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Stroeve, Sybert H.; Blom, Henk A.P.; Medel, Carlos Hernandez; Daroca, Carlos Garcia; Cebeira, Alvaro Arroyo; Drozdowski, Stanislaw

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Modelling and Simulation of Intrinsic Uncertainties in Validation of Collision Avoidance Systems

Sybert H. Stroeve,[1] and Henk A.P. Blom[2]
Royal Netherlands Aerospace Centre NLR, Amsterdam, The Netherlands

Carlos Hernandez Medel[3], Carlos Garcia Daroca[4], Alvaro Arroyo Cebeira[5]
everis Aerospace & Defence, Madrid, Spain

and
Stanislaw Drozdowski[6]
EUROCONTROL, Brussels, Belgium

Airborne Collision Avoidance Systems (ACAS) form a key safety barrier by providing last-moment resolution advisories (RAs) to pilots for avoiding mid-air collisions. Intrinsic uncertainties, such as noise in ACAS input signals and variability in pilot performance imply that the generation of RAs and the effectuated aircraft trajectories are non-deterministic processes. Existing ACAS validation methods reflect the intrinsic uncertainties to a limited extent only. This paper develops an agent-based model, which systematically captures uncertainties in ACAS input and pilot performance for Monte Carlo (MC) simulation of encounter scenarios. The agent-based model has been integrated with industry-specific implementations of TCAS II and ACAS Xa in a novel Collision Avoidance Validation and Evaluation Tool (CAVEAT). Through illustrative MC simulation results it is demonstrated that the intrinsic uncertainties can have significant effect on the variability in timing and types of RAs, and subsequently on the variability in miss distance. Even the MC simulation estimated mean miss distance can differ significantly from the deterministically simulated miss distance. Most importantly, the tails of miss distance probability distributions and probabilities of near mid-air collisions are affected. This stipulates that addressing intrinsic uncertainties through MC simulation is essential in evaluating ACAS.

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[1] Senior Scientist, Aerospace Operations Safety Institute, sybert.stroeve@nlr.nl

[2] Full Professor at Delft University of Technology, chair Air Traffic Management Safety, AIAA Member, h.a.p.blom@tudelft.nl

[3] Director, Aerospace Division, carlos.hernandez.medel@everis.com

[4] Senior Engineer, Aerospace Division, carlos.garcia.daroca@everis.com

[5] PhD Candidate, Universidad Politécnica de Madrid (current affiliation), alvaro.arroyo.cebeira@alumnos.upm.es

[6] Senior ACAS Expert, EUROCONTROL Head Quarters, stanislaw.drozdowski@eurocontrol.int

Nomenclature

$\varepsilon_{t,system,i}^{type}$ = particular type of sensor error at time t in a particular system of aircraft i

$\sigma_{t,system,i}^{type}$ = standard deviation at time t of a particular type of sensor error in a particular system of aircraft i

$\kappa_{system,i}^{type}$ = probability distribution of a particular type of sensor error in a particular system of aircraft i

$\alpha_{system,i}^{type}$ = autocorrelation factor of a particular type of sensor error in a particular system of aircraft i

τ_0 = time at the start of an encounter scenario

$s_{t,AC,i}^{z}$ = geodetic altitude of aircraft i at time t

$s_{t,PAS,i}^{z}$ = standard pressure altitude measured by the pressure altimetry system (PAS) of aircraft i at time t

$\tau_{\tau_1,PF,i}^{resp}$ = time of response to an ACAS advisory at time τ_1 by the pilot flying (PF) of aircraft i

$\theta_{t,PF,i}^{type}$ = mode of a particular type known at time t by the PF of aircraft i

$\mu_{PF,i}^{type}$ = mean of a performance variable of the PF of aircraft i

$\sigma_{PF,i}^{type}$ = standard deviation of a performance variable of the PF of aircraft i

$\overline{v}_{\tau_1,PF,i}^{z,RA}$ = vertical rate to attain in an RA as known at time τ_1 by the PF of aircraft i

$v_{\tau_1,PF,i}^{a,z}$ = current vertical rate as known at time τ_1 by the PF of aircraft i

$a_{\tau_1,PF,i}^{RA}$ = vertical acceleration chosen at time τ_1 by the PF of aircraft i

Abbreviations

AC = Aircraft

ACAS = Airborne Collision Avoidance System

ADS-B = Automatic Dependent Surveillance - Broadcast

AFCS = Automatic Flight Control System

ANSP = Air Navigation Service Provider

APFD = Auto-Pilot/Flight Director

AR = Auto-Regressive

ATC = Air Traffic Control

ATM = Air Traffic Management

CAVEAT = Collision Avoidance Validation and Evaluation Tool

CL = Climb (resolution advisory)

COC = Clear Of Conflict

CNS = Communication, Navigation, Surveillance

CPA = Closest Point of Approach

DDE = Do not Descend (resolution advisory)

DE = Descend (resolution advisory)

ENU = East-North-Up

GNSS = Global Navigation Satellite System

HMD = Horizontal Miss Distance

HMI = Human Machine Interface

InCAS = Interactive Collision Avoidance Simulator

LO = Level Off (resolution advisory)

MC = Monte Carlo

MOPS = Minimum Operational Performance Standards

NACp = Navigation Accuracy Category for position

NACv = Navigation Accuracy Category for velocity

NMAC = Near Mid-Air Collision

PAS = Pressure Altimetry System

PDF = Probability Density Function

PF = Pilot Flying

RA = Resolution Advisory

SD = Standard Deviation

SSR = Secondary Surveillance Radar

TA = Traffic Advisory

TCAS II = Traffic Alert and Collision Avoidance System II

UACS = Unmanned Aircraft Control System

UAS = Unmanned Aircraft System

VMD = Vertical Miss Distance

I. Introduction

A. Airborne Collision Avoidance System

The objective of an Airborne Collision Avoidance System (ACAS) is to provide advice to pilots for the purpose of avoiding potential collisions [1-3]. ACAS can issue two types of alerts: (1) Traffic Advisories (TAs), which aim to help the pilots in the visual acquisition of the intruder aircraft, and to alert them to be ready for a potential resolution advisory; and (2) Resolution Advisories (RAs), which are avoidance manoeuvres recommended to the pilot. An RA will tell the pilot the range of vertical rates within which the aircraft should be flown to avoid the threat aircraft. A clear of conflict message is posted when the intruding aircraft is no longer a threat.

ACAS II is the current ICAO standard and the Traffic Alert and Collision Avoidance System II (TCAS II) is its commercially available implementation, with version 7.1 [4] being required by ICAO Annex 10, Volume IV [2]. In TCAS II, Mode C and Mode S Secondary Surveillance Radar (SSR) transponders of nearby aircraft are interrogated and based upon the replies received, the system tracks the slant range, altitude and bearing of surrounding traffic. Using this information and a set of fixed rules for alert generation, TCAS II provides its advisories.

ACAS X is FAA sponsored R&D towards a more advanced ACAS [5, 6]. Arguments for its development include increased flexibility for future operations, increased adaptability for new surveillance inputs, reduced collision risk and less nuisance alerts, and collision avoidance capabilities for general aviation and unmanned aircraft systems (UAS) [6]. ACAS X has a system architecture that uses logic tables, which have been optimized for specific aircraft operations in particular airspaces. Changes in operations, aircraft types and airspaces can be effectively accommodated by off-line optimization of the logic tables. The modular architecture of ACAS X allows for effective use of multiple surveillance sources, including transponder-based, Automatic Dependent Surveillance - Broadcast (ADS-B), and others. Four variants of ACAS X are foreseen [6]: (1) ACAS Xa, which includes active interrogation of intruders and is intended as a successor of TCAS II; (2) ACAS Xo, which is a mode of ACAS Xa enabling operations with reduced separation; (3) ACAS Xp, which uses passive ADS-B to track intruders and is intended for general aviation; (4) ACAS Xu, which is a version for UAS. Minimum Operational Performance Standards (MOPS) have been published for ACAS Xa/Xo [7]. ICAO is working on inclusion of ACAS Xa in Annex

10, Volume IV and Doc 9863, where it is foreseen that ACAS Xa will be an alternate option for TCAS II v7.1 installations. The approval of ACAS Xa in Europe is pending subject to verification studies and regulatory action by EASA.

B. Standards & models for ACAS input and pilot performance

ICAO standards and recommended practices for the evaluation of the performance of collision avoidance logic are provided in Section 4.4 of Annex 10, Volume IV [2]. These include the use of stochastic standard error models for range, bearing and altitude measurements, a deterministic standard pilot model, describing delays and accelerations of pilot responses to RAs, and a standard encounter model, describing various characteristics of the trajectories of aircraft pairs in an encounter.

The MOPS of TCAS II and ACAS Xa [4, 7] give performance requirements on the measurement systems providing ACAS input that are different and typically more detailed than the ICAO standard error models. For instance, Annex 10 uses larger altimetry errors and a different probability distribution than the MOPS. Also the MOPS differentiate between variable and static components in the altimetry error, whereas Annex 10 considers the error to be static in an encounter. For errors in range and bearing measurements, normal distributions with fixed standard deviations are assumed in Annex 10, whereas the standard deviations are specified as being dependent on the transponder mode (Mode S, Mode C) in the ACAS MOPS.

Various models for pilot responses to RAs exist, which differ from the ICAO standard pilot model. Based on a large dataset of downlinked RAs, a Bayesian network for pilot response probability in [8] shows various dependencies on the operational context and an overall response probability of (only) 0.56. The two most important variables influencing the probability of response are the existence of a rate reversal (i.e. an RA that commands a vertical rate opposite to the current vertical rate) and the aircraft being on a parallel approach. A stochastic response model based on airborne-recorded data in [9] shows the variability in delay, vertical rate and acceleration of pilots. The implications of the differences in pilot models on the effectiveness of the overall collision avoidance system can be large.

C. Validation of novel ACAS designs

ACAS has shown to be an effective safety barrier in commercial aviation and a novel ACAS design has to be validated to operate under realistic operational conditions better than the existing ACAS design. Such operational validation process has been conducted each time a novel TCAS II version has replaced an earlier TCAS II system. For the operational validation of ACAS Xa [7] versus TCAS II v7.1 [4] such an operational validation has also been conducted [10]. This report compares the performance of ACAS Xa relative to TCAS II v7.1 on various characteristics, notably including numbers of RAs and probability of near mid-air collision (NMAC), i.e. the situation when two aircraft simultaneously come within 100 feet vertically and 500 feet horizontally. Simulations were performed for a large number of encounter sets, which describe aircraft trajectories and equipages in different traffic contexts. The simulation results basically show that the NMAC probability is lower for ACAS Xa, while the number of nuisance RAs is also lower. Apart from the many encounter sets, little information is provided in [10] on the noise and pilot models that were used in the simulations. In an independent study [11], earlier ACAS Xa development runs were evaluated by the OSCAR tool of DSNA/Egis Avia and the InCAS tool of EUROCONTROL. These tools were used to simulate in the orders of 10^5 to 10^6 encounters with varying equipage levels and types of pilot response. Whereas OSCAR is not public, InCAS (Interactive Collision Avoidance Simulator) is distributed by EUROCONTROL for evaluation of single TCAS II encounters as well as sets of encounters [12]. InCAS uses deterministic simulations of encounters to evaluate the performance of TCAS II and ACAS Xa. Overall, the statistics (RA types, NMAC probability) in validation reports like [10, 11] are mostly driven by the variety in encounter sets, representing differences in trajectories, altitude layers, equipage types, and pilot response mode. These encounter settings are known at the start of a simulation and they do not consider additional variability during simulations, such as measurement noise that may influence ACAS decision making [2, 4, 7].

D. Increasing role of uncertainty modelling in novel ACAS design

Given the intrinsic uncertainty (sensor errors) in the ACAS input signals, the generation of an ACAS advisory should be considered as a non-deterministic process, which yields a specific ACAS advisory realization as an outcome. In other words, the timing and senses of the generated RAs are uncertain, even for deterministic aircraft trajectories. In combination with the variability in responses by the pilots to RAs, these sensor errors imply uncertainty in the modified trajectories and in the resulting distance between the aircraft. The uncertainty in the modified trajectories is yet another source of uncertainty in the generation of modified RAs that follow the initial RAs. All these sources lead to uncertainty in the closest point of approach (CPA) in an encounter (Fig. 1).

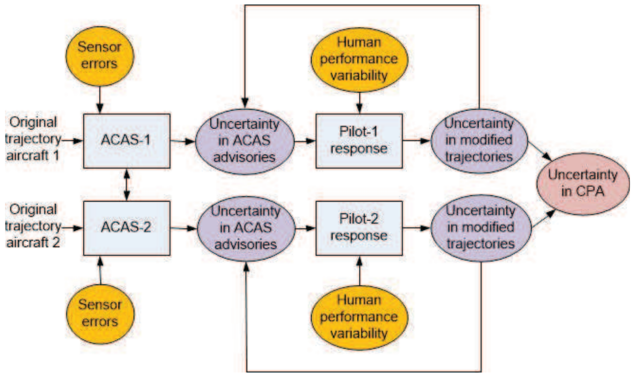

Fig. 1 Sources of uncertainty in evaluation of ACAS in an encounter of an aircraft pair

The principle of accounting for intrinsic uncertainty due to sensor errors and pilot response variability is playing an increasing role in the development of a novel ACAS design. In particular, the novel ACAS X development employs algorithmic approaches from the theory of decision making under uncertainty [13-16]. To capture uncertainty this theory uses probabilistic models of sensor errors and pilot responses, as well as Monte Carlo (MC) simulation based evaluations using these probabilistic models. In [14] zero-mean Gaussian distributions are used for slant range and bearing errors and the impact of various values of their standard deviations on simulated alert and NMAC rates are shown for three types of ACAS logics; other sensor errors (like pressure altitude) are assumed negligible and the pilot response is assumed to be deterministic. In [15] various error models are developed for bearing measurements, ranging from zero-mean Gaussian up to high-fidelity hidden Markov models, and the impact of these error models on simulated alert rate and risk ratio of TCAS II and ACAS X are shown. A study towards the development of ACAS for unmanned aircraft [16] presents MC simulation results for various accuracy levels of air-to-air radar and for variations in (deterministic) pilot response times. All above mentioned studies have effectively applied probabilistic modelling and MC simulation in support of novel ACAS design.

E. Need to incorporate uncertainty in the validation of novel ACAS design

The increasing role of uncertainty modelling and evaluation during the development of novel ACAS designs implies the need for a similar development for the validation of novel ACAS designs. For an independent operational validation of a novel ACAS design it is insufficient to simply copy the probabilistic models that have been used during the ACAS design process. Instead an independent and more complete suite of probabilistic models has to be developed and used in the validation of a novel ACAS design. Therefore the aim of this paper is to present the development of an agent-based model that incorporates probabilistic models for the various sources of uncertainty in the novel ACAS Xa design.

The value of such uncertainty modelling has been demonstrated by [17] for TCAS II v7.1. This study has developed an agent-based modelling and MC simulation approach that incorporates a suite of probabilistic models for sensor errors (range, bearing, altitude, climb rate), ownship and othership state estimation, and pilot response time for encounters of TCAS II v7.1 equipped aircraft. The thesis [17] also develops mathematical models for the TCAS II v7.1 filtering and decision logic, which are more detailed than earlier mathematical models, e.g. [18, 19]. The findings of [17] have shown that for TCAS II evaluation the incorporation of probabilistic models for various intrinsic uncertainties yields novel insight into the role played by intrinsic uncertainties that are missed by established tools like InCAS.

Stimulated by the findings of [17], this paper develops an agent-based modelling and MC simulation framework to represent and evaluate various sources of uncertainty in ACAS Xa encounter scenarios, and to compare this with results for TCAS II v7.1. Although the philosophy of [17] is followed, there are significant enhancements: i) incorporating ACAS Xa is a main objective; ii) the spectrum of sensor error models is extended to those in use by ACAS Xa; iii) pilot performance models are extended; and iv) instead of using mathematical models for ACAS filtering and decision logic, use is made of interfaces to industry-specific ACAS libraries (including TCAS II v7.1 and ACAS Xa). Complementary to these enhancements, the aim also is to embed these agent-based modelling and simulation methods in a user-friendly software environment that supports large-scale evaluations of sets of encounters with TCAS II and ACAS Xa equipped aircraft. This software environment is referred to as CAVEAT (Collision Avoidance Validation and Evaluation Tool), and can address both the common deterministic simulations and MC simulation of a broad repertoire of sensor errors and pilot performance. As such CAVEAT supports to considerably extend the current practice of validation exercises as discussed in Section I-C.

The paper is structured as follows. Section II presents the agent-based simulation model. Section III gives an overview of the CAVEAT software environment. Section IV shows deterministic and non-deterministic simulation results for TCAS II and ACAS Xa. Section V concludes with a discussion of the results obtained. An early version of this paper has been presented at the 2019 ATM Seminar [20].

II. Agent-based model

Agent-based modelling and simulation (ABMS) has been used for the CAVEAT development. An agent-oriented perspective is useful to conceptualise processes in complex human-machine (sociotechnical) systems, such as encounter scenarios. Agent-based modelling considers a sociotechnical system to be composed of several agents and the overall system behaviour emerges from the individual agent processes and their interactions. This provides a highly modular and transparent way of structuring a model, thus supporting systematic analysis, both conceptually and computationally. Agents in a sociotechnical system contain boundaries separating internal states and processes from states and processes external to the agent (in other agents / environment). Relations between an agent's internal and external states or processes are represented strictly via the inputs and outputs of the agent considered. This makes it easier to specify models of complex systems that consist of many interacting entities, thereby facilitating effective study of the emergent behaviour of such systems.

A high level overview of the model entities in an agent-based model of an encounter scenario is provided in Fig. 2. It consists of two or more aircraft, which remain in an airspace with particular weather conditions and terrain, and which may interact with Global Navigation Satellite Systems (GNSS), ground Communication, Navigation, Surveillance (CNS) systems, and Unmanned Aircraft Control Systems (UACS). The initial CAVEAT development is focussed on manned aircraft operations without ATC interaction. Its main modelling entity is the piloted aircraft, as shown in the left-hand side of Fig. 2. The key characteristics of the models are presented next; a complete overview of the models is provided in [21].

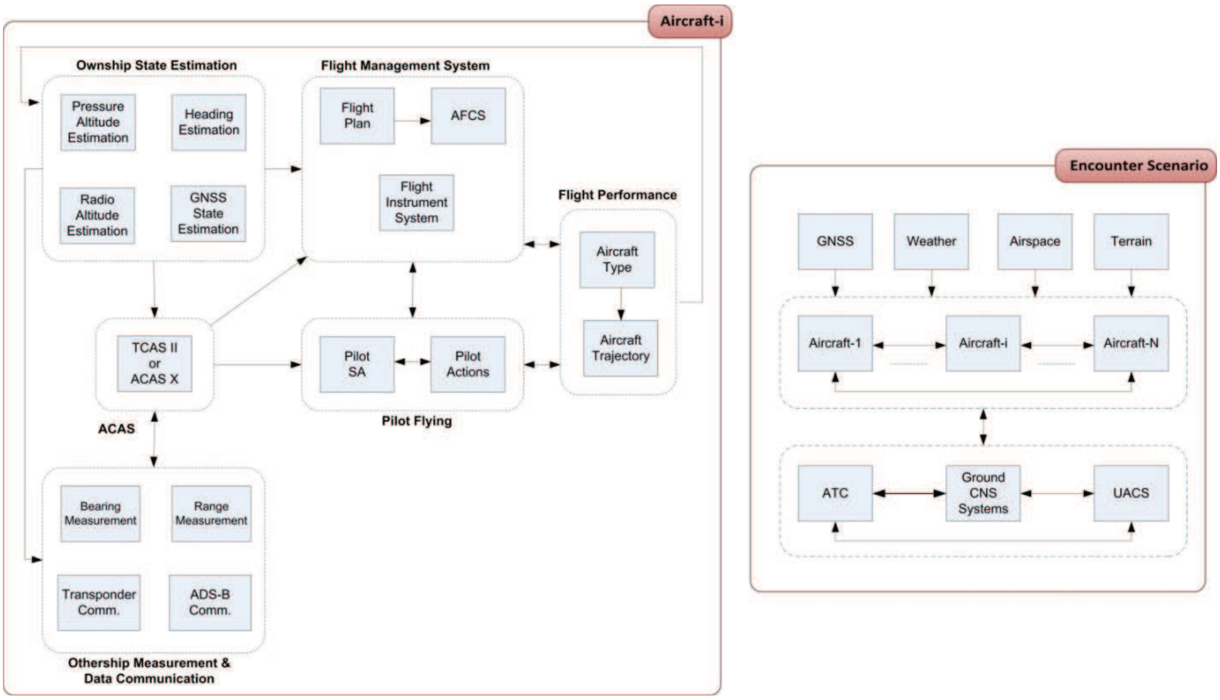

Fig. 2 Agent-based model of encounter scenario with N aircraft (right), where each aircraft contains the elements shown left

A. Environment

The simulations of an encounter scenario are performed in a local tangent plane East-North-Up (ENU) coordinate system, which has an origin that is provided in WGS84 coordinates by the user. The terrain in an encounter scenario is assumed to be flat at a geodetic altitude specified by the user. The wind in an encounter scenario is assumed to be constant and without wind shear, with a speed and direction that can be set by the user.

B. Flight performance

The flight performance describes the development of the position, speed and orientation of an aircraft, based on the flight control input by the automatic flight control system (AFCS) or the pilot flying (PF), and potentially influenced by the aircraft type.

C. Flight management system

The modelled flight management system (FMS) includes:

- Flight plan, which represents the 4D trajectory of the original encounter;

- AFCS, which is assumed to control the flight according to the flight plan before the PF takes over control in response to an RA;
- Flight instrument system, which provides information to the PF about flight states and the ACAS advised vertical speed.

D. Ownship state estimation

This set of models represents the estimation of ownship aircraft states that are used as input of ACAS and that are communicated to other aircraft by its transponder (Mode S, Mode C, ADS-B): pressure altitude estimation, radio altitude estimation, heading estimation, GNSS state estimation.

1. Pressure altitude estimation

The pressure or barometric altitude is a key input of TCAS II and ACAS Xa. The systems always utilize pressure altitude information which relates to the standard pressure. Static and variable errors can be discerned in the pressure altitude estimation. Static errors arise from variations in the location and physical condition of flush ports or static probes, and from the transmission of air pressure to the transducer. Variable errors include errors stemming from the transducer and those stemming from the quantization.

The pressure altimetry model represents both the variable (jitter) and static (bias) error components. Several model settings can be used, enabling its use according to stochastic models of ACAS MOPS [4, 7], ICAO Annex 10 [2], or a deterministic model. The error model for the bias in the pressure altimetry system (PAS) represents a constant error, which value is set at the start of the encounter scenario. This value is chosen from a zero-mean normal (Gaussian) distribution f^N, as used in the ACAS MOPS [4, 7], or from a zero-mean Laplacian distribution f^L, as used in [2]:

$$\{\varepsilon^{z,bias}_{t\geq\tau_0,PAS,i}\} : \begin{cases} f^N(\cdot;0,\sigma^{z,bias}_{\tau_0,PAS,i}) & \text{if } \kappa^{bias}_{PAS,i} = Normal \\ f^L(\cdot;0,\sigma^{z,bias}_{\tau_0,PAS,i}) & \text{if } \kappa^{bias}_{PAS,i} = Laplace \end{cases} \tag{1}$$

where $\sigma^{z,bias}_{\tau_0,PAS,i}$ is a standard deviation that depends on the altitude at the start of the scenario ($t = \tau_0$).

The error model for the jitter in the pressure altimetry system represents a time-varying error using a first-order autoregressive process, with values set at its sampling times (once per second):

$$\varepsilon_{t,PAS,i}^{z,jitter} = \begin{cases} \varepsilon_{t,PAS,i}^{noise} & \text{if } t = \tau_0 \\ \alpha_{PAS}^{jitter} \varepsilon_{t-T_{PAS,i}^{sample},PAS,i}^{z,jitter} + \varepsilon_{t,PAS,i}^{noise} & \text{if } t > \tau_0 \end{cases} \tag{2}$$

$$\{\varepsilon_{t,PAS,i}^{noise}\} : \; f^N(0, \sigma_{PAS,i}^{z,jitter} \sqrt{1-(\alpha_{PAS,i}^{jitter})^2}) \tag{3}$$

where $\alpha_{PAS,i}^{jitter}$ is the autocorrelation and $\sigma_{PAS,i}^{z,jitter}$ is the standard deviation of the jitter.

Overall, the standard pressure altitude as measured by the pressure altimetry system equals the geodetic altitude of an aircraft $s_{t,AC,i}^{z}$ and the two (bias and jitter) error components:

$$s_{t,PAS,i}^{z} = s_{t,AC,i}^{z} + \varepsilon_{t,PAS,i}^{z,bias} + \varepsilon_{t,PAS,i}^{z,jitter} \tag{4}$$

2. Radio altitude estimation

The radio altimeter provides an estimate of an aircraft's height above the ground. ACAS uses radio altitude data, when available, and barometric altitude data to estimate the ground level in order to reduce interrogations to and prevent advisories against aircraft that are on the ground.

The radio altitude model represents the height above terrain as estimated by the radio altimetry system. This estimate equals the actual height above terrain and a radio altimetry error. The error model represents a time-varying error using a first-order autoregressive process with a normal distribution, where the standard deviation depends on the height of the aircraft.

3. Heading estimation

Ownship heading estimation is based on heading sensors in the aircraft's heading reference system, such as the gyro and inertial reference system. In TCAS II, ownship heading estimates are (only) used for orientation of the TCAS II display [4]. In ACAS Xa, ownship heading estimates are also used to determine the bearing angles of intruders [7]. In particular, ACAS Xa uses ownship heading to improve the relative cross range velocity estimate of an intruder and to compute relative bearing for the display of ADS-B intruders.

A heading estimation model is used, where the estimated heading equals the true aircraft heading plus a heading error. The error model represents a time-varying error using an AR(1) process with a normal distribution, with a constant standard deviation and autocorrelation of the noise.

4. GNSS-based state estimation

The ACAS Xa design supports the use of GNSS-based ownship estimates of horizontal position and speed (WGS84 data). The model for the GNSS-based horizontal position estimation describes the aircraft position and position errors in the (x,y)-frame, and transformation towards the WGS84 frame. The error model uses a first-order autoregressive process with normal distributions for the (x,y)-components with standard deviations determined by the Navigation Accuracy Category for position (NACp). The horizontal velocity estimates use a similar model based on the Navigation Accuracy Category for velocity (NACv).

E. Othership measurement & interaction

This set of models represents othership measurement & coordination by transponder-based interaction between aircraft (Mode S, Mode C, ADS-B).

1. Slant range measurement

TCAS II and ACAS Xa use transponder-based slant range measurement. The MOPS define transponder mode-based requirements on errors in the slant range measurement.

The slant range measurement model represents the slant range as measured by an ownship with respect to an othership. It includes an error model that describes static and variable error components, which depend on the mode of the transponder signalling (Mode S or Mode C). The bias component is chosen from a normal distribution with a mode-dependent standard deviation. The jitter component is described by a first-order autoregressive process with a normal distribution and a mode-dependent standard deviation.

2. Bearing measurement

Bearing is the angle of another aircraft in the horizontal plane measured clockwise from the longitudinal axis of the own aircraft. The performance requirements for the transponder-based bearing measurement consider the transponder mode and the elevation angle between the aircraft.

The bearing measurement model includes an error model that describes a variable error by a first-order autoregressive process with a standard deviation that depends on the mode of the transponder signalling (Mode S or Mode C) and the elevation angle.

3. *Transponder communication*

The transponder communication model describes the transfer of othership data by Mode S or Mode C transponder-based signalling as received by an ownship. Key data elements include the Mode S address and the quantized pressure altitude, using 25 or 100 ft quantization steps.

4. *ADS-B communication*

ACAS Xa is designed to make use of ADS-B In data from intruder aircraft for surveillance and tracking when ADS-B reception systems are resident on the ownship. The ADS-B communication model describes the transfer of othership data to an ownship. Key data elements include the horizontal position and speed, the 25 or 100 ft quantized pressure altitude, the Mode S address, and the navigation accuracy categories.

F. Pilot flying

The model of the pilot flying (PF) includes components for situation awareness, response mode, delay, vertical rate and acceleration, and flight control action, as concisely explained next; see details in [21]. In combination these models extend earlier pilot models for responses to ACAS RAs. In [8] a detailed Bayesian network is used for modelling the pilot response probability, but the ICAO standard response model is used for the delay and acceleration. In [9] a model for a discretized probability density function of response delay, rate and acceleration is presented, which is combined with an altitude-dependent response probability. The model developed in this study applies a set of conditional probabilities given contextual conditionals (rather than a more complex Bayesian network), an RA-type dependent lognormal probability distribution for the response delay, and an advised rate dependent acceleration of the pilot response. The parameters in the overall model can be interpreted easily and allow for transparent sensitivity analysis.

1. *Pilot situation awareness*

The model of the situation awareness of the pilot flying represents the awareness of the PF of a range of elements regarding the state of the ownship (e.g. air speed, altitude, flying on a parallel approach), the flight plan, and ACAS advisories (e.g. RA being initial, modified or clear of conflict, RA being single threat or multiple threat, rate to maintain, limit rate). It is assumed that the situation awareness is updated instantaneously and without errors, such that it provides a timely and accurate set of the information provided to the pilot.

2. Pilot response mode

The pilot response mode model can be used in a deterministic setting, where the pilot responds either always or never to an ACAS advisory. The pilot response probability can be used in a stochastic setting, where probabilities for pilot response are used. For the response to initial RAs, conditional probabilities given altitude, rate reversal, parallel approach are used (8 values). For the response to modified RAs, conditional probabilities given reversal RA and response to previous RAs are used (4 values). The probability of response to clear-of-conflict (COC) advisories is assumed independent from the context (1 value). So, in total there are 13 conditional probabilities to be specified.

3. Pilot response delay

In a stochastic setting the delay in pilot response is chosen from a lognormal probability distribution f^{LN} with mean and standard deviation being dependent on the pilot responding to an initial RA, modified RA, or COC advisory:

$$\{\tau^{resp}_{\tau_1,PF,i}\} : \begin{cases} f^{LN}(\cdot;\mu^{\tau,ini}_{PF,i},\sigma^{\tau,ini}_{PF,i}) & \text{if } \theta^{res}_{\tau_1,PF,i} = Ini \\ f^{LN}(\cdot;\mu^{\tau,mod}_{PF,i},\sigma^{\tau,mod}_{PF,i}) & \text{if } \theta^{res}_{\tau_1,PF,i} = Mod \\ f^{LN}(\cdot;\mu^{\tau,coc}_{PF,i},\sigma^{\tau,coc}_{PF,i}) & \text{if } \theta^{res}_{\tau_1,PF,i} = COC \end{cases} \tag{5}$$

In a deterministic setting, fixed delays are used that depend on these types of advisories. This can be used to implement the ICAO standard pilot model with delays of 5 s and 2.5 s.

4. Vertical rate and acceleration

The vertical rate that the pilot will attain equals the ACAS-advised rate to maintain plus an error term chosen from a normal distribution. It follows from cockpit measurement data of [9] that there is a rising tendency in acceleration as function of the vertical speed to be attained. In line with this finding, the mean vertical acceleration is modelled as

$$\mu^{a,RA}_{\tau_1,PF,i} = \alpha^{a,RA}_{PF,i}(\theta^{RA}_{t,PF,i}) + \beta^{a,RA}_{PF,i}(\theta^{RA}_{t,PF,i})\left|\bar{v}^{z,RA}_{\tau_1,PF,i} - v^{a,z}_{\tau_1,PF,i}\right| \tag{6}$$

where $\overline{v}^{z,RA}_{\tau_1,PF,i}$ is the vertical rate to attain, $v^{a,z}_{\tau_1,PF,i}$ is the current vertical rate, and $\alpha^{a,RA}_{PF,i}$ and $\beta^{a,RA}_{PF,i}$ are parameters dependent on the situation awareness mode $\theta^{RA}_{t,PF,i}$ regarding the need for a low or high vertical acceleration of RA. The vertical acceleration is chosen from a lognormal PDF:

$$\{a^{RA}_{\tau_1,PF,i}\} : \ f^{LN}(\cdot; \mu^{a,RA}_{\tau_1,PF,i}, \sigma^{a,RA}_{PF,i}) \qquad (7)$$

In a deterministic setting the parameters can be set so, that the acceleration is 0.25g or 0.35g as specified by the ICAO standard pilot response model.

5. *Flight control action*

In the model, the pilot flying always follows the planned (original) trajectory in the horizontal plane, including the associated time stamps. If a preventive RA (e.g. Do Not Climb) is issued, then the PF ensures that the vertical speed of the aircraft remains in line with the rate limitation in the RA. If the PF responds to a corrective RA, then the PF adjusts the vertical speed using the determined delay and acceleration towards the vertical rate. After a COC advisory the vertical speed is changed towards the vertical speed in the flight plan and next the vertical speed according to the flight plan is followed.

G. Airborne Collision Avoidance System (ACAS)

1. *TCAS II*

Simulation of the tracking and decision logic of TCAS II versions 7.0 [22], 7.1 [4] and 7.2 (variation of version 7.1 with optimized RA thresholds [23]) is included. The C++ libraries of the algorithms for these TCAS II versions stem from InCAS version 3.3 and they were developed by the MITRE corporation and subsequently adjusted for EUROCONTROL by Evosys to accommodate versions 7.1 and 7.2.

2. *ACAS Xa*

Simulation of the tracking and decision logic of ACAS Xa is done for version V15R4 as published in the ACAS Xa/Xo MOPS [7]. It uses C++ libraries of ACAS Xa V15R4, which were developed and validated by Honeywell Aerospace and partners in SESAR 2020 Project 11.

III. Software environment

A. Functional Overview of CAVEAT

A preparatory study led to a high-level specification for the development of CAVEAT [24]. Questionnaires and interviews with a variety of InCAS users were applied to understand its current use and desired options for improvement. Subsequently a high-level composition has been developed that consists of four modules (Fig.3):

- *Encounter Determination*. This module sets the encounter for which the simulations are done. It reconstructs the aircraft trajectories using available measurement data (e.g. radar data) and it allows the user to create synthetic encounters.
- *Simulation*. This module simulates the performance of the technical systems (ACAS, avionics, aircraft) and pilot flying of an encounter scenario specified by the user. Principally, this uses MC simulation, which evaluates the uncertainty in an underlying agent-based model (e.g. sensor errors, pilot performance variability).
- *Evaluation.* This module determines characteristics of the simulation results, such as the closest point of approach (CPA) and statistics of RA times and CPA.
- *Visualization.* This module visualizes results of a single simulation run or the statistics of sets of simulation runs.

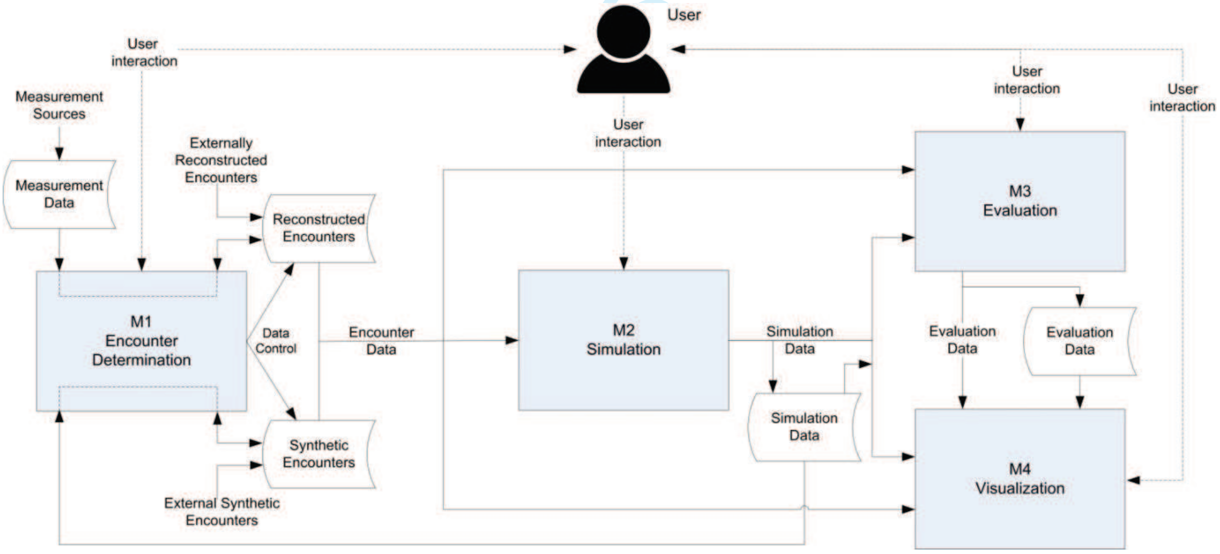

Fig. 3 High-level CAVEAT composition

B. Foreseen use types of CAVEAT

The envisioned use types of CAVEAT include the following.

- *Incident and accident investigation.* Simulation of occurred encounters, leading to insight in the ACAS advisories that can happen in the given situation and the possible implications for aircraft trajectories.
- *Evaluation of ACAS designs*. Simulation of large sets of encounters for comparison of ACAS designs (e.g. ACAS Xa versus TCAS II).
- *Evaluation of ACAS related systems.* Simulation of encounter scenarios including ACAS related systems, such as TCAS Alert Prevention and Auto-Pilot/Flight Director (APFD) automatic responses.
- *Compatibility analysis.* Simulation to analyse the compatibility of different ACAS systems (e.g. TCAS II and ACAS Xa), as well as ACAS and ATC systems.
- *Evaluation of changes in airspace and ATM*. Simulation for analysis of the implications of new airspace structures, new ATM systems, and unmanned aircraft systems (UAS).
- *Evaluation of changes in regulations*. Simulation to study new regulations in relation to above use types.

Retrospective analysis is supported by the first use type, while the other use types support prospective analysis. High-level requirements were set on the CAVEAT modules for their support to above use types. Key innovations of CAVEAT with respect to InCAS are the MC simulation facility and the extendibility for new systems. MC simulation of encounter scenarios provides a broad overview of probabilities of ACAS advisories and probability density functions (PDFs) of advisory times and CPA, rather than the result of a single-shot simulation. The extendibility will support analysis of relations with UAS, ACAS Xu, and air traffic control (ATC) systems.

C. CAVEAT’s simulation core

The simulation core forms the computational heart of CAVEAT and it is composed of several modules. The input manager module imports the encounter scenario files and simulation settings in the working environment. The simulation module implements the simulation scheduler and evaluates the agent-based models of all aircraft for the time steps in an encounter scenario. The evaluation module calculates relevant statistics. The output manager module exports results of the simulations to output files, including ACAS events, modified trajectories, and statistics.

The simulation core of CAVEAT receives encounter scenarios as input and produces for these scenarios the simulated ACAS advisories and the modified trajectories following the pilot responses to the RAs, implying a CPA and possibly an NMAC event. Four types of simulation can be discerned:

1. *Deterministic simulation of a single encounter scenario*. This is a single-run simulation of one encounter with all models used in a deterministic setting. It just yields the ACAS events and modified trajectories of the encounter.
2. *Deterministic simulation of multiple encounter scenarios*. This comprises single-run simulation for each encounter scenario in a set of N_{ES} encounter scenarios, with all models in a deterministic setting. The simulation results provide a basis for statistics for the set of encounter scenarios, e.g. NMAC probability and CPA empirical PDF.
3. *Monte Carlo simulation of a single encounter scenario*. This comprises a number N_{MC} of MC simulation runs for a single encounter scenario with one or several models in a stochastic setting. These simulations yield distributions of advisories (types, timing) and trajectory characteristics (CPA, NMAC) for the single encounter scenario considered.
4. *Monte Carlo simulation of multiple encounter scenarios*. This comprises a number N_{MC} of MC simulation runs for each encounter scenario from a set of N_{ES} encounter scenarios, where one or several models are used in a stochastic setting. Hence in total this involves $N_{MC}N_{ES}$ simulation runs, which yield distributions of advisories and trajectory characteristics for the set of encounter scenarios considered.

The sensor error models used in this study represent static errors (bias), typically modelled by Gaussian distributions, and variable errors (jitter), modelled by first-order autoregressive processes. For each MC simulation run (3 or 4 above) an independent sample from the bias distribution is used during the full MC simulation run. For the jitter an independent sample from the initial jitter distribution is drawn, and subsequently the jitter may evolve during each numerical simulation time step according to the difference equations of the jitter models.

D. CAVEAT's front-end

The front-end represents the processing of input and output by the CAVEAT human-machine interface (HMI). At the input side, the HMI allows the user to specify the encounter scenarios that are to be simulated. This is done by combining encounters with scenario configurations. Encounter files describe the 4D original trajectories, and some aircraft and flight properties of the aircraft in an encounter. The user can select a set of encounter files. Scenario configurations describe all settings of the agent-based models, including their deterministic or stochastic mode of functioning and all parameter values that determine their behaviour. The HMI allows the user to completely define scenario configurations, which are next stored in XML-files. As a basis for the simulations, the user combines encounters with scenario configurations and sets the number of (Monte Carlo) simulation runs for each encounter scenario.

At the output side, the HMI provides overviews of the simulation results. For particular simulation runs, the HMI shows the trajectories and the ACAS advisories in plots of the horizontal and vertical frames. For the results of sets of simulation runs, various statistics are shown. These include tables with statistics of advisory times (e.g. mean, median. percentiles), box-and-whisker plots of advisory times, empirical PDF of advisory times, conditional probabilities of the sense given an RA (e.g. Level Off, Climb, Descend), empirical PDF of CPA, vertical missed distance (VMD) and horizontal missed distance (HMD), and NMAC probability.

IV. Illustrative simulation results

This section illustrates differences between deterministic and MC simulation for encounter scenarios using two encounters listed in Table 1. Encounter E2 is most critical, as without intervention it would lead to a collision. Table 2 lists a number of scenarios, which define the following settings for both aircraft in each encounter: (a) sensor errors according to the ACAS MOPS [4, 7] or no sensor errors; (b) variability in the delay, rate and acceleration of the pilot response, or no such variability (ICAO standard pilot response model); (c) the pilot response probability being either 100% or 80% per RA. The scenarios represent combinations of these sensor error and variability settings. Scenario D is deterministic, and scenarios S1 to S3 are stochastic, where the number of sensor errors and variability sources is increasing in scenarios S1 to S3.

Table 1 Description of encounters between aircraft pairs

Encounter	Horizontal	Vertical	HMD (ft)	VMD (ft)
E1	Crossing	AC1 climbs AC2 is level	3038	200
E2	Crossing	AC1 is level AC2 is level	0	0

Table 2 Description of scenarios

Scenario	Sensor errors	Pilot Dynamic Variability	Pilot Response Probability
D	none	none (standard)	100%
S1	MOPS	none (standard)	100%
S2	MOPS	delay, rate, acc.	100%
S3	MOPS	delay, rate, acc.	80%

Encounters and scenarios are combined in encounter scenarios and simulated for TCAS II v7.1 and ACAS Xa V15R4 with both aircraft having the same ACAS type. The deterministic encounter scenarios are evaluated by a single simulation run each, the other stochastic encounter scenarios are evaluated by a MC simulation of 10,000 runs in each. As an example, Fig. 4 shows results of a deterministic simulation of encounter scenario E1-D with TCAS II v7.1, leading to the advisories Level Off (LO), Climb (CL) and Clear Of Conflict (COC). As a result the aircraft divert from their original trajectories and a VMD of 597 ft is attained instead of 200 ft for the original trajectories (HMD is 3038 ft).

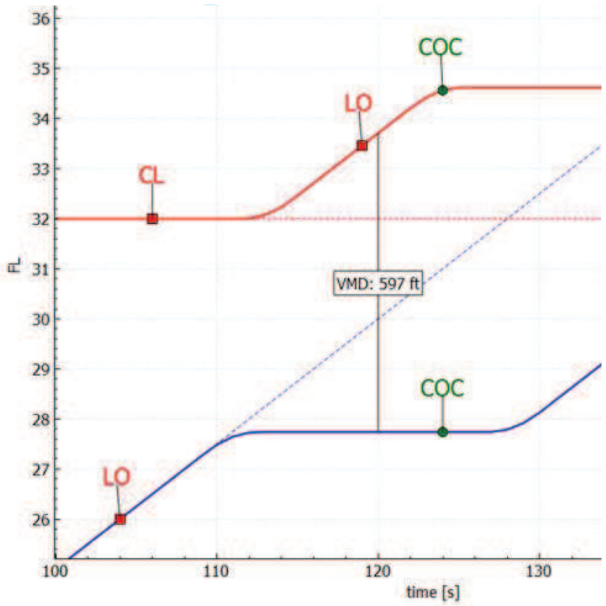

Fig 4. Vertical profile of deterministic simulation of encounter scenario E1-D with TCAS II v7.1 (dashed lines: original trajectories; solid lines: modified trajectories)

To illustrate the possible implications of sensor errors on the timing and probabilities of ACAS advisories, Table 3 shows results of deterministic simulation of scenario D (no sensor errors) versus MC simulation of scenario S1 (with sensor errors) for encounter E1 with TCAS II v7.1. It shows the probabilities of initial and subsequent RAs, the conditional probabilities of the sense of the RAs (LO: Level Off, DE: Descend, CL: Climb, DDE: Do not Descend), and the mean and standard deviation of the time of the RAs. The deterministic simulations (E1-D) show LO for aircraft 1 and CL followed by LO for aircraft 2, as also illustrated in Figure 4. The simulations with sensor errors (E1-S1) show a richer variety of possible RAs. The initial RA of aircraft 1 may be followed by additional modified RAs, e.g. a second RA in 3.6% of the cases. There is not always a modified RA for aircraft 2. The senses of the RAs may vary w.r.t. the deterministic simulation, e.g. Do not Descend instead of Climb for the initial RA of aircraft 2. There exists variation in the timing of the RAs due to the sensor errors as expressed in the standard deviations.

Table 3. Probabilities and timing of TCAS II v7.1 RAs in deterministic and MC simulations for encounter 1

Enc. Sc.	**AC**	**Adv.**	**P(RA)**	**P(Sense|RA)**	**Time (s)**	
					μ	**σ**
E1-D	1	RA-1	-	*LO*	*104.4*	-
		COC	-	-	*124.4*	-
	2	RA-1	-	*CL*	*106.6*	-
		RA-2	-	*LO*	*119.6*	-
		COC	-	-	*124.6*	-
E1-S1	1	RA-1	100%	LO: 97.4% DE: 2.6%	105.0	2.2
		RA-2	3.6%	LO: 69.8% DE:30.2%	113.2	4.3
		RA-3	1.0%	LO: 100%	117.3	2.4
		COC	100%	-	124.4	0.3
	2	RA-1	100%	CL: 91.6% DDE: 8.4%	106.6	2.6
		RA-2	88.9%	LO: 90.6% CL: 9.4%	118.2	2.4
		COC	100%	-	124.8	0.8

In encounter E2, there are even larger differences in the advisories due to the sensor errors (Table 4). Whereas the deterministic simulation (E2-D) shows that aircraft 1 is advised first to descend and aircraft 2 to climb, the MC simulation shows that when sensor errors are accounted for (E2-S1), the probabilities of climb and descend advisories are distributed about equally. This can be explained by the aircraft flying at the same level in this encounter, such that errors in the pressure altitude can trigger the upward or downward advisories. This illustrates that a deterministic simulation may provide a very limited overview of what can actually occur.

Table 4. Probabilities and timing of TCAS II v7.1 RAs in deterministic and MC simulations for encounter 2

Enc. Sc.	**AC**	**Adv.**	**P(RA)**	**P(Sense|RA)**	**Time (s)**	
					μ	**σ**
E2-D	1	RA-1	-	*DE*	*135.4*	-
		RA-2	-	*LO*	*156.4*	-
		COC	-	-	*186.4*	-
	2	RA-1	-	*CL*	*135.6*	-
		RA-2	-	*LO*	*155.6*	-
		COC	-	-	*185.6*	-
E2-S1	1	RA-1	100%	CL: 50.6% DE: 49.3%	135.2	0.9
		RA-2	100%	LO: 99.8%	153.3	1.9
		COC	100%	-	186.0	0.3
	2	RA-1	100%	DE: 50.6% CL: 49.2%	135.2	0.9
		RA-2	100%	LO: 99.0%	153.2	2.4
		COC	100%	-	186.0	0.3

Statistics of the VMD and NMAC probability in the various encounter scenarios are shown in Table 5 for both TCAS II v7.1 and ACAS Xa V15R4. It follows that the mean VMD in the stochastic scenarios can differ considerably from the deterministic results. The size of this difference depends on the encounter, the scenario, and the ACAS type. For instance, in encounter E1 the sensor errors in scenario S1 lead to a mean VMD that is only slightly smaller than found in the deterministic simulations for both TCAS II and ACAS Xa, whereas in encounter E2 the same types of sensor errors (scenario S1) lead to a mean VMD that is considerably smaller than the deterministic simulation results. It follows from Table 5 that the standard deviation (SD) of the VMD increases with the inclusion of sensor errors (S1), pilot dynamic variability (S2), and the possibility of no pilot response (S3). The size of the increase depends on the encounter, the scenario, and the ACAS type. For instance, the possibility of no pilot response (S3) leads to a SD that is much larger than observed in scenario S2 in encounter E2, whereas a modest increase can be observed in encounter E1. The 0.5% percentiles of the VMD of the stochastic encounter scenarios show that the VMD can be much smaller than observed in the deterministic simulation. The location of the lower tails of the probability distributions depends on the encounter, the scenario, and the ACAS type. In encounter E1, these lower-end VMD values are about factors 2 to 3.6 smaller than the deterministic VMD result. In encounter E2, the 0.5% percentile reaches the value of 0 ft in scenario S3 for both TCAS II and ACAS Xa. The NMAC probabilities in Table 4 show that in encounter scenario E2-S3 near mid-air collisions can occur both for TCAS II and ACAS Xa, whereas none are observed in the deterministic simulations or in the simulations that exclude the possibility of non-response by the pilot.

Table 5. Mean, standard deviation (SD), and 0.5% percentile of VMD, and NMAC probability of simulations of the set of encounter scenarios for TCAS II and ACAS Xa

ACAS type	Encounter scenario	VMD (ft)			P(NMAC) %
		Mean	SD	0.5%	
TCAS II v7.1	E1-D	*597*	-	-	0
	E1-S1	580	119	247	0.00
	E1-S2	554	136	218	0.00
	E1-S3	486	156	200	0.00
ACAS Xa V15R4	E1-D	*714*	-	-	0
	E1-S1	697	106	289	0.00
	E1-S2	707	135	259	0.00
	E1-S3	629	181	200	0.00
TCAS II v7.1	E2-D	*900*	-	-	0
	E2-S1	783	80	525	0.00
	E2-S2	867	108	555	0.00
	E2-S3	963	297	0	0.58
ACAS Xa V15R4	E2-D	*1200*	-	-	0
	E2-S1	1061	107	725	0.00
	E2-S2	1146	118	796	0.00
	E2-S3	1054	295	0	1.14

The statistics of Table 5 are further illustrated by the empirical PDFs of the VMD for encounter E1 and E2 in Fig. 5 and Fig. 6, respectively, in case of the deterministic scenario and stochastic scenarios S1 and S3 for both TCAS II v7.1 and ACAS Xa V15R4. These graphs clearly illustrate the wide range of VMD that is attained as a result of the uncertainty sources and they show that the VMD empirical PDFs can be multimodal. As such they show that a deterministic simulation without intrinsic uncertainty provides a very limited account of the VMD that can be attained.

Comparing the results of TCAS II v7.1 and ACAS Xa V15R4 in Table 5, it follows that for these encounter scenarios the mean VMD observed in the stochastic cases and the VMD in the deterministic cases are larger for ACAS Xa, and the 0.5% percentiles are larger or equal for ACAS Xa. These observations are in line with Figs. 5 and 6, which show that the empirical PDFs of ACAS Xa are shifted to the right with respect to those of TCAS II. They also have different forms, which indicates that different kinds of strategies are used by TCAS II and ACAS Xa. Regarding the effectiveness of collision avoidance, a key observation is that in spite of all the presented VMD statistics showing larger values for ACAS Xa, the NMAC probability is nevertheless about a factor two higher for ACAS Xa in encounter scenario E2-S3. The empirical PDFs of E2-S3 in Fig. 6 show that whereas the TCAS II results show no VMD values below 400 ft except for values very close to zero, the ACAS Xa results show a range of VMD values from 400 to 0 ft. The values in the range below 100 ft contribute to the larger NMAC probability of ACAS Xa in this encounter scenario. More detailed analysis would be required to understand the types of mechanisms leading to the range of low VMD values, which could be used as a first step towards improvement of the performance. While this limited set of simulation results is not meant to draw general conclusions on the performance of ACAS Xa versus TCAS II, the simulation results clearly illustrate the potential impact of sensor errors and pilot performance variability. As such they indicate the necessity to well account for such sources of uncertainty when comparing TCAS II and ACAS Xa.

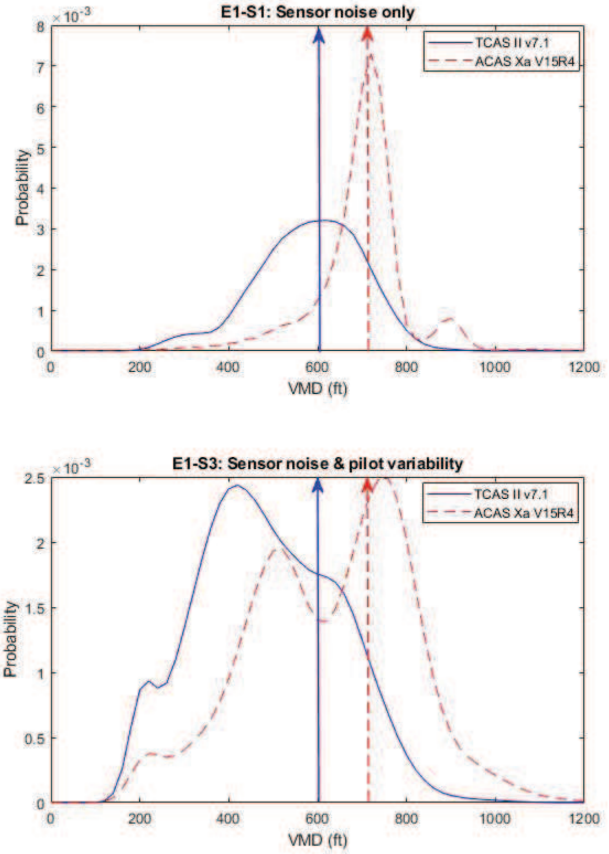

Fig. 5. Deterministic simulation results of encounter scenario E1-D (arrows) and empirical PDFs of the VMD for MC simulation of encounter scenarios E1-S1 (top) and E1-S3 (bottom) for TCAS II v7.1 and ACAS Xa V15R4.

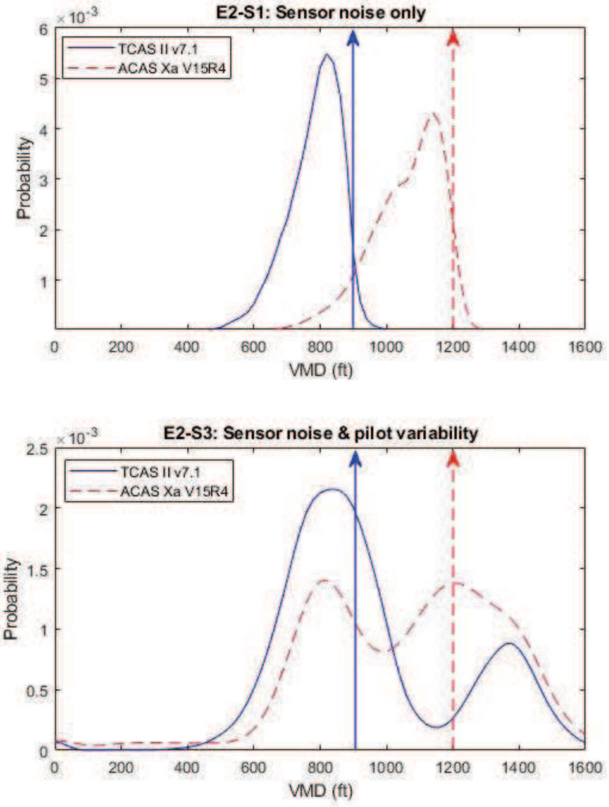

Fig. 6. Deterministic simulation results of encounter scenario E2-D (arrows) and empirical PDFs of the VMD for MC simulation of encounter scenarios E2-S1 (top) and E2-S3 (bottom) for TCAS II v7.1 and ACAS Xa V15R4.

V. Discussion and conclusions

There is no doubt that ACAS is an important safety barrier. There are numerous cases in which TCAS II effectively warned pilots and supported them in resolving close encounters. The development of ACAS X is intended to further strengthen the ACAS safety record, while reducing the number of nuisance RAs. However, the extent by which ACAS improves the level of safety, the influence of various sources of uncertainty (measurement noise, pilot performance variability), and the variability in ACAS advisories in an encounter scenario can only be well understood if the simulation environment explicitly incorporates the relevant sources of variability and uncertainty in the encounter scenarios. Whereas modelling and MC simulation of intrinsic uncertainty due to sensor errors and pilot performance variability is well known in the ACAS design field [13-16], this is lagging behind in the field of independent validation of novel ACAS designs. Earlier ACAS validation studies placed emphasis on assessment of the implications of the variability in geometries, altitude layers and equipage types in encounters. Such variabilities are known at the start of an encounter and can thus be straightforwardly included in a deterministic simulation. However, a complete assessment of the implications of the many intrinsic uncertainty sources in combination on the effectiveness of ACAS is needed to bring validation of novel ACAS designs at a higher level.

The main innovation in the agent-based modelling and simulation of this paper is the scope of the intrinsic uncertainty models for the novel ACAS Xa design by extending results of [17] in establishing a similar innovation for TCAS II v7.1. Whereas earlier work has typically focused on describing the sensor errors in particular systems while neglecting other sensor errors and/or neglecting pilot response variability, the objective in this study has been to describe errors in all sensors that are used by ACAS and to describe various key features of pilot performance variability. This allows to systematically evaluate the impact of uncertainty during TCAS II and ACAS Xa encounters. The MC simulation results shown in this paper illustrate the variability in timing and types of RAs that can be obtained in encounter scenarios for both TCAS II and ACAS Xa. In combination with variability in pilot performance, the results show considerable dispersion in the VMD for encounter scenarios and the impact on NMAC probability in encounter scenarios. The results also illustrate that deterministic simulation results can be quite different from the mean of MC simulation results, and this even applies without pilot performance variability. The latter shows that intrinsic sensor errors alone may trigger RAs at earlier instances than in deterministic simulations. These results stipulate that addressing intrinsic uncertainty by MC simulation is essential for proper evaluation of TCAS II and ACAS Xa.

Such evaluation of TCAS II and ACAS Xa by MC simulation can support retrospective as well as prospective analysis. In retrospective analysis, MC simulation of a single encounter provides insight in the probability distributions of the types and timings of RAs and the associated miss distance distribution given a pilot response model. An investigator (e.g. at an ANSP) can compare RAs that actually occurred in an encounter with the simulated distributions for the encounter to assess the likelihoods of the observed RA types and timings. This can, for instance, help understanding why some hard-to-explain RAs have occurred. So, rather than tuning aircraft trajectories such that expected RAs are achieved, the investigator attains an overall picture of the probabilities of RAs and CPAs that can be obtained in an encounter.

In prospective analysis, MC simulation of sets of encounters supports various use types, such as evaluation of ACAS designs, evaluation of ACAS related systems, evaluation of changes in airspace, ATM and regulations, and analysis of system compatibility. Such simulations address the variability between encounters (like encounter geometries and altitude layers) as well as the variability in processes during the encounters (like sensor errors and pilot performance). As argued in this paper, it is essential to have a complete understanding of the implications of all sources of variability and uncertainty in encounter scenarios. Attained results in RAs, CPA and NMAC probabilities depend on each of these sources. They affect the means and dispersion in these results. Most importantly, they affect the tails of the probability distributions, which directly relates to the collision avoidance purpose of ACAS.

This paper has focused on the development of a novel modelling and simulation environment for evaluation of a considerable number of intrinsic uncertainties on the effectiveness of ACAS. Only some illustrative examples for the simulation of encounter scenario were provided to illustrate the potential of the developed approach. In follow-up research, the CAVEAT environment can be used for a systematic evaluation of the large set of encounter data that has been collected over the years for TCAS II events. Such encounters can be evaluated in detail by studying the implications of intrinsic uncertainty. Appropriate sizes of encounter sets and numbers of MC simulation runs in such evaluations need to be better understood in future research.

A complementary follow-up research activity is to gain a detailed understanding of the influence of processes in encounter scenarios on RAs and their trajectory implications by sensitivity analysis. Such sensitivity analysis applies systematic variation of parameter values (e.g. noise levels, pilot parameters) to arrive at an overview on the performance indicators of interest (e.g. numbers of RAs and NMAC events). Parameters with large sensitivities reveal the most important processes, which may most effectively be optimized in the design or addressed in regulations. For example, sensitivity analysis may reveal that system A is much more sensitive for noise in range measurement than system B, and this may be a reason to improve the design of system A or to adapt the requirements on range measurements. The simulation results in the examples suggest that the pilot performance variability models can have a large effect on miss distance in the encounter scenarios. However, a systematic sensitivity analysis remains to be conducted for parameters of the pilot performance and this will be important for a correct understanding of ACAS effectiveness.

Another potential direction for follow-up work is to further improve the pilot model or one or more of the sensor models. For example for particular sensors more complex models have been developed in the literature (e.g. hidden Markov models for bearing measurements [15]). It may be useful to incorporate such more detailed error models, if it would follow from sensitivity analysis that errors in the particular sensor have a considerable impact on the ACAS metrics, and that this cannot be improved by a better setting of the existing model parameters. This also means that results obtained through sensitivity analysis form an important key in making decisions on the further development of the sensor and pilot models.

All sensor error models used in this study describe the performance in nominal conditions, meaning that failure conditions such as sensor systems not working or working completely out of their nominal range are not represented. Such failures, their probabilities and their impact should be considered separately in an overall safety assessment. The current standard is to do so using a static fault tree. However as has been pointed out by Tang et al. [19], if the number of aircraft involved in an encounter grows it will become relevant to use a systematic modelling formalism, such as coloured Petri nets.

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Disclaimer

The opinions expressed are those of the authors and do not necessarily reflect the views of NLR, everis, or EUROCONTROL.

VI. References

[1] ICAO. Airborne Collision Avoidance System (ACAS) Manual International Civil Aviation Organization, Doc 9863, 2nd Edition.
[2] ICAO. Annex 10 Aeronautical telecommunications, Volume IV Surveillance and collision avoidance systems. International Civil Aviation Organization, July 2014.
[3] EUROCONTROL. ACAS Guide: Airborne Collision Avoidance. Edition 3.0, December 2017.
[4] EUROCAE. Minimum operational performance standards for Traffic Alert and Collision Avoidance System II (TCAS II), Volume I. ED-143.
[5] Kochenderfer MJ, Chryssanthacopoulos JP, Weibel RE. A new approach for designing safer collision avoidance systems. Ninth USA/Europe ATM R&D Seminar, Berlin, Germany, 2011.
[6] FAA. Concept of operations for the Airborne Collision Avoidance System X. Federal Aviation Administration, Version 2, Revision 0, 18 April 2013.
[7] EUROCAE. Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS X) (ACAS Xa AND ACAS Xo). ED-256, October 2018.
[8] Londner EH, Moss RJ. A Bayesian network model of pilot response to TCAS resolution advisories. Twelfth USA/Europe Air Traffic Management Research and Development Seminar, Seattle, USA, 2017.
[9] Cloerec A. Final report on the analysis of airborne recorded data and pilot model specification. EUROCONTROL, ASARP Project, ASARP/WP/19/D, 26 April 2005.
[10] FAA. Post-FRAC Operational Validation Report. Federal Aviation Administration, ACAS-RPT_18_018_V1R0, DO-385 V1R0, 10 August 2018.
[11] Sanz L, Dean G, Huck V, Buleza I, Price A, Hayward R. VALR-ACASX-OPT1 Validation report for the evaluation of ACAS Xa optimized for Europe. SESAR Joint Undertaking, Project 04.08.01, Deliverable D92, Version 00.01.01, 11 March 2016.
[12] EUROCONTROL. InCAS 3.0 User Manual. 5 February 2014.
[13] Kochenderfer MJ. Decision making under uncertainty. Cambridge, Massachusetts, USA: The MIT Press; 2015.
[14] Chryssanthacopoulos JP, Kochenderfer MJ. Accounting for State Uncertainty in Collision Avoidance. Journal of Guidance, Control, and Dynamics. 2011;34:951-60. doi:10.2514/1.53172.
[15] Panken AD, Kochenderfer MJ. Error model estimation for airborne beacon-based surveillance. IET Radar, Sonar & Navigation. 2014;8:667-75. doi:10.1049/iet-rsn.2013.0266.
[16] Edwards M. A Safety Driven Approach to the Development of an Airborne Sense and Avoid System. Infotech@Aerospace 2012, Garden Grove (CA), USA, 2012. doi:10.2514/6.2012-2485.
[17] Gellert BF. Agent-based modelling and simulation of TCAS operations under uncertainty. Delft, The Netherlands: Delft University of Technology, Faculty of Aerospace Engineering; 2017.
[18] Netjasov F, Vidosavljevic A, Tosic V, Everdij MHC, Blom HAP. Development, validation and application of stochastically and dynamically coloured Petri net model of ACAS operations for safety assessment purposes. Transportation Research part C: emerging technologies. 2013;33:167-95. doi:10.1016/j.trc.2012.04.018.
[19] Tang J, Piera MA, Guasch T. Coloured Petri net-based traffic collision avoidance system encounter model for the analysis of potential induced collisions. Transportation Research part C: emerging technologies. 2016;67:357-77. doi:https://doi.org/10.1016/j.trc.2016.03.001.
[20] Stroeve SH, Blom HAP, Hernandez Medel C, Garcia Daroca C, Arroyo Cebeira A, Drozdowski S. Development of a Collision Avoidance Validation and Evaluation Tool (CAVEAT): Addressing the intrinsic uncertainty in TCAS II and ACAS X. Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019), Vienna, Austria, 2019.

[21] Stroeve SH, Blom HAP, Cañizares CV, Bakker GJ. CAVEAT Phase 2 Models and Algorithms. Royal Netherlands Aerospace Centre NLR, NLR-CR-2018-429, June 2020.
[22] RTCA. Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Airborne Equipment. RTCA, RTCA DO-185A, 16 December 1997.
[23] Mari C, Mouland C. VALR-OT Validation Report on Optimising ACAS RA Thresholds. SESAR Joint Undertaking, Project 04.08.02, D10, Edition 00.01.01, 18 January 2013.
[24] Stroeve SH, Bussink FJL, Blom HAP. InCAS High Level Specifications. Royal Netherlands Aerospace Centre NLR, NLR-CR-2016-597, March 2017.