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Cooperative and Non-Cooperative *Decision Making for UAS Detect-and-Avoid:*
A Novel Unified Approach

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Outline

- Requirements Overview
- DAA Design Criteria
- DAA Unified Method (Cooperative/Non-Cooperative)
- Functional Architecture
- Decision Logic for Autonomous Operations
- CNS Integrity Monitoring and Augmentation
- Avionics Based Integrity Augmentation (ABIA)
- SAA/ABIA Simulation Case Studies
- Conclusions and Future Work

Requirements Overview

- Cooperative and non-cooperative Detect-and-Avoid (DAA) is a paramount capability to enable Unmanned Aircraft (UA) to routinely access all classes of airspace
- DAA capability has to be equivalent or exceed the see-and-avoid capability of pilots in manned systems
- Operations during day and night in allweather conditions
- Field of Regard (FOR) and system response adequate for platform dynamics

Design Criteria

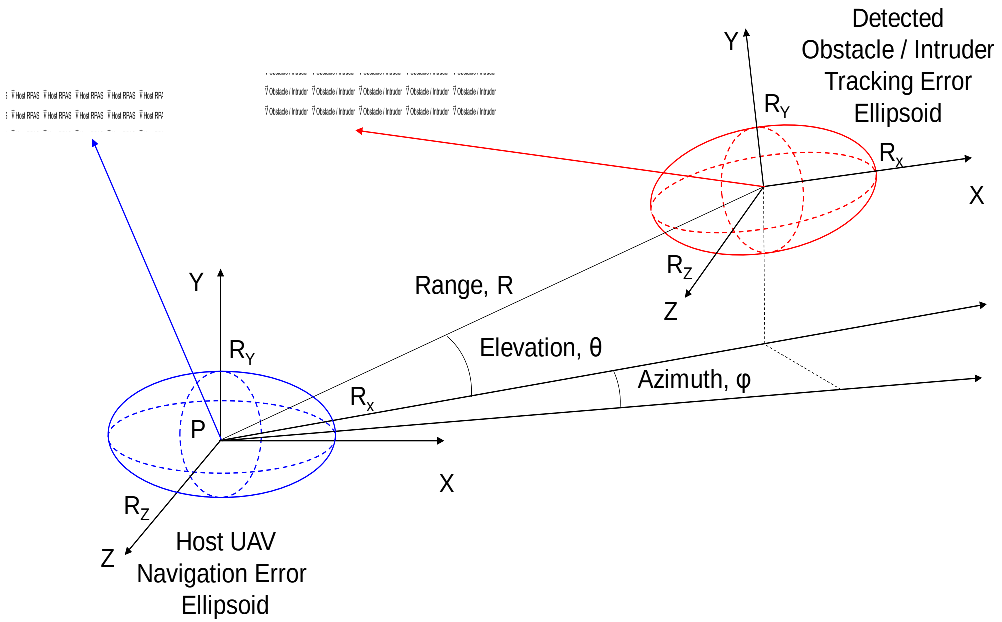
- The Field of View (FOV) of the UA has to be equivalent or superior to that of a pilot in the cockpit
- Accurate and precise intruder detection (both static and dynamic), recognition and trajectory prediction (dynamic)
- Early obstacle detection for allowing timely execution of the avoidance manoeuvres
- Effective integration schemes for multisensor data fusion (both GNC and TDA loops)
- Identification of the primary means of integrity monitoring and augmentation in cooperative and non-cooperative sensors/systems

DAA Functions

- **Detect**: data acquisition, image stabilization, intra-frame enhancement
- **Track**: Low-level tracking, high level tracking, data fusion
- **Evaluate**: Trajectory estimation within a given time horizon, calculate risk of collision
- **Prioritise**: Risk of collision vs. threshold and low level tracking vs. threshold
- **Declare**: Deterministic/stochastic decision making process
- **Determine Action**: Avoidance trajectories generation
- **Command**: Avoidance trajectory communication to pilot, Flight Control System (FCS), Mission Management System (MMS)
- **Execute**: Manoeuvre execution, history function, return-to-path

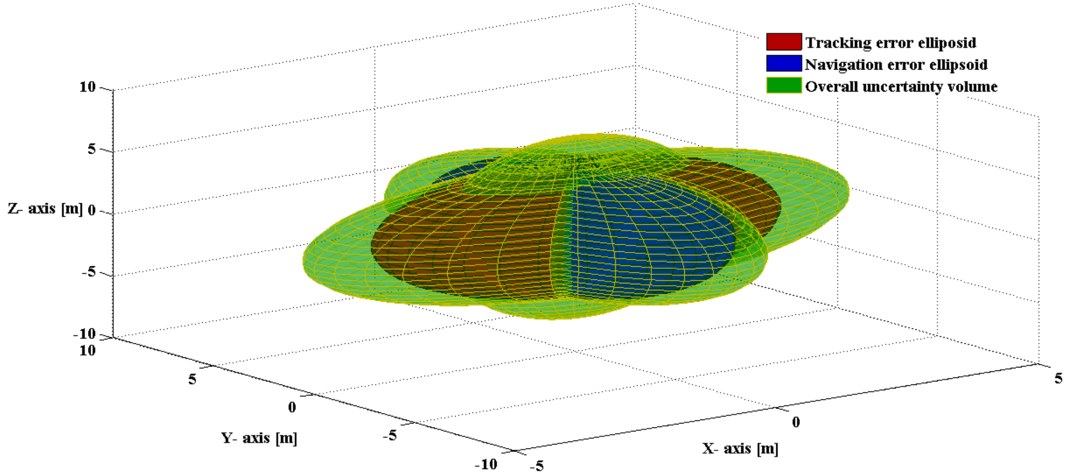
DAA Unified Method

- The overall uncertainty volume in the airspace surrounding the intruder tracks is determined
- Accomplished by considering both navigation and tracking errors affecting the measurements and translating them to unified range and bearing uncertainty descriptors, which apply both to cooperative and non-cooperative scenarios



DAA Unified Method

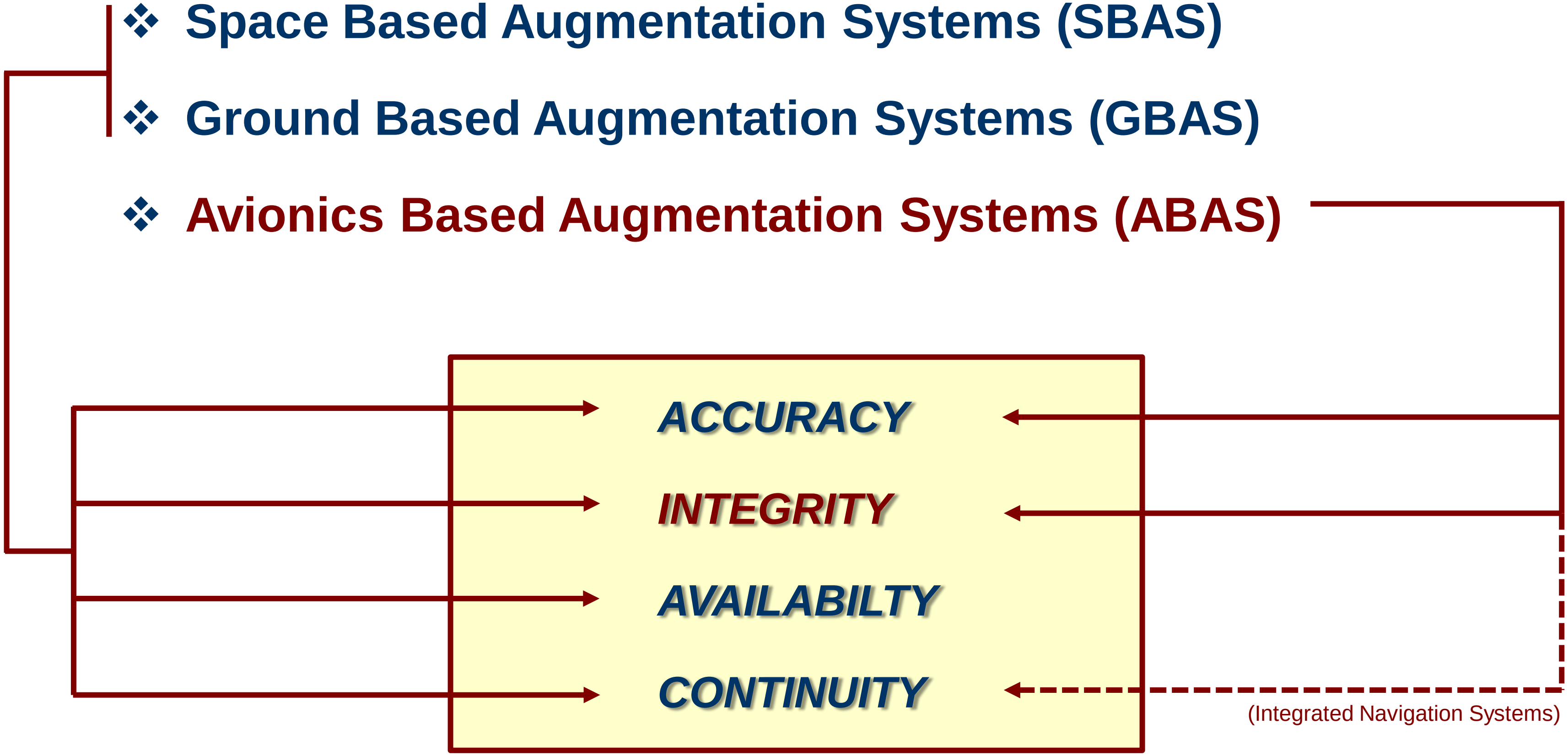
- Errors are statistically independent (e.g., NC-SAA) or dependent (e.g., ADS-B C-DAA), the uncertainty volume is obtained for uncorrelated or correlated errors respectively
- When the errors are correlated, covariant and contravariant tensors analysis is adopted
- Uncertainty volume for uncorrelated measurements is obtained by inflating the navigation ellipsoid with the tracking error components



CNS Integrity Augmentation

- To allow the high levels of autonomous decision making required in DAA, the entire Communication, Navigation and Surveillance (CNS) sensors/systems chains and the associated GNC/TDA loops must guarantee very high levels of integrity
- Integrity is a measure of the level of trust that can be placed in the performance of a system. For CNS, this means that either a specified level of performance is available (with a specified max probability of failure) or, if not, a usable integrity flag is generated within a specified max Time-To-Alert (TTA)
- In addition to integrity monitoring (inherently reactive), in UAS applications there is a strong need for **Integrity Augmentation** including <u>both predictive and reactive features</u>
- In UAS the adoption of **Avionics Based Integrity Augmentation** (ABIA) would allow an extended spectrum of autonomous and safety-critical operations

GNSS Augmentation Case Study



- Space Based Augmentation Systems (SBAS)
- Ground Based Augmentation Systems (GBAS)
- Avionics Based Augmentation Systems (ABAS)

ACCURACY

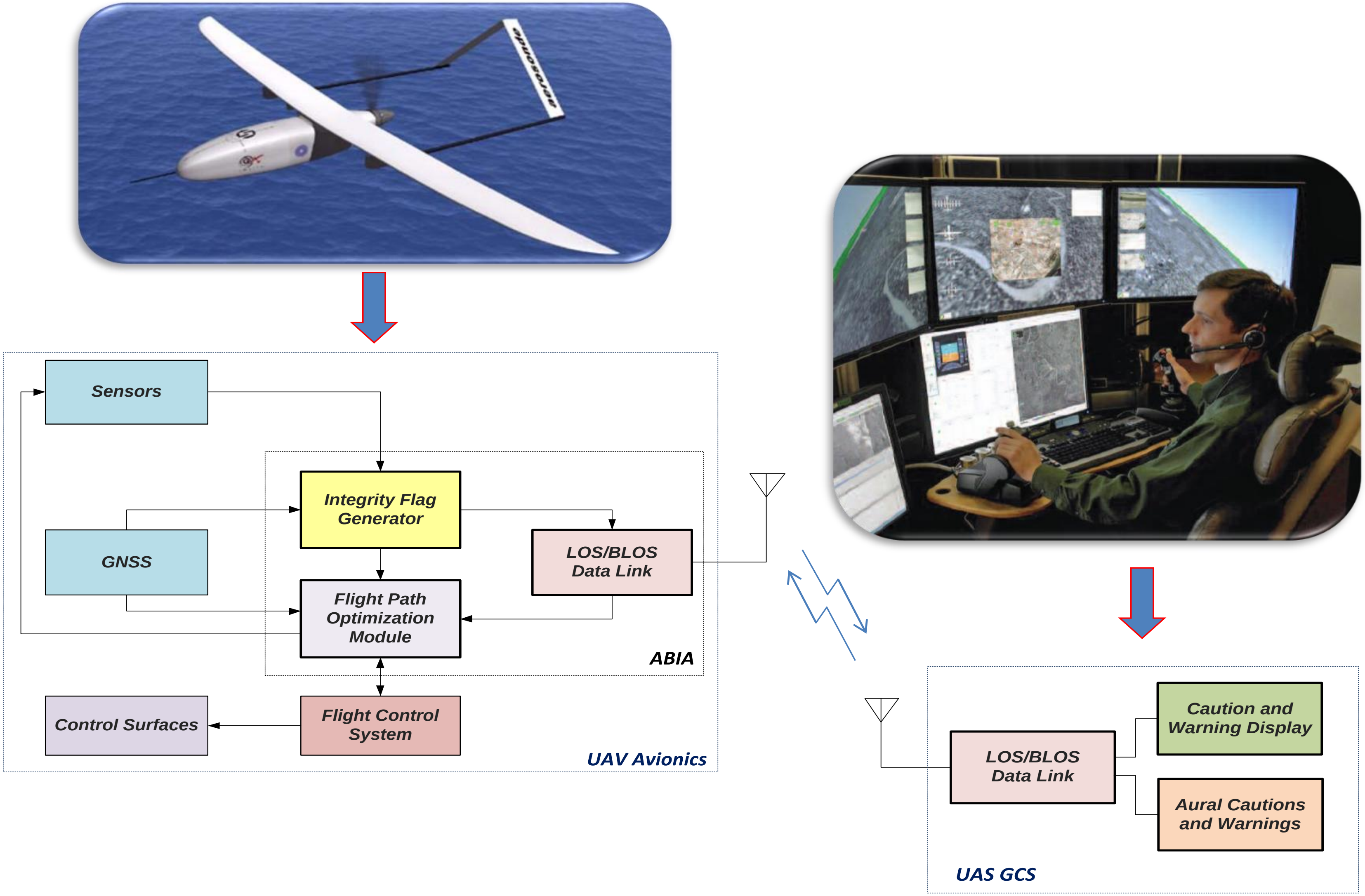
INTEGRITY

AVAILABILTY

CONTINUITY

(Integrated Navigation Systems)

ABIA Architecture



Sensors

Integrity Flag Generator

GNSS

LOS/BLOS Data Link

Flight Path Optimization Module

ABIA

Control Surfaces

Flight Control System

UAV Avionics

LOS/BLOS Data Link

Caution and Warning Display

Aural Cautions and Warnings

UAS GCS

ABIA Key Definitions

ALERTS

Caution Integrity Flag (CIF):

A **predictive annunciation** that the GNSS data delivered to the avionics system is going to exceed the Required Navigation Performance (RNP) thresholds specified for the current and planned flight operational tasks (GNSS alert status)

Warning Integrity Flag (CIF):

A **reactive annunciation** that the GNSS data delivered to the avionics system has exceeded the Required Navigation Performance (RNP) thresholds specified for the current flight operational task (GNSS fault status)

TTA

ABIA Time-to-Caution (TTC):

The **minimum time allowed** for the caution flag to be provided to the user before the onset of a GNSS fault resulting in an unsafe condition

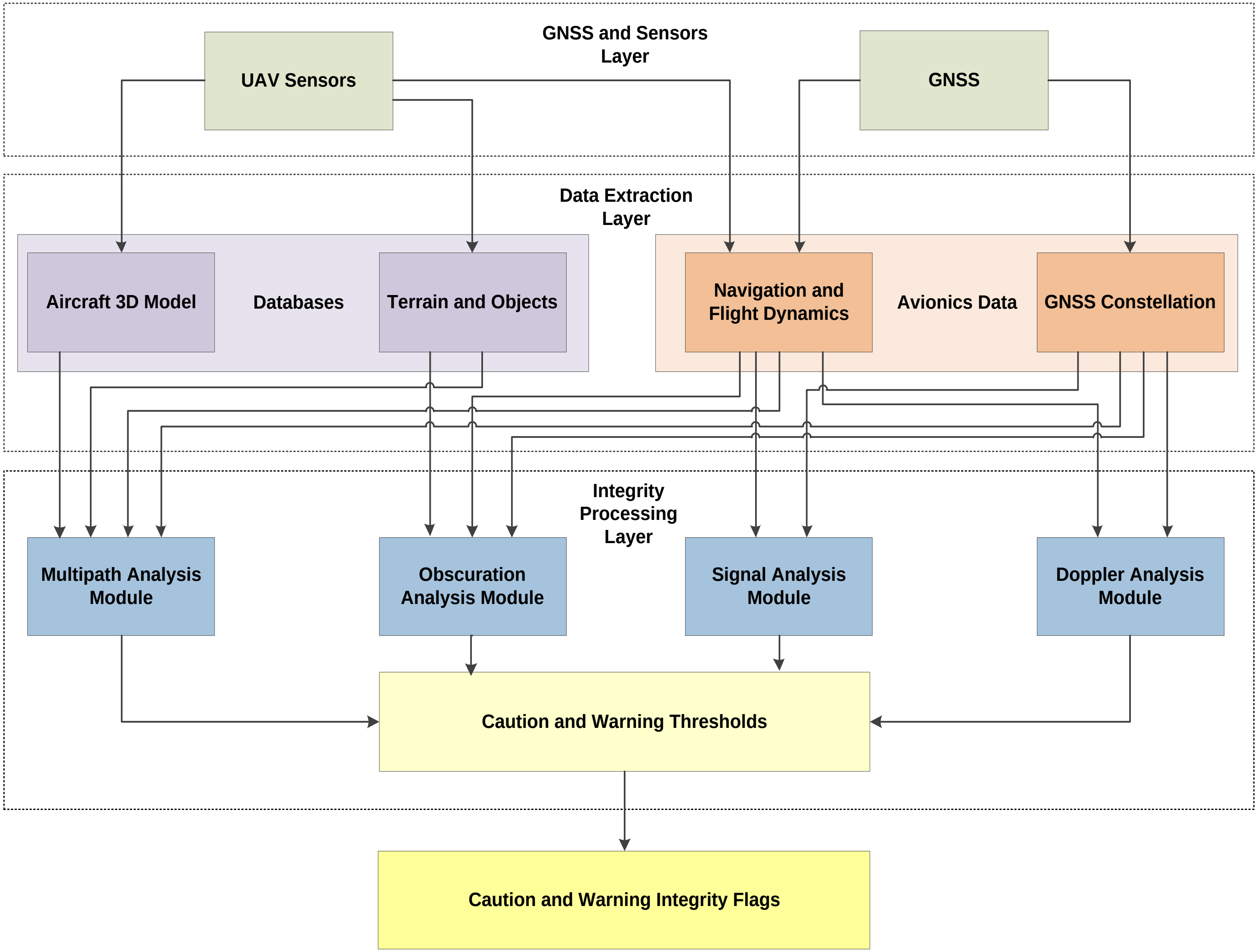
ABIA Time-to-Warning (TTW):

The **maximum time allowed** from the moment a GNSS fault resulting in an unsafe condition is detected to the moment that the ABIA system provides a warning flag to the user

GNSS Threats

- **Causes of GNSS data degradation or loss** (A/C level):
  - **Obscuration**
  - **Bad satellite geometry (DOP)**
  - **Fading (low C/N_0)**
  - **Doppler shift (signal tracking, acquisition time)**
  - **Multipath effect (C/N_0, range and phase errors)**
  - **Interference and Jamming**
- Understanding the physics of these phenomena and developing reliable mathematical models was essential in order to properly design the GNSS ABIA system
- The GNSS threats are avoided by adding (statistical sense) the resulting errors (signal degradations or data losses) to the uncertainty volume defined by the DAA unified approach

IFG Architecture



GNSS and Sensors Layer

UAV Sensors

GNSS

Data Extraction Layer

Aircraft 3D Model

Databases

Terrain and Objects

Navigation and Flight Dynamics

Avionics Data

GNSS Constellation

Integrity Processing Layer

Multipath Analysis Module

Obscuration Analysis Module

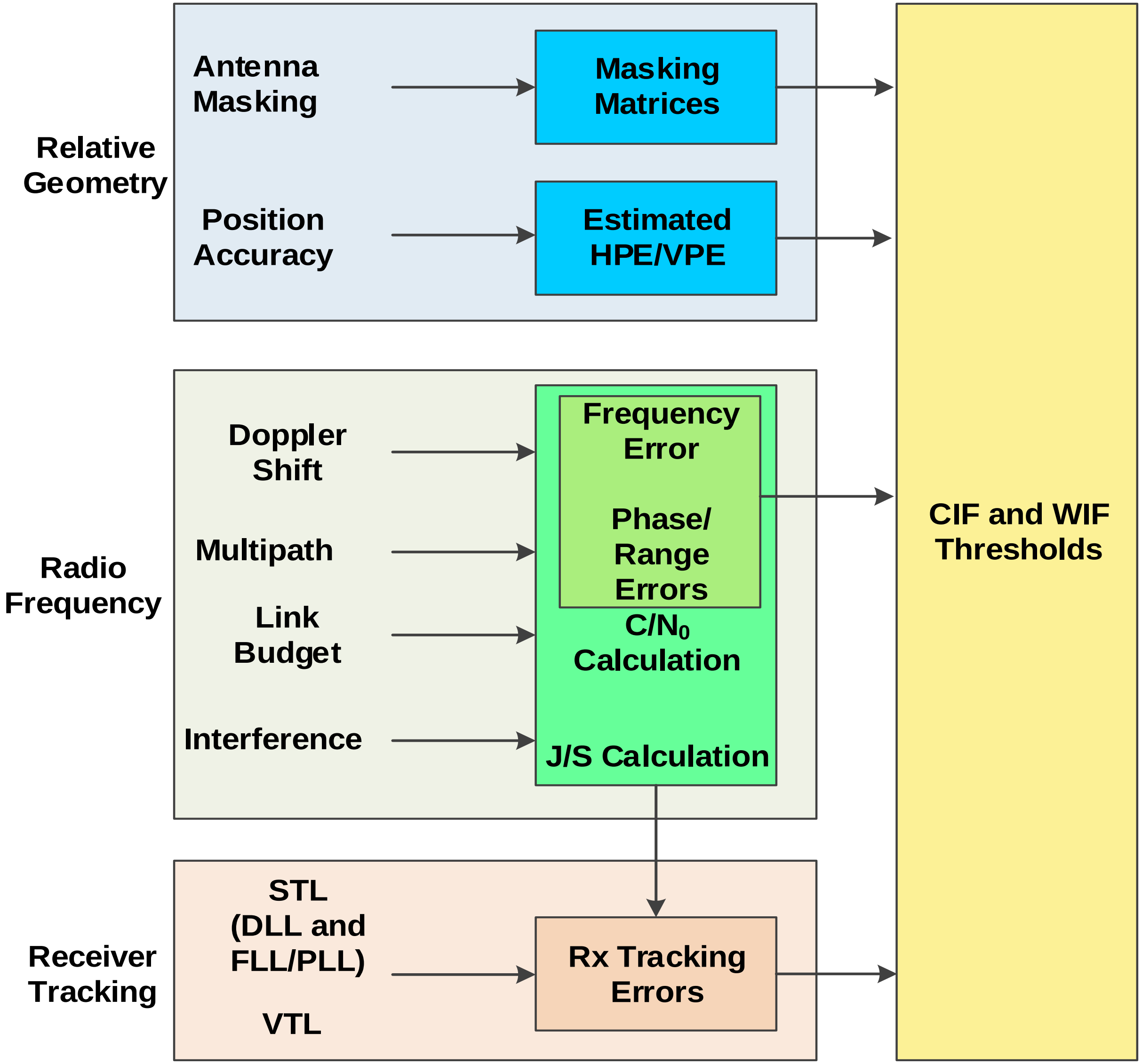
Signal Analysis Module

Doppler Analysis Module

Caution and Warning Thresholds

Caution and Warning Integrity Flags

CIF/WIF Thresholds



Minimum Time for CIF (Predictive) is a function of the required predictive behaviour. We use:

TTC = TTT + 2AMT

TTT = Time-to-Threat

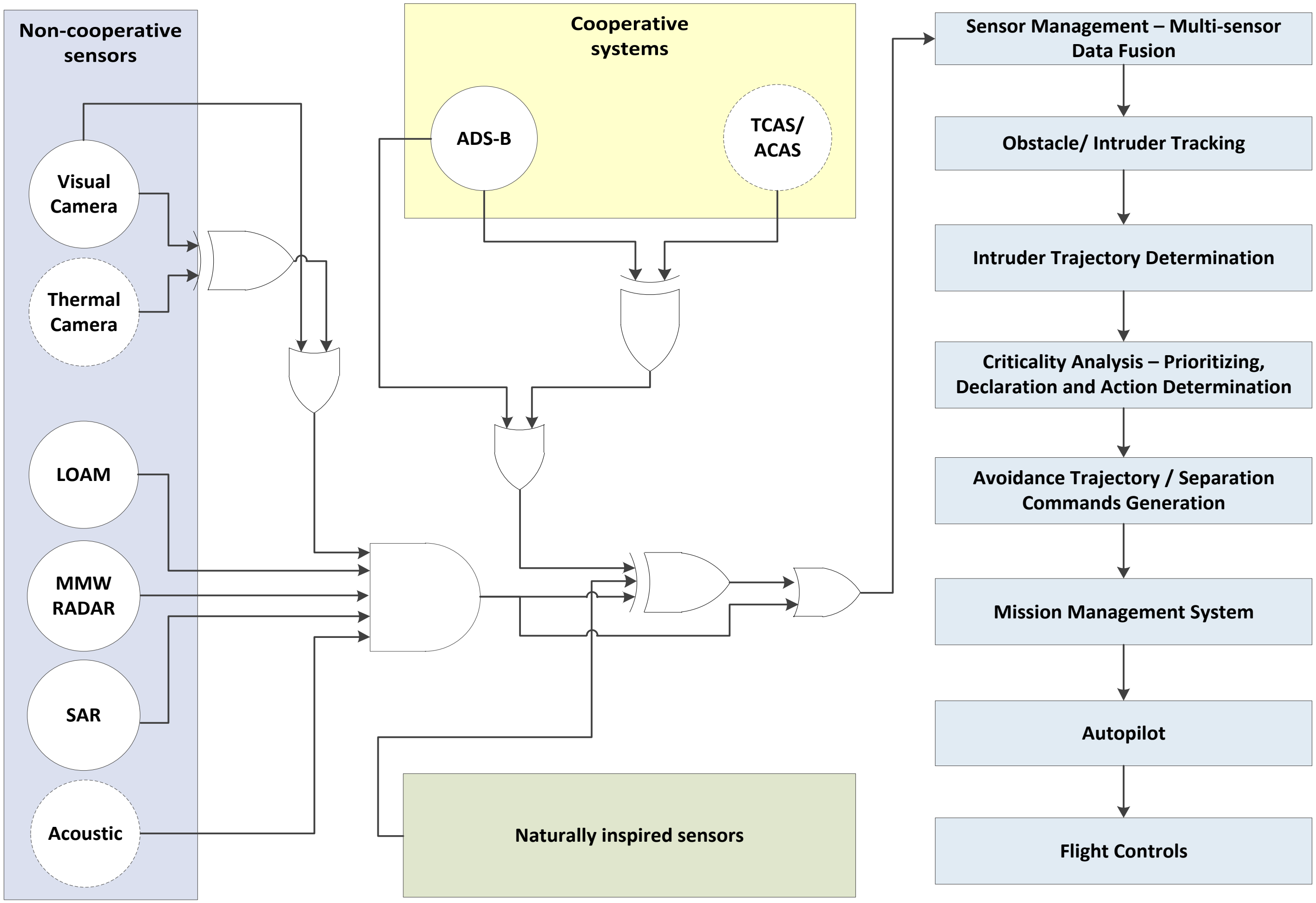
AMT = Avoidance Manoeuvre Time

DAA Reference Architecture

Sensor/ System	Type	Information	Trajectory
Visual camera	NC, Passive	Azimuth, Elevation	Extracted
Thermal camera	NC, Passive	Azimuth, Elevation	Extracted
LIDAR	NC, Active	Range, Bearing	Extracted
MMW Radar	NC, Active	Range, Bearing	Extracted
SAR	NC, Active	Range, Bearing	Extracted
Acoustic	NC, Active	Azimuth, Elevation	Extracted
ADS-B	C	Position, Altitude and Velocity	Provided
TCAS/ ACAS	C	Range, Altitude	Extracted

- Both non-cooperative sensors and cooperative systems are part of the DAA reference system architecture

DAA Reference Architecture

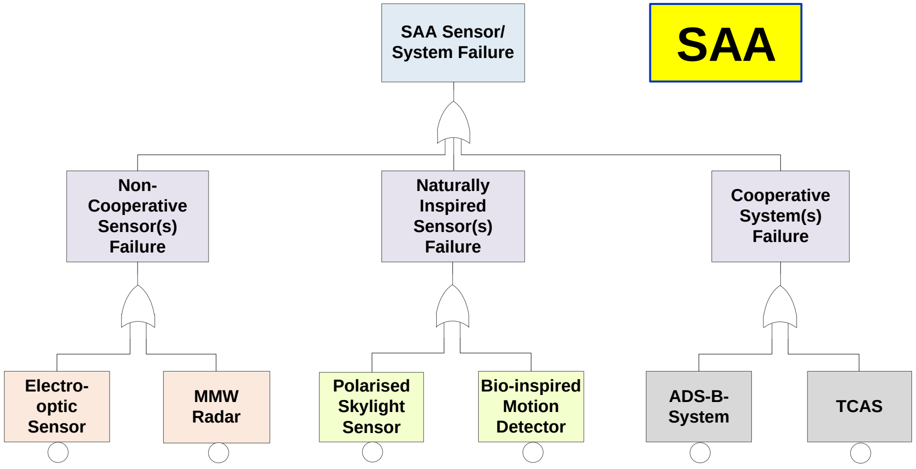


Adaptive BDL

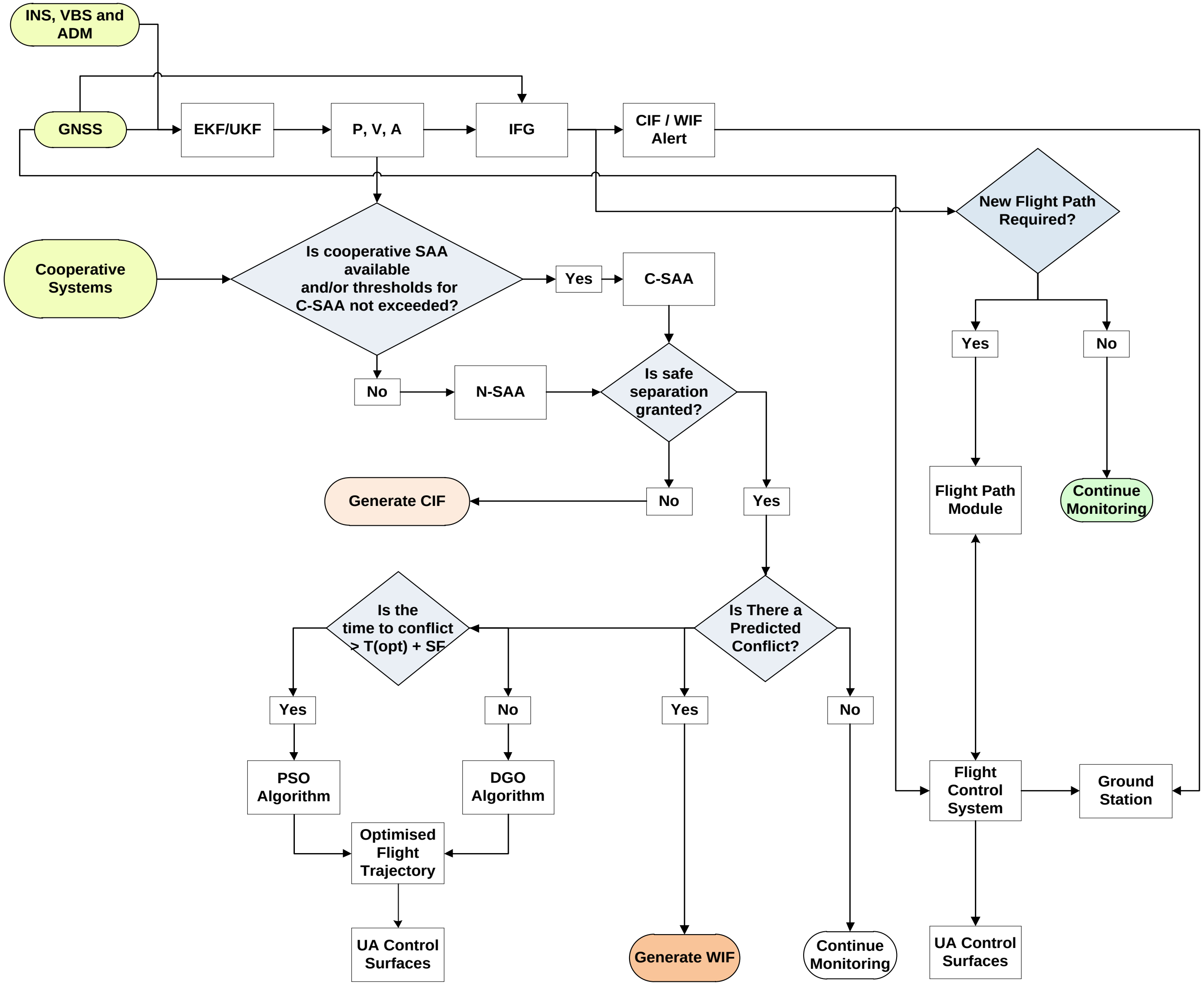
- Instead of implementing an hardwired decision logic (a pre-defined set of instructions) , we adopt a Dynamically Reconfigurable or Adaptive Bolean Decision Logic (ABDL) based on CNS systems Integrity Monitoring and Augmentation (AMAF) features

- The sensors/systems providing the most reliable DAA solution are automatically selected, providing robustness in all flight phases and supporting all-weather operations

- The relatively simple method lays foundations for the development of an airworthy DAA capability and a pathway for manned/unmanned aircraft coexistence in all classes of airspace



ABIA/DAA Integration Architecture



INS: Inertial Navigation System

VBS: Vision-Based Sensors

ADM: Aircraft Dynamics Model

EKF: Extended Kalman Filter

UKF: Unscented Kalman Filter

P, V, A: Position, Velocity, Attitude

IFG: Integrity Flag Generator

CIF: Caution Integrity Flag

WIF: Warning Integrity Flag

C-SAA: Cooperative SAA

N-SAA: Non-Cooperative SAA

PSO: Pseudospectral Optimisation

DGO: Differential Geometry Optimisation

Conflict Detection and Resolution

- **Trajectory prediction**, which estimates the flight mode of the intruder based on the information derived from cooperative/non-cooperative sensors and predicts the future trajectory of the intruder
- **Conflict detection**, calculating the time to separation violation point and conflict probability within the look-ahead time, based on relative range, velocity, and altitude difference
- **Conflict resolution**, which uses all available information to resolve the conflicts
- **Monitoring the avoidance manoeuvre**, which verifies that conflicts are being resolved as planned

ABIA/DAA Simulation

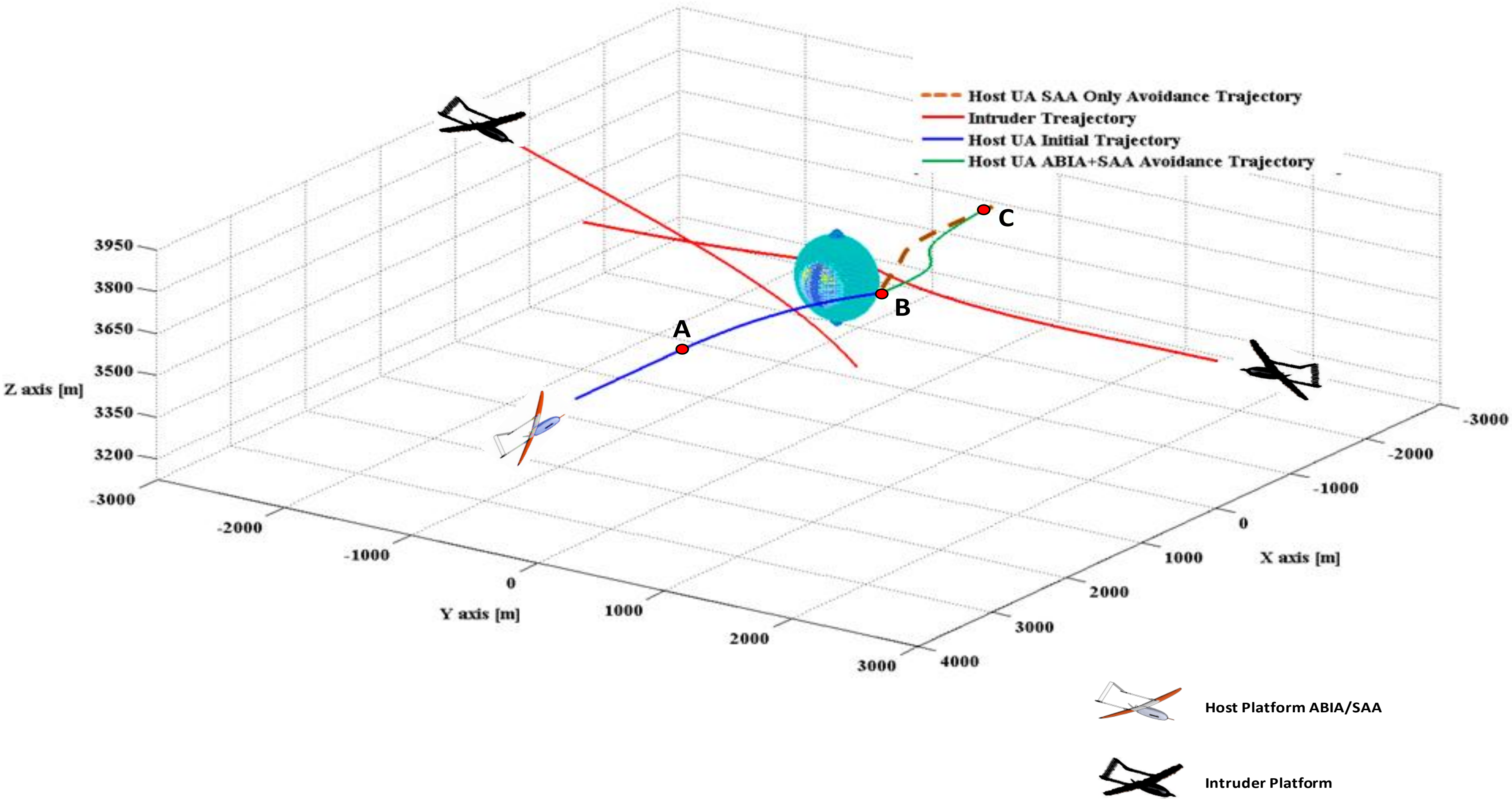
❖ C-DAA and N-DAA case studies:

- Test platforms:
  - AEROSONDE UAV (ABIA host platform)
  - AIRBUS 320 (A320) and AEROSONDE UAV Intruders
- N-DAA test scenario:
  - A320 and AEROSONDE UAV (ABIA host) - A320 descending
- C-DAA test scenarios:
  - 3 × AEROSONDE (1 ABIA host) – 1 UAV descending

ABIA/DAA Simulation

- Avoidance volume generated by the DAA system (sum of navigation and tracking errors) based on DAA Unified Approach (SUM)
- Pseudospectral Optimization (PSO) or Constrained Geometric Optimization (CGO) techniques are used to generate the new trajectory based on the available time to conflict (host entering the avoidance volume)
- Avoidance trajectory is initiated by the DAA system when the probability of collision exceed the required threshold
- Time and fuel are used in the cost functional, the dynamic model as dynamic constraint, and the elevation criteria as path constraints (both PSO and CGO)
- Boundary conditions are set from the value of the flight parameters at CIF time step
- A collision avoidance trajectory free of GNSS integrity degradation is generated

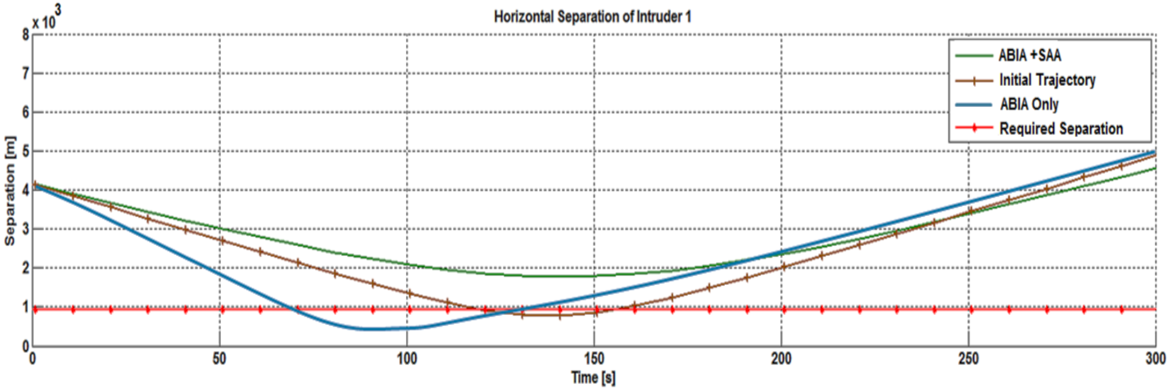
C-DAA Simulation

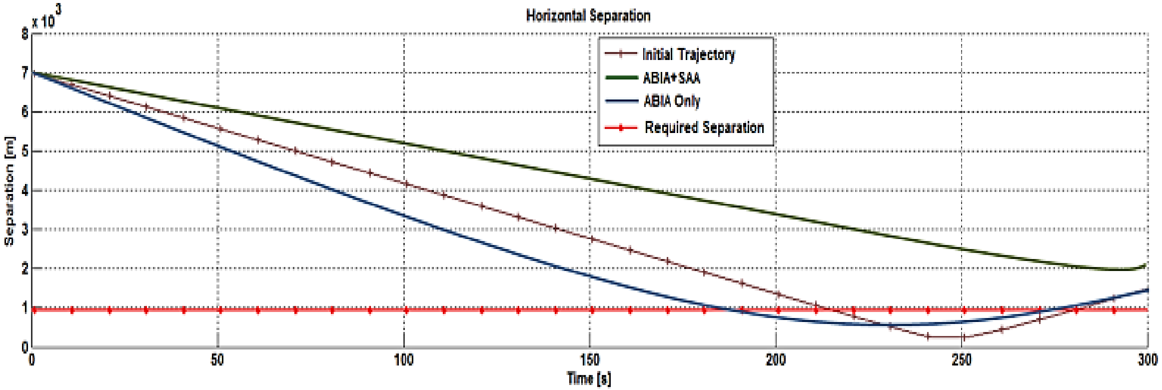


C-DAA Simulation

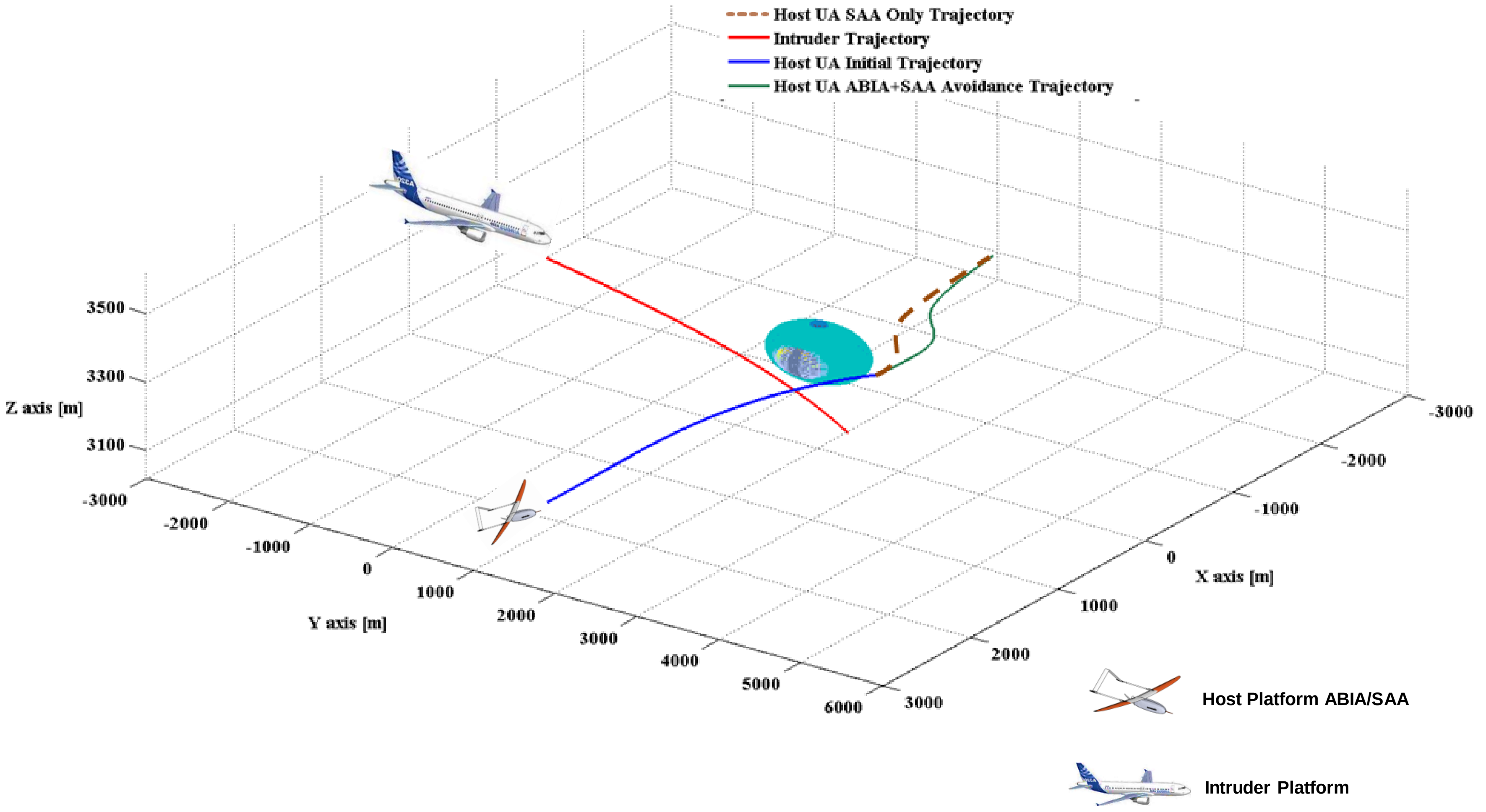
- Three different points are shown on the host platform trajectory:
- ✓ (A) DAA Break-off Point: Corresponding to the point where the host UAV initiates the avoidance trajectory (commanded by the DAA system). The cost function criteria adopted in this case is minimum time.
- ✓ (B) DAA Safe Manoeuvring Point: Corresponding to the point where the host UAV can manoeuvre safely (any manoeuvre within its operational flight envelope) has 0 Risk-Of-Collision (ROC). The DAA cost function criteria switches to minimum time and minimum fuel from this point onwards to get back on the original (desired) track.
- ✓ (C) ABIA Re-join Point: Corresponding to the point where the host UAV re-joins the original (desired) track without GNSS data degradations.

C-DAA Simulation

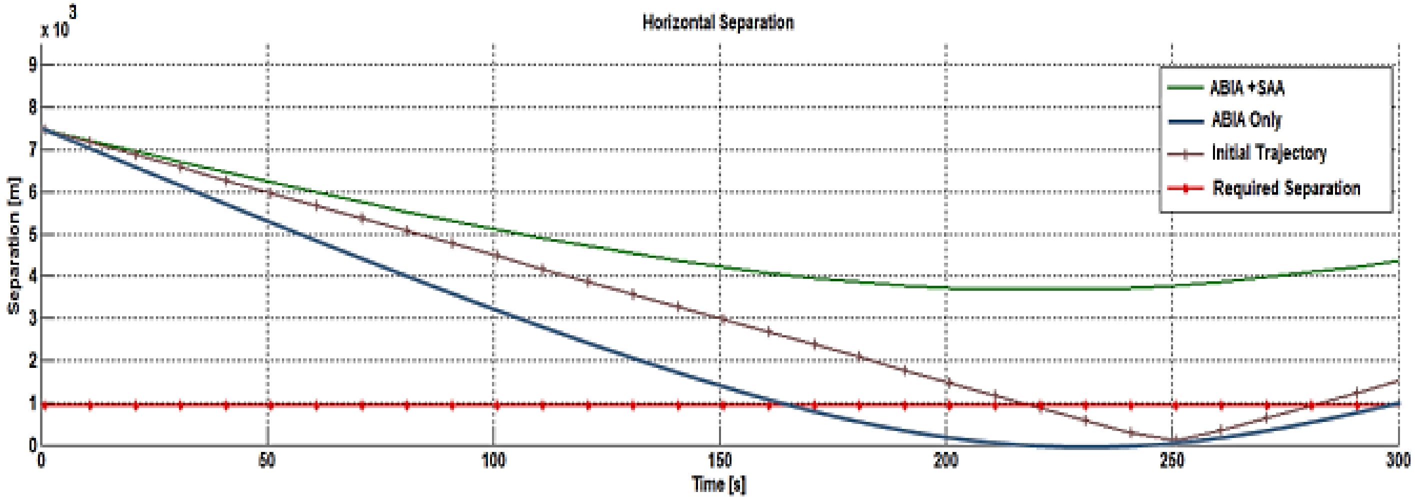




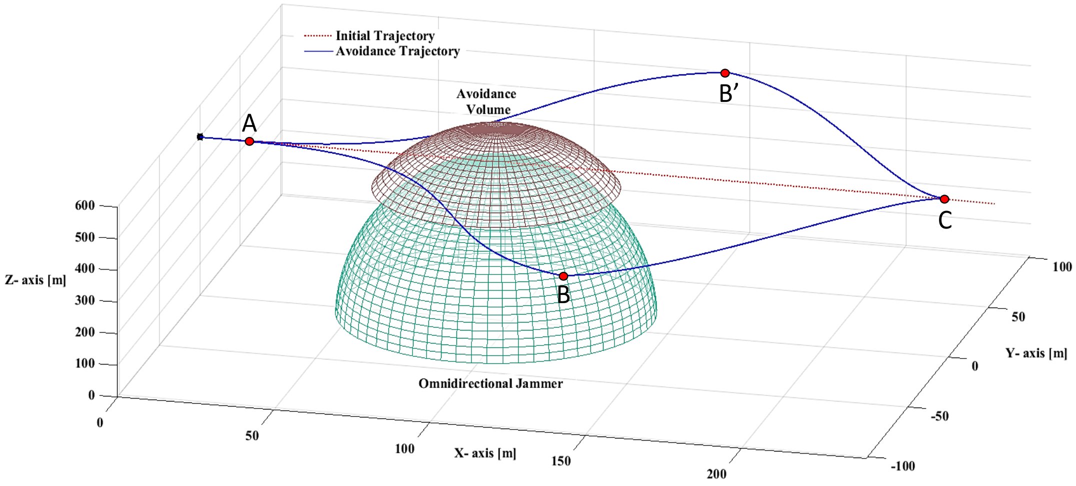
N-DAA Simulation

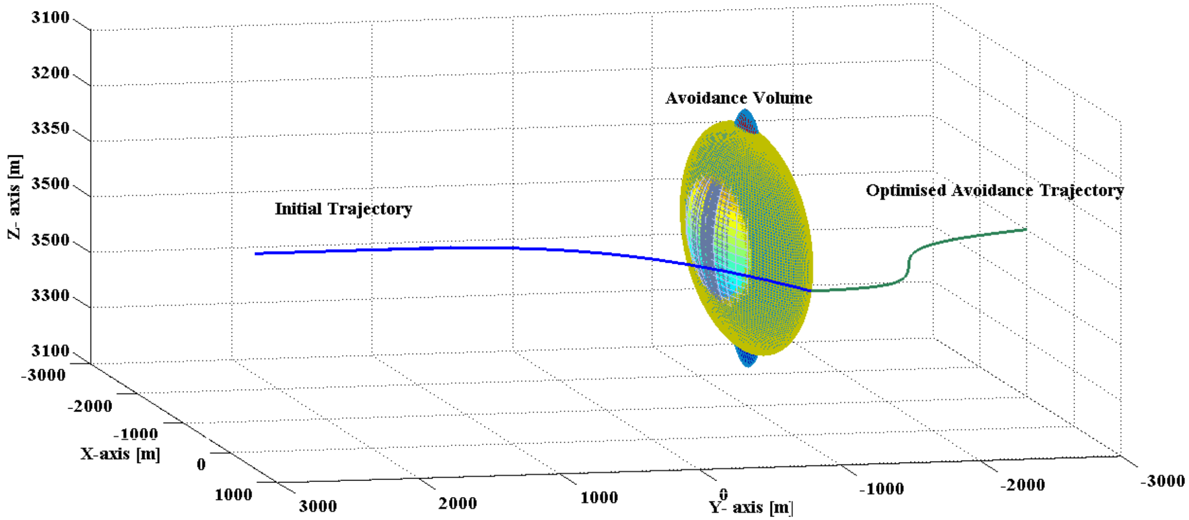


N-DAA Simulation Results



Avoidance of Jamming





- The simulation was performed using AEROSONDE UAV 6-DOF dynamics model
- After jamming is detected and located, the optimal avoidance trajectory is generated preventing degradation or losses of navigation data during the whole jammer avoidance manoeuvre.

Conclusions (1)

- A unified approach to cooperative and non-cooperative DAA was developed to calculate the overall uncertainty volume associated with the intruder tracks
- The integration of DAA and ABIA (CNS) was studied and an integrated architecture for DAA/ABIA (GNSS case) was presented
- The ABIA IFG module is capable of generating integrity flags to provide both caution and warning signals when GNSS signals are degraded or lost
- After the integrity caution flag is generated, the time available for the pilot/autopilot to react (before the integrity event is detected and the warning flag is generated), is at least TTT + 2AMT
- The trajectory optimization problem was formulated and the real-time capability of the FPO module (using pseudospectral and other methods) was verified

Conclusions (2)

- The ABIA integration into an existing RPAS SAA architecture was studied in realistic C-SAA and N-SAA scenarios
- In the C-SAA and N-SAA scenarios investigated and in the dynamic conditions explored, all mid-air collision threats were successfully avoided by implementing adequate trajectory optimisation algorithms
- The proposed ABIA/SAA integration architecture is capable of achieving adequate performance by avoiding critical satellite signal losses while fulfilling the separation requirements for SAA
- The ABIA/SAA system is capable of avoiding both directional and non-directional jamming
- The approach provides autonomy and robustness in all flight phases. This method lays foundations for the development of an airworthy SAA capability

Future Work

- Extend the ABIA/DAA concepts to the Aeronautical Data Link (ADL) application domain and investigate ABIA LOS and BLOS communication interfaces for UAS applications
- Investigate ABIA/DAA evolution for Next Generation Flight Management System (NG-FMS) applications:
  - Trajectory Optimization for Future CNS+A Systems
  - 4DT Intent Based Operations
  - NG-FMS Integration
- Evaluate the potential of ABIA/SAA to enhance the performance of next generation CNS/ATM systems for Performance/Intent Based Operations (PBO/IBO) and Four-Dimensional Trajectory (4DT) management
- Study possible applications of the ABIA/SAA concepts to advanced mission planning and forensic (accident investigation) applications

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