Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019)

Development of a Collision Avoidance Validation and Evaluation Tool (CAVEAT)

Addressing the intrinsic uncertainty in TCAS II and ACAS X

Sybert Stroeve[1], Henk Blom[1], Carlos Hernandez Medel[2], Carlos García Daroca[2],
Alvaro Arroyo Cebeira[2,4], Stanislaw Drozdowski[3],
[1]Netherlands Aerospace Centre NLR, Amsterdam, The Netherlands
[2]everis Aerospace & Defence, Madrid, Spain
[3]EUROCONTROL, Brussels, Belgium
[4]Current affiliation: Universidad Politécnica de Madrid, Madrid, Spain

sybert.stroeve@nlr.nl, henk.blom@nlr.nl, carlos.hernandez.medel@everis.com, carlos.garcia.daroca@everis.com,
alvaro.arroyo.cebeira@alumnos.upm.es, stanislaw.drozdowski@eurocontrol.int

***Abstract*—Airborne Collision Avoidance Systems (ACAS) form a key safety barrier by providing last-moment resolution advisories (RAs) to pilots for avoiding mid-air collisions. For the generation of advisories ACAS uses various ownship state estimates (e.g. pressure altitude) and othership measurements (e.g. range, bearing). 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. These can be analysed effectively by Monte Carlo (MC) simulation of the various uncertainties in encounter scenarios. Existing ACAS simulation tools reflect the intrinsic uncertainties to a limited extent only. In recognition of the need of an ACAS evaluation tool that supports MC simulation of these uncertainties, this paper develops an agent-based model, which captures uncertainties in ACAS input and pilot performance for the simulation of encounter scenarios, while using ACAS algorithms (TCAS II, ACAS Xa). The novel ACAS evaluation tool is named CAVEAT (Collision Avoidance Validation and Evaluation Tool). Through illustrative MC simulation results it is demonstrated that the uncertainties can have significant effect on the variability in timing and types of RAs, and subsequently on the variability in the closest point of approach (CPA). It is shown that even mean results of MC simulation can differ significantly from results of a deterministic simulation. Most importantly, the tails of CPA probability distributions are affected. This stipulates that addressing all intrinsic uncertainties through MC simulation is essential for proper evaluation of ACAS.**

***Keywords – TCAS II, ACAS X, ACAS, Monte Carlo simulation, collision risk, uncertainty*[1]**

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 only 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 currently foreseen: (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

[1] The R&D in this paper has been conducted with support from EUROCONTROL in the scope of SESAR 2020 Project 11.

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. Evaluation of ACAS designs

An operational validation report [10] compares the performance of ACAS Xa [7] with TCAS II v7.1 [4] for various characteristics, notably including the probability of a near mid-air collision (NMAC[2]) and numbers of RAs. 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 state estimation and measurement noise considered in [2, 4, 7].

D. Evaluating uncertainty through Monte Carlo simulation

Given the intrinsic uncertainty (measurement noise) 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. Thus, even for an encounter between an aircraft pair with deterministic trajectories and equipment types, the time of an RA is not deterministic, but it rather is a random variable that satisfies some probability density function (PDF). Similarly the RA sense (e.g. Climb, Level Off) may be of probabilistic nature. In order to simulate such random RA outcomes well, uncertainty models of the ACAS input signals must be used and a sufficient number of sensor error realizations have to be sampled from these uncertainty models and used in each Monte Carlo (MC) simulation. Such MC simulation must also include non-deterministic models to represent the variability in pilot performance in response to RAs. In general, a simulation model is needed that represents all relevant variability in state estimates, measurements, pilot performance, aircraft manoeuvring and environmental influences in an encounter scenario. MC simulation using a sufficient number of runs provides the basis to calculate the relevant statistics for the encounter scenario. Through an MSc study [13] it has been shown that this approach in capturing all uncertainties worked well for the evaluation of TCAS II.

The purpose of this paper is to present the development and application to TCAS II and ACAS Xa of an agent-based ACAS simulation environment that can switch between the established deterministic type of simulation and the novel MC type of simulation of various uncertainties.

The paper is structured as follows. Section II presents a high-level specification of the CAVEAT development, addressing its decomposition and foreseen use. Section III presents the agent-based simulation model. Section IV gives an overview of the CAVEAT software. Section V shows deterministic and non-deterministic simulation results for TCAS II and ACAS Xa. Section VI concludes with a discussion of the results obtained.

---

[2] The situation when two aircraft simultaneously come within 100 feet vertically and 500 feet (0.08 NM) horizontally.

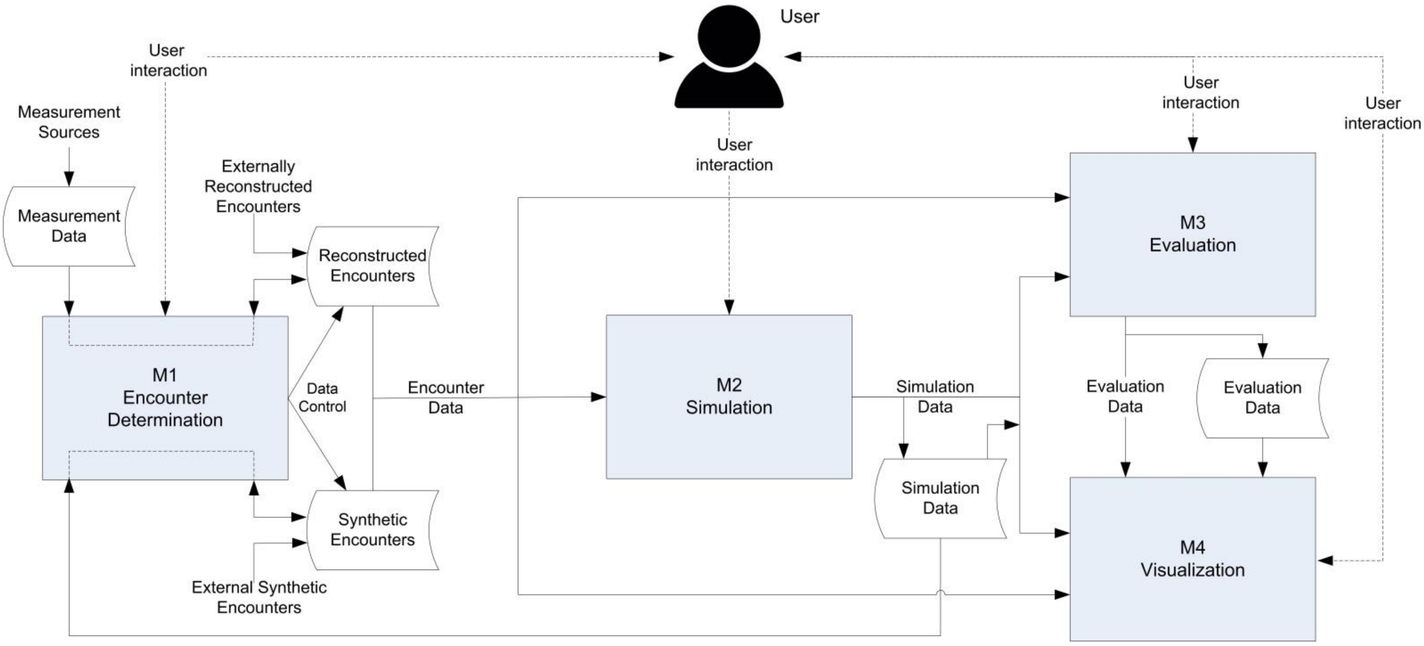


Figure 1. High-level CAVEAT composition

II. HIGH-LEVEL SPECIFICATION

A preparatory study led to a high-level specification for the development of CAVEAT [14]. 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 (Figure 1):

1. *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.
2. *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 noise, pilot performance variability).
3. *Evaluation.* This module determines characteristics of the simulation results, such as the closest point of approach (CPA) and statistics of RA times and CPA.
4. *Visualization.* This module visualizes results of a single simulation run or the statistics of sets of simulation runs.

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 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.

III. 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 Figure 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 Figure 2. The key characteristics of the models are presented next.

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.

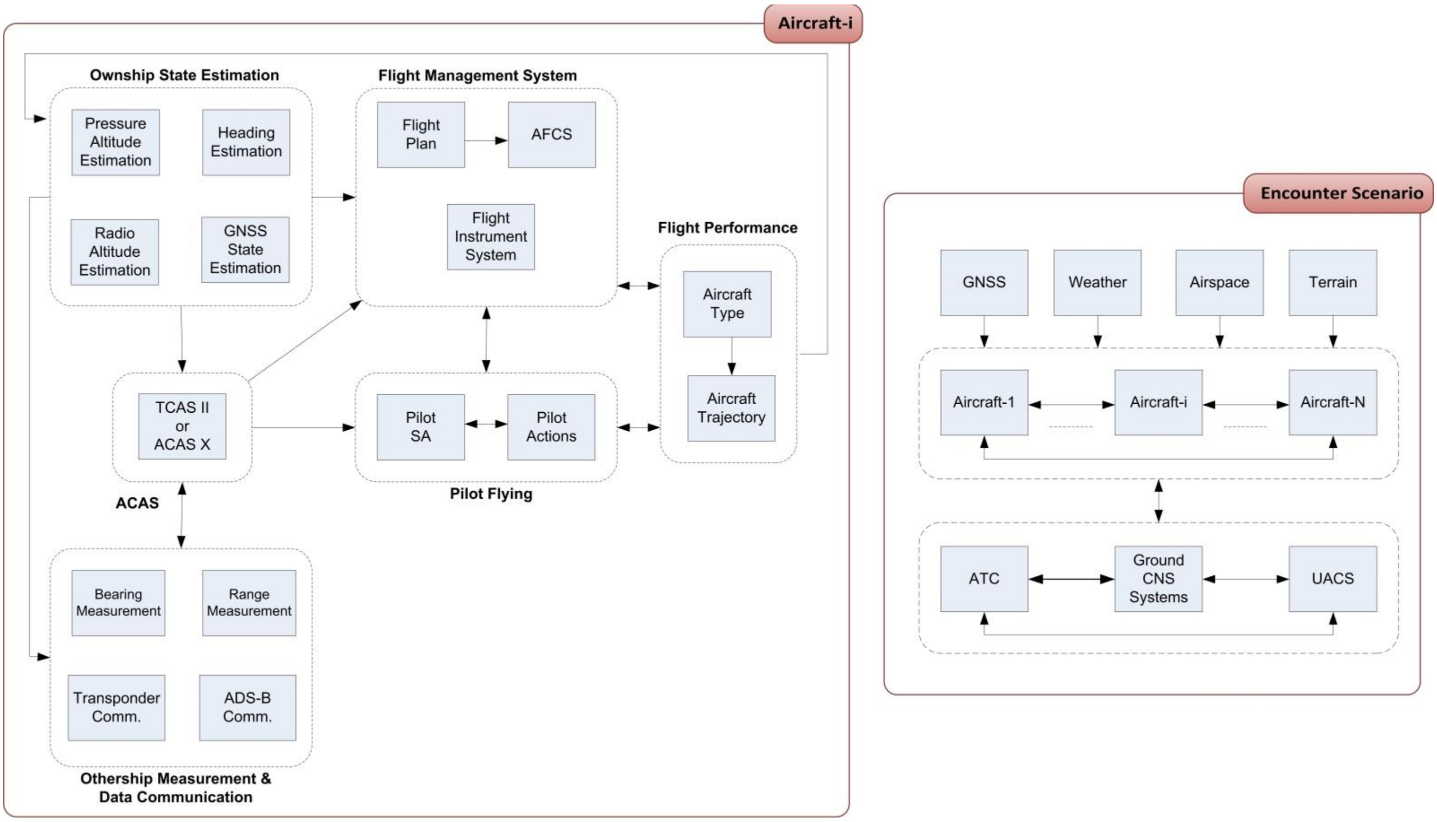


Figure 2. Agent-based model of encounter scenario with N aircraft (right), where each aircraft contains the elements shown left

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]:

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

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):

$$\varepsilon^{z,jitter}_{t,PAS,i} = \begin{cases} \varepsilon^{noise}_{t,PAS,i} & \text{if } t = \tau_0 \\ \alpha^{auto}_{PAS}\varepsilon^{z,jitter}_{t-T^{sample}_{PAS,i},PAS,i} + \varepsilon^{noise}_{t,PAS,i} & \text{if } t > \tau_0 \end{cases}$$

$$\{\varepsilon^{noise}_{t,PAS,i}\} \sim f^N(0,\sigma^{z,jitter}_{PAS}\sqrt{1-(\alpha^{auto}_{PAS,i})^2})$$

where α^{auto}_{PAS} is the autocorrelation and $\sigma^{z,jitter}_{PAS}$ 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 $s^z_{t,AC,i}$ and the two (bias and jitter) error components:

$$s^z_{t,PAS,i} = s^z_{t,AC,i} + \varepsilon^{z,bias}_{t,PAS,i} + \varepsilon^{z,jitter}_{t,PAS,i}$$

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 explained next.

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. For the response to modified RAs, conditional probabilities given the response to previous RAs are used. The probability of response to clear-of-conflict (COC) advisories is assumed independent from the context. In total there are 13 conditional probabilities that can be set by the user.

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:

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

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 set as

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

where $\bar{v}^{z,RA}_{\tau_1,PF,i}$ 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:

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

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

CAVEAT supports simulation of TCAS II versions 7.0 [15], 7.1 [4] and 7.2 (variation of version 7.1 with optimized RA thresholds [16]). 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

CAVEAT supports simulation of ACAS Xa. It will include C++ libraries of ACAS Xa V15R4 [7], which were developed and validated by Honeywell Aerospace and partners in SESAR 2020 Project 11. The illustrative simulation results in this paper are based on a Julia implementation of ACAS Xa V15R2, which is a near-final development version of ACAS Xa.

IV. Software Tool

The development of the CAVEAT software has followed a Waterfall approach, including requirements specification, functional and technical designs, construction, and systematic testing (unitary, integration, system tests). An object-oriented design methodology has been used and all software components have been implemented in ANSI C++. CAVEAT is fully operable in Microsoft Windows. At the highest level its architecture consists of a front-end and a back-end.

A. 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.

B. Back-end

The back-end is 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 back-end 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 JSON and CSV output files, including ACAS events, modified trajectories, and statistics.

V. Illustrative Simulation Results

The main results of simulation of encounter scenarios are 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. *Single-encounter deterministic simulation*. 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. *Multi-encounter deterministic simulation*. This comprises single-run simulation for each encounter in a set, with all models in a deterministic setting. The simulation results provide a basis for statistics for the set of encounters, e.g. NMAC probability and CPA empirical PDF.
3. *Single-encounter Monte Carlo simulation*. This comprises a number of simulation runs for a single encounter 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.
4. *Multi-encounter Monte Carlo (MC) simulation*. This comprises a number of simulation runs for each encounter from a set of encounters, where one or several models are used in a stochastic setting. These simulations yield distributions of advisories and trajectory characteristics for set of encounters.

In this paper we illustrate the differences between deterministic and MC simulation for encounter scenarios using two encounters listed in Table I. Encounter E2 is most critical, as without intervention it would lead to a collision.

Table II lists a number of scenarios, which define the following settings for both aircraft in each encounter: (a) sensor noise according to the ACAS MOPS [4, 7] or no sensor noise; (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 noise and variability settings. Scenario D is deterministic, and scenarios S1 to S3 are stochastic, where the number of noise and variability sources is increasing from S1 to S3.

TABLE I. 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 II. Description of Scenarios

Scenario	Sensor noise	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 V15R2 (both aircraft have 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 1000 runs in each. As an example, Figure 3 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 522 ft is attained instead of 200 ft for the original trajectories (HMD is 3038 ft).

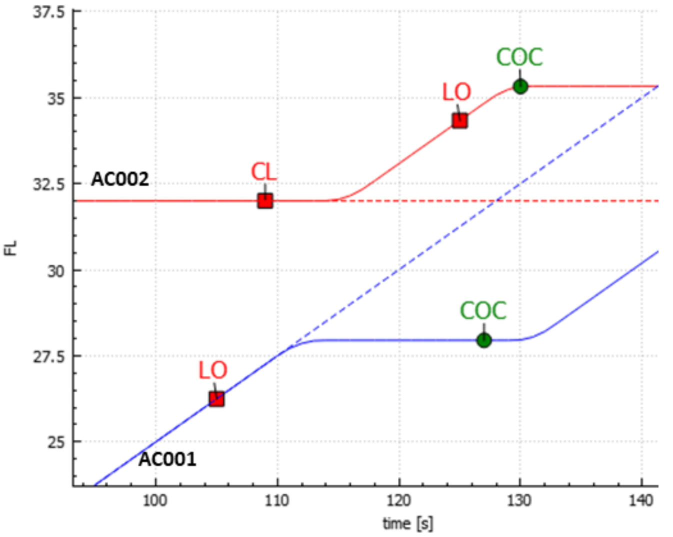


Figure 3. Vertical profile of deterministic simulation of encounter scenario E1-D with TCAS II v7.1. Dashed lines: original trajectories, solid lines: modified trajectories.

To illustrate the possible implications of sensor noise on the timing and probabilities of ACAS advisories, Table III shows results of deterministic simulation of scenario D (no sensor noise) versus MC simulation of scenario S1 (with sensor noise) for encounters E1 and E2 with TCAS II v7.1 In encounter E1 there are small probabilities for additional RAs to occur and the timing of the RAs varies with respect to the deterministic simulation. In encounter E2, there are larger differences in the advisories due to the sensor noise. Whereas the deterministic simulation shows that aircraft 1 is advised first to descend and aircraft 2 to climb, the MC simulation shows that when sensor noise is accounted for, 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 noise in the pressure altitude can trigger the upward or downward advisories.

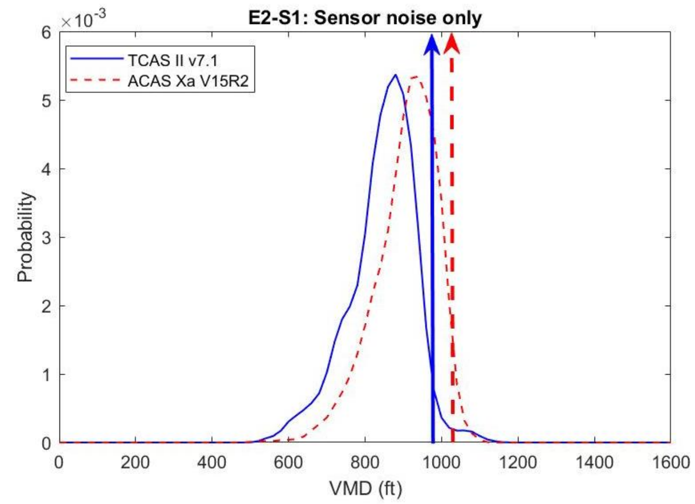
Statistics of the VMD in the encounter scenarios are shown in Table IV for TCAS II v7.1 and ACAS Xa V15R2. It follows that the variance of the VMD increases with the inclusion of sensor noise, pilot dynamic variability, and the possibility of no pilot response. The mean VMD in the stochastic scenarios can differ considerably from the deterministic results; this is especially manifest for encounter E2. The 0.5% percentiles of the VMD are much smaller than the deterministic results, up to 0 ft for encounter scenario E2-S3 for ACAS Xa V15R2. These results are further illustrated by empirical PDFs of encounter E2 shown in Figure 4.They indicate a considerable spread in VMD that can be attained when accounting for sensor noise and pilot performance variability. Whereas often larger VMDs are attained by ACAS Xa V15R2, it also shows a higher probability of NMAC distances (<100 ft) in encounter scenario E2-S3. While these simulation results are not meant to draw general conclusions on the performance of ACAS Xa versus TCAS II, they clearly illustrate the potential impact of sensor noise and pilot performance variability.

TABLE III. RESULTS OF DETERMINISTIC AND MC SIMULATIONS FOR PROBABILITIES AND TIMING OF ADVISORIES IN ENCOUNTER SCENARIOS WITH TCAS II V7.1 (LO: LEVEL OFF, DE: DESCEND, CL: CLIMB, DDE: DO NOT DESCEND).

Enc. Sc.	**AC**	**Adv.**	**P(RA)**	**P(Sense|RA)**	**Time (s)**	
					μ	**σ**
E1-D	1	RA-1	-	*LO*	*105*	-
		COC	-	-	*127*	-
	2	RA-1	-	*CL*	*109*	-
		RA-2	-	*LO*	*125*	-
		COC	-	-	*130*	-
E1-S1	1	RA-1	100%	LO: 97% DE: 3%	105.3	1.7
		RA-2	6%	LO: 53% DE:47%	113.4	3.5
		RA-3	3%	LO: 100%	119.4	3.5
		COC	100%	-	127.0	0.2
	2	RA-1	100%	CL: 94% DDE: 6%	109.1	2.6
		RA-2	94%	LO: 94% CL: 6%	121.4	2.3
		RA-3	1%	LO: 100%	124.8	0.4
		COC	100%	-	127.5	0.9
E2-D	1	RA-1	-	*DE*	*138*	-
		RA-2	-	*LO*	*160*	-
		COC	-	-	*189*	-
	2	RA-1	-	*CL*	*138*	-
		RA-2	-	*LO*	*160*	-
		COC	-	-	*189*	-
E2-S1	1	RA-1	100%	CL: 51% DE: 49%	138.2	0.9
		RA-2	100%	LO: 100%	157.5	2.1
		COC	100%	-	189.0	0.0
	2	RA-1	100%	DE: 51% CL: 49%	138.2	0.8
		RA-2	100%	LO: 100%	157.6	2.0
		COC	100%	-	189.0	0.0

TABLE IV. MEAN, STANDARD DEVIATION AND 0.5% PERCENTILE OF VMD OF SIMULATIONS OF THE SET OF ENCOUNTER SCENARIOS

ACAS type	**Encounter scenario**	**VMD (ft)**		
		Mean	**SD**	**0.5%**
TCAS II v7.1	E1-D	*522*	-	-
	E1-S1	519	111	236
	E1-S2	524	123	223
	E1-S3	466	143	200
ACAS Xa V15R2	E1-D	*723*	-	-
	E1-S1	691	96	252
	E1-S2	720	116	306
	E1-S3	639	162	201
TCAS II v7.1	E2-D	*975*	-	-
	E2-S1	845	85	600
	E2-S2	891	112	547
	E2-S3	916	230	458
ACAS Xa V15R2	E2-D	*1025*	-	-
	E2-S1	906	78	650
	E2-S2	951	98	653
	E2-S3	916	230	0



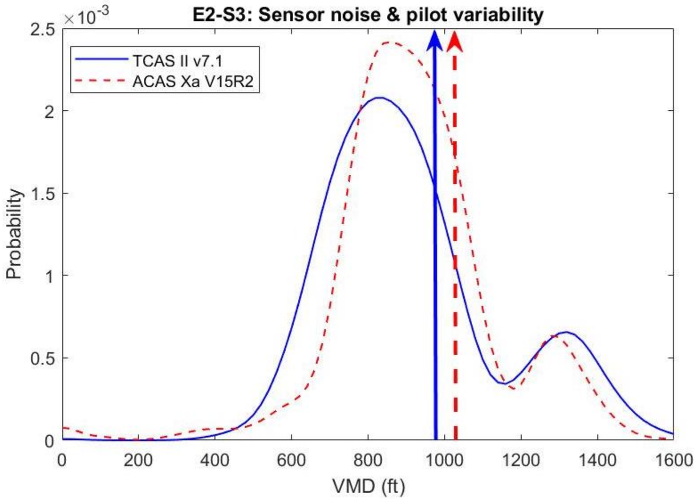


Figure 4. Deterministic simulation results of encounter scenario E2-D (arrows) and empirical PDFs of the VMD for MC simulation of encounter scenarios E2-S1 (top) and E2-S3 (bottom) for TCAS II v7.1 and ACAS Xa V15R2.

VI. 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 all relevant sources of variability and uncertainty in encounter scenarios. In earlier validation studies emphasis was placed 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 and transparent assessment of the effects of other sources contributing to uncertainty in the encounter scenarios has been lacking.

As a way forward, the R&D in this paper shows the development of agent-based modelling and simulation of ACAS encounter scenarios, notably including a variety of uncertainty models for sensor noise and pilot performance. 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. In combination with variability in pilot performance, the results show considerable dispersion in the VMD for encounter scenarios. Clearly, such dispersion influences the NMAC probability in encounter scenarios. The results also illustrate that even without pilot performance variability, deterministic simulation results can be quite different from the mean of MC simulation results. This can be caused by noise levels that trigger RAs at earlier instances than simulated in no-noise scenarios. These results stipulate that addressing uncertainty by MC simulation is essential for proper evaluation of TCAS II and ACAS X.

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 CPA distribution given a pilot response model. An investigator 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 measurement noise 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. As such, proper evaluation requires both a representative set of encounters and evaluation of the intrinsic uncertainty in encounter scenarios. Appropriate sizes of encounter sets and numbers of MC simulation runs in such evaluations need to be better understood in future research.

A detailed understanding of the influence of processes in encounter scenarios on RAs and their trajectory implications requires a sensitivity analysis. Such a 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 agent-based model and its simulation have been implemented in a CAVEAT software tool. Its implementation in C++ supports fast simulation and the human machine interface provides broad control over the models and the interpretation of statistics. The flexibility offered by the CAVEAT HMI to tune each parameter in the agent-based model effectively supports the conduct of such sensitivity analysis. CAVEAT will be a transparent and flexible ACAS simulation environment, which will allow the larger ACAS community to take advantage of the possibility to switch between deterministic simulation and MC simulation of encounter scenarios.

ACKNOWLEDGEMENT

We thank Carmelo Javier Villanueva Cañizares, Daniel Rubio Garcia, Cristina Midori Fukuda Leon, Eduardo Pablos Ruiz, Ángela Merino Pérez, Volker Huck, David Phu, Garfield Dean, Frank Bussink and Bert Bakker for their support of the CAVEAT development. We thank MITRE and Honeywell for making available their TCAS II and ACAS Xa/Xo libraries, respectively.

DISCLAIMER

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

REFERENCES

[1] ICAO. Airborne Collision Avoidance System (ACAS) Manual International Civil Aviation Organization, Doc 9863, 2012.
[2] ICAO. Annex 10 Aeronautical telecommunications, Volume IV Surveillance and collision avoidance systems. International Civil Aviation Organization, 2014.
[3] EUROCONTROL. ACAS Guide: Airborne Collision Avoidance. 2017.
[4] EUROCAE. Minimum operational performance standards for Traffic Alert and Collision Avoidance System II (TCAS II), Volume I. ED-143, 2008.
[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, 2012.
[7] EUROCAE. Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS X) (ACAS Xa AND ACAS Xo). ED-256, 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, 2005.
[10] FAA. Post-FRAC Operational Validation Report. Federal Aviation Administration, ACAS-RPT_18_018_V1R0, DO-385 V1R0, 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, 2016.
[12] EUROCONTROL. InCAS 3.0 User Manual. 2014.
[13] Gellert BF. Agent-based modelling and simulation of TCAS operations under uncertainty. MSc thesis,, Delft University of Technology, Faculty of Aerospace Engineering, August 2017.
[14] Stroeve SH, Bussink FJL, Blom HAP. InCAS High Level Specifications. Netherlands Aerospace Centre NLR, NLR-CR-2016-597, 2017.
[15] RTCA. Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Airborne Equipment. RTCA, RTCA DO-185A, 1997.
[16] 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, 2013.

AUTHOR BIOGRAPHIES

Sybert Stroeve has a M.Sc. degree in Electrical Engineering of Twente University (1991) and a Ph.D. degree in Mechanical Engineering of Delft University of Technology (1998). He is Senior Scientist at NLR with key interests in human performance modelling and agent-based dynamic risk modelling for air transport safety management.

Henk Blom is Full Professor at Delft University of Technology (chair Air Traffic Management Safety) and Principal Scientist at National Aerospace Laboratory NLR, both in The Netherlands. He received his BSc and MSc degree from Twente University in 1975 and 1978 respectively, and his PhD from Delft University of Technology in 1990. Dr. Blom has forty years experience in exploiting the theory of stochastic modelling and analysis for safety risk analysis and multi-sensor data fusion.

Carlos Hernandez Medel has a M.Sc degree in Aerospace Engineering from Universidad Politécnica de Madrid (1997). He is Director of everis Aerospace & Defense with more than 18 years of professional experience in aerospace and defence in large program management and business development, with more than 10 years in the development and operations of EGNOS and Galileo, dealing with systems integration, safety-critical software and hardware development as well as operation & maintenance services.

Carlos Garcia Daroca has a M.Sc degree in Aerospace Engineering from Universidad Politécnica de Madrid (2014). He is senior engineer at everis Aerospace & Defense with key interest in develop and deliver new or improved solutions across the entire air transport management ecosystem, focus on the safe and efficient integration of the unmanned aviation (UTM). He is eager to break new ground in a constant shifting landscape, assuming new challenges and achievement on the air transportation world.

Alvaro Arroyo Cebeira received the M.Sc. degree in Aerospace Engineering from Universidad Politécnica de Madrid (2016). He was involved in CAVEAT development as everis Aerospace & Defense engineer. He is currently working toward the Ph.D. degree in Aerospace Engineering at the same university with key interests in collision avoidance algorithms, estimation, UTM and self-driving car.

Stanislaw Drozdowski is a Senior ACAS Expert at EUROCONTROL HQ in Brussels. He is engaged in the works of RTCA SC-147 and EUROCAE WG-75 on the development of ACAS X. Within WG-75 he is a chairman of Operations Working Subgroup. Previously, he worked as a system engineer with Northrop Grumman and as an Air Traffic Controller in Poland and New Zealand.