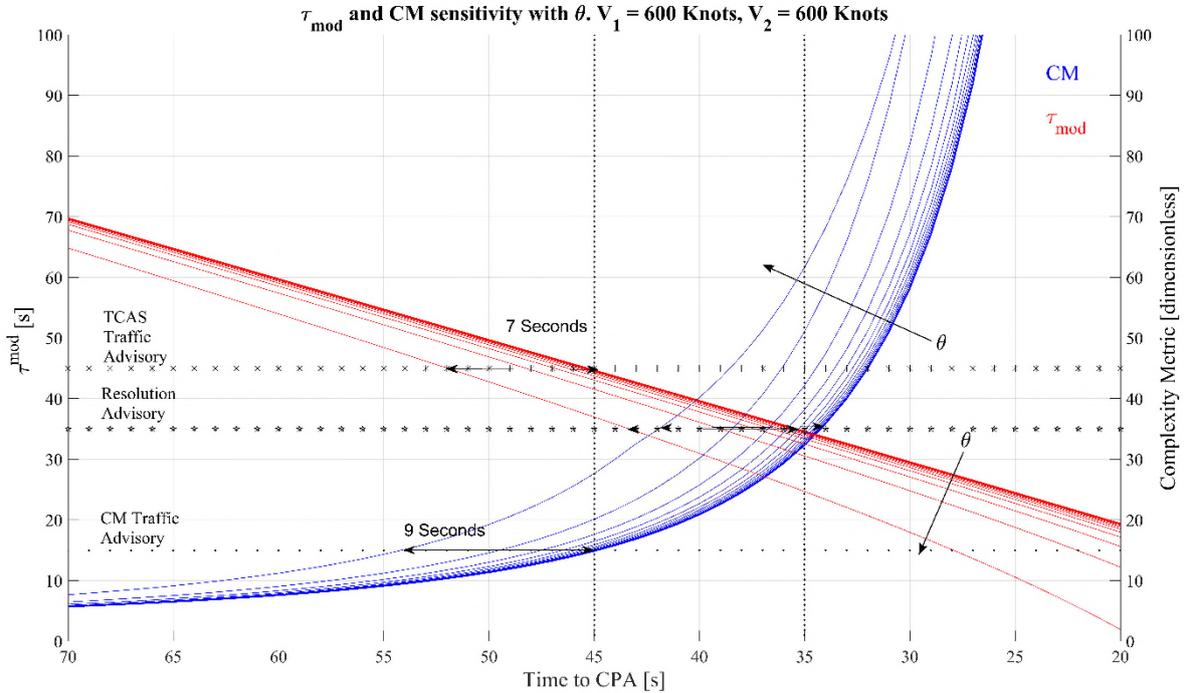

Figure 3. τ_{mod} and CM_H Sensitivity with θ.

In this case depending on the initial relative motion of both aircraft, τ_{mod} is reached at different t_{tau_mod}. For a given value of τ_{mod}, t_{tau} is determined by the following expression:

$$(t_{CPA} - t_{tau\_mod}) = \frac{\tau_{mod}}{2} \cdot \left(1 + \sqrt{1 + \frac{4 \cdot DMOD^2}{V(v_1, v_2, \theta) \cdot (\tau_{mod})^2}}\right) \quad (16)$$

And then range is given again by expression $\overrightarrow{r_{21}}(t_{tau\_mod})$.

D. Intrinsic Complexity in the CPA reference model

Intrinsic Complexity has been introduced previously, see (8). For two aircraft encounter, the metric contains two different components, that is to say, horizontal complexity and vertical complexity. In the framework previously established, the former is defined as follows:

$$CM_H = \left(1 + \frac{\left(\frac{R}{2}\right)^2}{\left(\max(\frac{R}{2}, \|\overrightarrow{r_{21}}\|)\right)^2}\right) \cdot e^{-T_{SM} \cdot \left(\frac{\overrightarrow{v_{21}} \cdot \overrightarrow{r_{21}}}{\|\overrightarrow{r_{21}}\|^2}\right)} \quad (17)$$

Where R indicates a characteristic distance, defining a surrounding area associated to the aircraft. Following (11) and (12), equation (17) can be expressed as follows:

$$CM_H(t) = \left(1 + \frac{\left(\frac{R}{2}\right)^2}{\left(\max(\frac{R}{2}, \sqrt{V(v_1, v_2, \theta) \cdot (t_{CPA} - t)^2})\right)}\right) \cdot e^{\frac{T_{SM}}{(t_{CPA}-t)}} \quad (18)$$

There are two possible cases for (18), depending on the relative distance between both aircraft. In case that $\frac{R}{2} > \|\overrightarrow{r_{21}}\|$, then

$$CM_H(t) = 2 \cdot e^{\frac{T_{SM}}{(t_{CPA}-t)}} \quad (19)$$

On the contrary, i.e. $(\frac{R}{2} \leq \|\overrightarrow{r_{21}}\|)$, the metric is formulated as follows:

$$CM_H(t) = (1 + \frac{R^2}{4} \cdot \frac{1}{V(v_1, v_2, \theta) \cdot (t_{CPA} - t)^2}) \cdot e^{\frac{T_{SM}}{(t_{CPA}-t)}} \quad (20)$$

As for the τ_{mod} case, in order to obtain the range locus for a given threshold based on this metric, the process below is followed.

Firstly, t_{IC}, which is the time when the threshold is exceeded, is derived. Then, range is obtained, given again by $\overrightarrow{r_{21}}(t_{IC})$. For cases where $\frac{R}{2} > \|\overrightarrow{r_{21}}(t)\|$, the following expression applies:

$$t_{IC} = \left(t_{CPA} - \frac{T_{SM}}{\ln\left(\frac{C_{mH}}{2}\right)}\right) \quad (21)$$

Otherwise, the expression is defined as follows:

$$\frac{CM_H \cdot V(v_1, v_2, \theta) \cdot (t_{CPA} - t)^2}{\left(\frac{R}{2}\right)^2 + CM_H \cdot V(v_1, v_2, \theta) \cdot (t_{CPA} - t)^2} - e^{\frac{T_{SM}}{(t_{CPA}-t)}} = 0 \quad (22)$$

And then, t_{IC} is obtained by numerically solving (22).

IV. EXPERIMIENTAL DATA AND RESULTS

A. Parameters selection

Parameters influencing on studied indicators (τ, τ_{mod} and CM_H) are established in this section. These three indicators are function of v_1, v_2 and θ. In addition, τ_{mod} is affected by DMOD whereas for CM_H, T_{SM} and R are the parameters playing a main role.
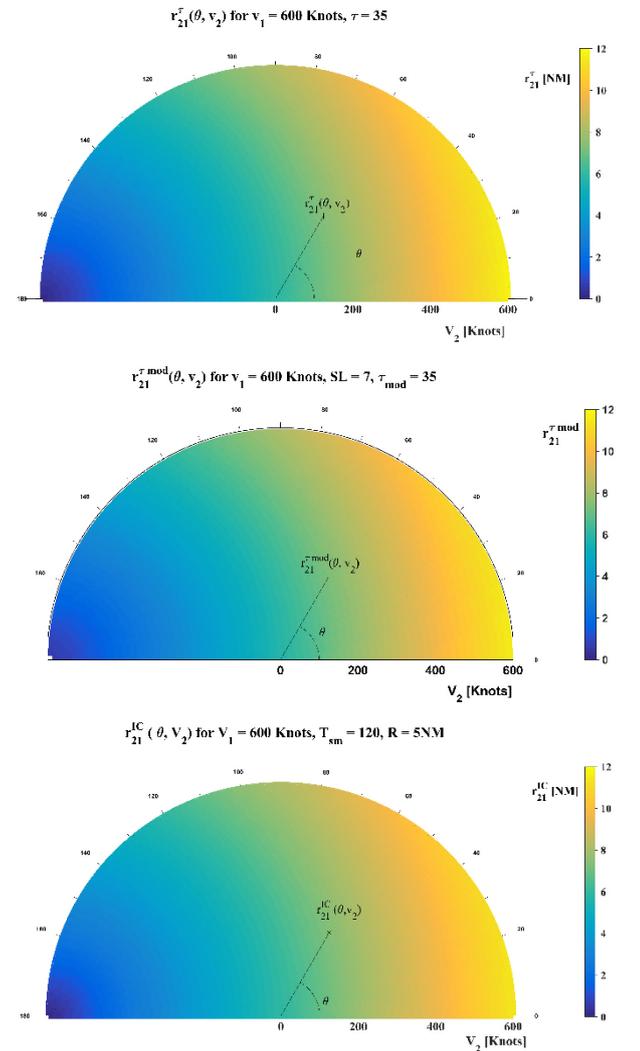

Figure 4 Range Locus for different indicators.

Top $\tau = 35$, middle $\tau_{mod} = 35$ and, bottom $CM_H = 35$.

For this example, v_1 will be equal to 600 Knots. It has been selected in order to reflect TCAS Maximum Closing Speed (closure rate) conditions for traffic with opposite headings (see Table 3-1 of [1]).

For DMOD, a SL = 7 is considered as it reflects the scenario which will be handled by AGENT. Therefore, DMOD is equal to 1.1 NM. Finally, for R and T_{SM}, values of 5NM and 120 s are chosen. The former represents the radius used for defining the high-density volume around the aircraft which is limiting TCAS, and for the latter [1], 120 s characterises the typical late-phase of the separation management layer of ATM.

B. Complexity Metric Threshold

In order to compare the three indicators, a reference value for the intrinsic complexity should be chosen. In order to do so, values for the CM and τ_{mod} for two high-speed aircraft, in this case 600 Knots, have been compared. Although those speeds are unrealistic, the same criterion of reflecting the maximum Closing Speed for TCAS has been followed.

For a SL=7, the threshold for issuing a RA are 35 seconds. In order to study the behaviour of both metrics, τ_{mod} is intersected with the intrinsic complexity. Approximately, both indicators intersect for aircraft with opposite headings when τ_{mod} is equal to 35 seconds, which also corresponds to a value of 35 for the intrinsic complexity.

Then, the comparisons among τ, τ_{mod} and CM_H are evaluated for the same value of 35 (seconds in the case of tau, and dimensionless for the intrinsic complexity).

C. Range comparison

To solve formulae (14), (16) and (21)-(22), v_1 is fixed, and then different values for v_2 and θ are studied. Comparisons are presented by charts in polar coordinates, where the radial axis indicates v_2, and the angle represents θ.

In the case of τ, the result, (13) establishes a direct linear relation between τ and t. It reflects that τ only represent the exact time-to-go to the CPA when both aircraft are in perfect collision opposite headings and assuming constant speed. Therefore, range between ownship and intruder is directly given by selecting a Sensitivity Level for TCAS.

The upper locus in Figure 4 presents the range values when tau equals 35 seconds. With this reference system, for all considered intruder speeds and thetas, tau is equal to 35 seconds and it is equivalent to the time-to-go to the CPA. It can be observed how the range decreases as the module of the relative speed does. In the first column of Table I, Table II and Table III different range values depending on v_2 and θ are shown. It reflects expected results as the maximum range occurs when aircraft are in opposite headings at maximum speed, which results in a relative speed of 1200 Knots.

For τ_{mod} and CM_H, equations (16) and (21)-(22) are solved in order to obtain τ_{mod} and t_{IC} for different values of v_2 and θ. Then, the range equation is propagated for the previously obtained time series. As a result, range values for the distributions of v_2 and θ are shown in the central and bottom charts of Fig. 2.

Analysing qualitatively the three cases, it can be observed that the three indicators behave similarly, in terms of the aircraft range at the moment of crossing the threshold.

More precisely, in Table I, Table II and Table III ranges are compared for different values of θ and v_2. Results reflect that for opposite headings, the CM is slightly delayed with regard to τ_{mod}, about 1.5 seconds. The same situation occurs when theta is 90 degrees, but in this case, the difference is significantly reduced, and never implies more than 1 second of delay. In the case of close to parallel trajectories (small theta angles), or overtaking situations, the CM is crossing the threshold before than the other two metrics, and always the range is higher than the DMOD.

TABLE I. RANGE BETWEEN OWNSHIP AND INTRUDER FOR THETA = 0 AND TAU, TAU_MOD, CM = 35.

V2 [Knots]	Range [NM] for Tau, Tau_Mod, CM = 35. Theta = 0		
	tau	tau_mod	CM
300	8.75	8.78	8.63
400	9.72	9.75	9.55
500	10.69	10.72	10.48
600	11.67	11.69	11.4

TABLE II. RANGE BETWEEN OWNSHIP AND INTRUDER FOR THETA = 90 AND TAU, TAU_MOD, CM = 35.

V2 [Knots]	Range [NM] for Tau, Tau_Mod, CM = 35. Theta = 90		
	tau	tau_mod	CM
300	6.52	6.57	6.54
400	7.01	7.05	7.00
500	7.59	7.63	7.54
600	8.25	8.29	8.16

TABLE III. RANGE BETWEEN OWNSHIP AND INTRUDER FOR THETA = 180 AND TAU, TAU_MOD, CM = 35.

V2 [Knots]	Range [NM] for Tau, Tau_Mod, CM = 35. Theta = 180		
	tau	tau_mod	CM
300	2.92	3.02	3.24
400	1.94	2.09	2.33
500	0.972	1.22	1.17
600	0	undetermined	0

D. τ_{mod} *and CM sensitivy with* θ

In Figure 3 it is represented the evolution of τ_{mod} and CM relative to the time-to-go to the CPA. Different trends, for τ_{mod} (red) and CM (blue), for θ changes are shown. For both indicators, as θ increases, starting from 0, curves are moving to the left, i.e. the threshold is crossed earlier. This can also be interpreted as, when the module of the relative speed decreases, both curves move to the left.

Let's now consider the time for which the Traffic Advisory threshold is reached. Figure 3 shows how both metrics behave in the same manner, although for opposite and same heading scenarios, time differences when the TA is issued are slightly different. In addition, it could be seen how TA would be triggered earlier for the CM metric. Finally, for selecting the CM threshold the same criteria than for RA threshold selection has been followed. In this case, a τ_{mod} threshold of 45 equals approximately to a CM value of 15.

V. CONCLUSIONS

Intrinsic Complexity applied to detect threats at the late phase of the Separation Management layer, closed to TCAS layer, has been presented. The aim of this paper was to assess the coherence between threat detection indicators, provided by the complexity metric and TCAS indicators, and to determine whether or not the proposed complexity metric can allow an operational integration in the detection process between Separation Management and the Collision Avoidance layers.

A simple encounter model has been presented to this purpose, to ease the evaluation of the indicators for pair-wise encounters. It has been shown that the proposed horizontal complexity metric and TCAS τ_{mod} behave similarly, in terms of the range between aircraft when alert thresholds are reached for all relative angles and speeds.

In addition, results show the well-known dependence of TCAS τ and τ_{mod} with relative speeds and encounter angles. When relative speeds decrease and heading angles become more similar, the range at the alert threshold also is reduced. The introduction of τ_{mod} mitigates derived problems, such as alerts are issued earlier when aircraft tend to identical headings.

For the complexity metric, the same performance is observed in terms of range and time to the CPA when resolution advisories would be issued. For traffic advisories, the complexity metric triggers the alert earlier for same headings than for opposite ones. This feature facilitates an increased situational awareness for the late separation management phase as it identifies complex scenarios with low deterioration rates.

To conclude, preliminary analysis of the proposed horizontal complexity metric shows that it derives to TCAS horizontal indicator at the transition stage between separation management and collision avoidance layers. As a result, resolution actions based on complexity could remove the risk of non-coherent actions issued by different safety nets, if TCAS is considered an independent and fixed one.

Further work should be conducted in order to determine the evolution of the intrinsic complexity for multi aircraft encounters and to incorporate the three-dimensional problem. Finally, a process for late resolution clearances that are coherent with TCAS ones should be defined

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