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Communication, Navigation and Surveillance
Performance Criteria for Safety-Critical Avionics and ATM Systems

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Abstract

The demand for improved safety, integrity and efficiency due to the rapid growth of aviation sector and the growing concern for environmental sustainability issues poses significant challenges on the development of future Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM) and Avionics (CNS+A) systems. High-integrity, high-reliability and all-weather services are required in the context of four dimensional Trajectory Based Operations / Intent Based Operations (TBO/IBO). The Next Generation Flight Management Systems (NG-FMS) and the Next Generation Air Traffic Management (NG-ATM) systems are developed allowing automated negotiation and validation of the aircraft intents provided by the NG-FMS. After describing the key system architectures, the mathematical models for trajectory generation and CNS performance criteria evaluation are presented. In this paper, the method for evaluating navigation performance is presented, including a detailed Monte Carlo simulation case study. The proposed approach will form a basis for evaluating communication and surveillance performances as well in future research. The Monte Carlo simulation results demonstrate the capability of the proposed CNS+A system architectures to comply with the required navigation performance criteria in the generation of optimized aircraft trajectory profiles.

Keywords: CNS+A systems, Flight Management System, Air Traffic Management, Safety, Integrity, Trajectory-Based Operations and Intent Based Operations.

Introduction

Technological advancements in civil and military avionic systems have led to significant operational improvements in the performance of mission- and safety-critical tasks. The avionic systems in civil aircraft account for 35-40 % of the total cost while it could be more than 50 % in the case of military aircraft [1]. The global air traffic is growing at a rapid pace and its increase is predicted to double in the next 15 years [2]. At the same time, a scenario is witnessed wherein civil and military applications of Remotely-Piloted Aircraft Systems (RPAS) have much expanded in recent years. RPAS are employed in view of their ability to perform tasks with higher manoeuvrability and longer endurance. Another remarkable factor of reckoning is that they provide cost-effective and safe alternatives to manned aircraft in several operational scenarios. In order to integrate RPAS into non-segregated airspace, they are likely to require enhanced navigational capabilities in order to meet the Required Navigational Performance (RNP) and Reduced Vertical Separation Minima (RVSM) expected of manned aircraft. Additionally, it is also essential to fulfill the required communication and surveillance requirements to ensure minimum lateral and vertical safe separation distances [3]. There have been a number of large-scale and regional research initiatives addressing the challenges posed to Air Traffic Management (ATM) modernisation beforehand. International Civil Aviation Organization (ICAO) in its Global Air Navigation Capacity & Efficiency Plan (Doc 9750) has identified the following four key performance improvement areas [4]:
efficient flight path, optimum capacity and flexible flights, airport operations and globally interoperable systems and data. The Single European Sky Air Traffic Management Research (SESAR) and the Clean Sky Joint Technological Initiative (JTI) for Aeronautics and Air Transport are the prominent programmes defining the future air transportation in Europe addressing the problems pertaining to both operational improvements and environmental issues [5-10]. The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has set ambitious target aims to address the environmental sustainability of aviation in its Strategic Research Agenda [11, 12]. The Next Generation Air Transportation System (NextGen) programme in the USA, in collaboration with SESAR, leads the transformation towards air transport modernisation [13]. Based on the requirements set by both the large-scale and regional programmes, the challenges posed to avionic and ATM system developers are identified including improving safety, increasing capacity, improving efficiency and environmental sustainability of aviation. Additionally, the introduction of interoperable and flexible systems in a cost effective manner is also identified as an important objective. Innovative solutions are expected from the Communication, Navigation, Surveillance, Air Traffic Management (CNS/ATM) and Avionics (CNS+A) domain to fulfil the identified requirements. CNS+A is defined as CNS systems, employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global ATM system. The CNS+A concept was first introduced by the Future Air Navigation Systems (FANS) special committee of the ICAO [14]. The underlying CNS+A concepts are:

- Four Dimensional (4D) Trajectory Based Operations / Intent Based Operations (TBO/IBO).
- PBO enabled by System Wide Information Management (SWIM).
- Improved Human Machine Interface and Interaction (HMI2), interoperability for airborne and ground interfaces and higher levels of automation.
- Collaborative Decision Making (CDM) to allow all stakeholders involved in flight management to participate in the enhancement of system performance by utilising more accurate information from airborne systems.
- Air Traffic Flow Management (ATFM) and Dynamic Airspace Management (DAM).
- Role shifting of ground ATM command and control oriented units to a highly automated decision-making system in an interoperable environment, based on the User Preferred Trajectories (UPT).
- CNS+A technologies for RPAS, specifically addressing Sense-and-Avoid (SAA) functions.

The CNS+A concepts enable more accurate estimation of CNS performances and involve higher levels of automation. In order to enable these enhanced concepts and capabilities, new ground-based and airborne CNS+A systems are required. Modern avionics and ground-based systems for planning and real-time execution of Four Dimensional Trajectory (4DT) functionalities, including multi-objective 4DT optimisation, negotiation and validation in the TBO context are currently developed. CNS+A systems with integrity monitoring and augmentation functionalities fulfilling RNP, Required Communication Performance (RCP), Required Surveillance Performance (RSP) and thus Required Total System Performance (RTSP) are envisaged. The automated systems allow the aircraft equipped with novel avionic systems to fly user-preferred optimal flight paths and thus they limit the intervention of the air traffic controllers to high-level and emergency decision making process. These airborne systems will provide better and precise airborne navigation services, optimal collision avoidance and aircraft separation assistance, and effective, secure and reliable communication links [15-20]. Fig. 1 illustrates the RTSP factors and the associated time frames.
Conventionally, the Flight Management Systems (FMS) act as the key enabler of automated navigation and guidance services in manned aircraft. In RPAS, the Mission Management System (MMS) reduces the ground control pilot’s workload by acting both as a mission planner and a mission monitor. Additionally, due to the growing concern for environmental sustainability of aviation has resulted in active research on improving the operational efficiency and safety, while reducing the environmental impacts of aviation [11, 12]. In this context, the Next Generation Flight/Mission Management Systems (NG-FMS/NG-MMS) are key enablers for generating globally optimal trajectories that fulfil the evolving operational, safety and environmental requirements. The NG-MMS is developed for Four Dimensional (4D) Trajectory/Intent Based Operations (TBO/IBO) in combination with the Next Generation Air Traffic Management (NG-ATM) systems and Next Generation Airborne Data Link (NG-ADL) communications. The efficiency and effectiveness of NG-ATM strategies are directly driven by the nature of information sharing and its underlying operational and technological frameworks. In the recent years, RPAS are increasingly used for a number of applications and the need for their integration into the civilian airspace has led to the development of a host of dedicated automation services. In this perspective, cooperative and non-cooperative SAA functions are key technology enablers that can support the RPAS to access non-segregated airspace and hence they are incorporated as part of the NG-MMS. Additionally, suitable processing/interfaces required for achieving Performance Based Operations (PBO) are considered essential requirements to be addressed as part of the CNS+A system design.

**System Architecture**

The NG-FMS architecture is primarily based on the core functionalities namely flight planning (FPLN), localisation and state determination, trajectory optimisation (TRAJ), performance predictions (PRED) and guidance. Additionally, the MMS also provides auto-throttle controls for engines and communicates with the 4D Trajectory Planning, Negotiation and Validation (4-PNV) system. The NG-MMS is based on a multi-objective and multi-model 4D-Trajectory (4DT) optimisation approach. The databases associated are Magnetic Deviation Database (MAG–DB), Navigation Database (NAV–DB) and aircraft Performance Database (PERF–DB). The primary NG-MMS modules are:

- Trajectory Planning/ Optimisation – This module performs 4DT planning and optimisation functions for pre-tactical, tactical and emergency situations. The 4DT optimiser includes the models pool and constraints pool involves a number of cost functions. A number of cost functions are considered for optimisation including
minimum fuel consumption, flight time, operative cost, noise impact, emissions and contrails. The databases include navigation, performance, magnetic deviation and environmental databases. The implementation of 4DT optimisation algorithms as part of the identified system architecture modules allows for the development of TBO aspects. However, for addressing PBO, the inclusion of specific modules incorporating mathematical models for CNS+A performance parameters is required.

- Trajectory Monitoring – It performs state estimation, calculating the deviations between the active 4DT intents and the estimated/predicted aircraft states.
- Path Correction – It corrects the path deviation in terms of lateral, vertical and time profiles and the generated steering commands are provided to the guidance module of the NG-FMS.
- Trajectory Negotiation and Validation – It carries out the process of negotiation, which can be initiated by the pilot via the NG-MMS or by the 4-PNV system.
- MMS Performance Manager – It monitors the active 4DT intents for errors to address integrity requirements. The integrity analysis module is based on Required Navigation Performance (RNP), Required Communication Performance (RCP) and Required Surveillance Performance (RSP) managers.
- MMS Integrity Manager – This module is based on Avionics-Based Integrity Augmentation (ABIA) [13, 14]. The inputs from the different sensor candidates are augmented based on predefined decision logics and the result is passed as input to an Integrity Flag Generator (IFG).

The negotiation and validation of 4DT intents by the NG-MMS / NG-ATM system is dependent on:

- On-board validation based on synchronization, sufficient fuel, compliance with dynamics (time performances, turn performances, speed, altitude), obstacle separation, locally sensed weather, compliance with the Integrated Vehicle Health Management (IVHM) system regarding the aircraft health status and other issues.
- Ground-based validation based on air traffic separation (lateral, vertical, longitudinal), sector occupancy, airspace restrictions (special use areas) and time based restrictions (night time noise abatement procedures).

With the increasing levels of automation in air transportation and the enhancements in navigation technologies, integrity monitoring and augmentation systems have gained enormous importance. Navigation errors as a result of the Guidance, Navigation and Control (GNC) system errors are evaluated in the NG-FMS. Avionics-Based Integrity Augmentation (ABIA) system [13, 14] for mission- and safety-critical GNSS applications are adopted as software functions in the NG-FMS. In this context, the error sources affecting pseudo-range GNSS observables are taken into account in evaluating the performance. Measurements from a number of navigation sensors are considered and fed to an Extended Kalman Filter (EKF) for data fusion. The integrity flag generator uses a set of predefined Caution and Warning Integrity Flags (CIF/WIF) threshold parameters to trigger the generation of both caution and warning flags associated with navigation, communication and surveillance performance degradations. Additionally, typical error sources affecting other navigation sensors (Inertial Navigation System (INS), radio navigation, etc.), autopilot and Flight Control Systems (FCS) are also considered in computing the overall GNC error budget. Fig. 2 illustrates the integrity monitoring module for the CNS performance parameters.
Fig. 2: NG-FMS integrity monitoring

Fig. 3 is a schematic block diagram of the NG-FMS performance management modules. The performance management blocks are defined for all CNS+A parameters. They derive the inputs from the four dimensional trajectory planner and optimiser module. The RNP, RSP and RCP integrity management modules generate integrity flags that are utilised by the 4DT module. The RNP, RSP and RCP performance management modules are interfaced with the 4-PNV system on the ground.

Fig. 3: NG-FMS performance management

Fig. 4 is a schematic block diagram of the CNS+A systems. The optimisation of the 4DT trajectories is performed on-board by the NG-FMS/NG-MMS. The innovative 4-PNV system
receives multiple options of 4DT intents from each manned and unmanned aircraft equipped with the novel automation systems. The availability of multiple trajectory options provides the 4-PNV system with various options for identifying, in real-time, an optimal and conflict-free trajectory for each aircraft. Once the optimal conflict-free trajectories have been identified, the 4-PNV system instructs each aircraft to fly the validated trajectories and an acknowledgement is sent by the aircraft to the 4-PNV system. A number of RPAS equipped with NG-MMS are controlled by the ground command, control and intelligence system aided by Line-Of-Sight (LOS) and Beyond Line-Of-Sight (BLOS) communication links. The ground inter-communication system consists of a ground-to-ground communication network between the 4-PNV system, Air Navigation Service Provider (ANSP) and the Airline Operation Centre (AOC). The key enabling CNS+A systems for RPAS include:

- Line-of-Sight (LOS) and Beyond Line-of-Sight (BLOS) communication systems.
- High-integrity airborne and ground-based RPAS navigation systems and integrated fail-safe avionics architectures.
- The adoption of fused cooperative/non-cooperative surveillance systems incorporating collision avoidance and collaborative conflict resolution capabilities in a network-centric operational scenario.
- The interactions between the Guidance, Navigation and Control (GNC) and Tracking, Decision and Avoidance (TDA) loops.

Based on the surveillance information obtained and the communication datalinks between a number of aircraft, as well as aircraft and ground, the navigation performance is obtained forming a CNS loop. Fig. 5 illustrates the GNC loop, TDA loop and CNS performance parameters with a clear focus on integrity. The TDA loop consists of the following functions:

- Track: A group of sensors collect the required data from the environment. Tracking is accomplished by the continuous acquisition of obstacle/intruder data.
- Decision Logics: As the intruder aircraft/obstacle is tracked, suitable decision logics are employed for identifying the possibility of collisions.
- Avoid: Once a possibility of collision is detected, then the on-board computers determine an action to avoid the collision by re-generating the 4DT and optimising it against the set constraints and performance parameters.
The CNS+A systems are located on board aircraft, in air traffic control (ATC) centers, in low earth orbit, and in ground stations around the world. Each works in concert with another to improve the movement and control of air traffic. Two-way communications between ground operators and aircraft will be implemented solely by digital transmissions. This will include the transmission of meteorological and Notices to Airman (NOTAM) messages along with company communications and air traffic advisories. Pre-set and free text messages will be passed both manually and automatically using packet switching methods compatible with the International Standards Organization's (ISO) Open Systems Interconnection (OSI) reference model. In order to evaluate performance based CNS, RNP was introduced to define the operational requirements for a navigation system in the airspace. RCP is a concept to define the operational requirements for communication systems that support ATM functions [20, 21]. Table 1 lists the RCP parameters. ICAO specifies four key parameters to describe the communication system performance namely:

- **Transaction time**: the maximum time for communication system to complete an operational transaction.
- **Continuity**: the probability of the communication system that an operational transaction completes within the transaction time.
- **Availability**: the probability of the communication system being available when an operational transaction needs to be initiated.
- **Integrity**: the probability that an operational transaction is completed within the transaction time with no undetected errors.

**Table 1: RCP parameters**

<table>
<thead>
<tr>
<th>RCP specification</th>
<th>Transaction time [s]</th>
<th>Continuity</th>
<th>Availability</th>
<th>Integrity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>400</td>
<td>0.999</td>
<td>0.999</td>
<td>Malfunction = $10^{-5}$ per flight hour</td>
</tr>
<tr>
<td>240</td>
<td>240</td>
<td>0.999 (safety) 0.9999 (efficiency)</td>
<td>Malfunction = $10^{-5}$ per flight hour</td>
<td></td>
</tr>
</tbody>
</table>
RNP extends the capabilities of NG-FMS by providing real-time estimates of navigation uncertainty, assurance of performance through its containment concepts and ensures repeatability and predictability of air navigation services [23]. This precise characterization of airplane performance is a key to designing more efficient airspace routes and procedures. The RNP type is defined as a 95% containment value and a measure of navigation performance accuracy. The RNP threshold values are listed in Table 2. ICAO specifies four key parameters to describe the navigation system performance namely:

- **Accuracy**: the ability of the system to maintain the position within a specified error with 95% probability.
- **Integrity**: the quality which relates to the trust that can be placed in the correctness of the navigation information. Integrity risk is the probability of an undetected failure of the specified accuracy.
- **Continuity of service**: the ability of the system to perform its function without unscheduled interruptions.
- **Availability**: the ability of the system to provide the required guidance at the initiation of the intended operation.

### Table 2: Navigation specifications for different phases of flight

<table>
<thead>
<tr>
<th>RNP/RNAV Levels</th>
<th>Flight Phase</th>
<th>Accuracy [NM]</th>
<th>Alarm Limit [NM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNAV 10</td>
<td>En route</td>
<td>10 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>RNAV 10</td>
<td>En route, arrival</td>
<td>5 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>RNAV 2</td>
<td>En route, arrival, departure</td>
<td>2 nm</td>
<td>4 nm</td>
</tr>
<tr>
<td>RNAV 1</td>
<td>En route, arrival, approach, departure</td>
<td>1 nm</td>
<td>2 nm</td>
</tr>
<tr>
<td>RNP 4</td>
<td>En route</td>
<td>4 nm</td>
<td>8 nm</td>
</tr>
<tr>
<td>Basic RNP 1</td>
<td>Arrival, approach, departure</td>
<td>1 nm</td>
<td>2 nm</td>
</tr>
<tr>
<td>RNP APCH</td>
<td>Final approach</td>
<td>0.3 nm</td>
<td>0.6 nm</td>
</tr>
</tbody>
</table>

RSP is a set of performance requirements defined for surveillance systems. A surveillance system is used to ensure that aircraft are separated correctly. The position information needs to be updated every four seconds in high traffic airspace [22]. However, in low-traffic airspace such as oceanic and remote airspace, the updating time is slightly longer, so position information needs to be updated every twelve seconds. The future systems are envisaged to have the ability to support free flight. Table 3 lists the RSP parameters. ICAO specifies four key parameters to describe the surveillance system performance namely:

- **Survellance data transit time**: the required time for surveillance data delivery.
- **Integrity**: the required probability that surveillance data is delivered with no undetected error.
- **Continuity**: the ability of the system to perform its function within the update time without any errors being detected.
- **Availability**: the ability of the system to provide the required surveillance function at the initiation of the intended operation.
Table 3: RSP parameters

<table>
<thead>
<tr>
<th>RSP specification</th>
<th>Surveillance delivery time [s]</th>
<th>Continuity</th>
<th>Availability</th>
<th>Integrity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>400</td>
<td>0.999</td>
<td>0.999</td>
<td>Malfunction = $10^{-5}$ per flight hour</td>
</tr>
<tr>
<td>180</td>
<td>180</td>
<td>0.999</td>
<td>0.999 (safety) and 0.9999 (efficiency)</td>
<td>Malfunction = $10^{-4}$ per flight hour</td>
</tr>
</tbody>
</table>

Assuming normal distribution with mean as zero on position error as a result of navigation, communication and surveillance errors, the probability density functions are defined as:

\[
f_{\text{RNP}}(x) = \frac{1}{\sqrt{2\pi}\sigma_{\text{Nav}}} e^{-\frac{x^2}{2\sigma_{\text{Nav}}^2}}
\]

(1)

\[
f_{\text{RCP}}(x) = \frac{1}{\sqrt{2\pi}\sigma_{\text{Comm}}} e^{-\frac{x^2}{2\sigma_{\text{Comm}}^2}}
\]

(2)

\[
f_{\text{RSP}}(x) = \frac{1}{\sqrt{2\pi}\sigma_{\text{Sur}}} e^{-\frac{x^2}{2\sigma_{\text{Sur}}^2}}
\]

(3)

where $\sigma_{\text{Nav}}, \sigma_{\text{Comm}}, \sigma_{\text{Sur}}$ are the standard deviation values resulting from navigation, communication and surveillance errors respectively. The values of $\sigma_{\text{Nav}}, \sigma_{\text{Comm}}, \sigma_{\text{Sur}}$ are obtained based on the definition of the containment region.

The evaluation of the navigation performance is presented in this paper and in a similar manner; the communication and surveillance performances can be evaluated. The NG-FMS trajectory optimisation algorithms are based on a 3-degree-of-freedom (3-DoF) point mass Aircraft Dynamics Model (ADM) with variable mass. The 3-DoF equations of motion describing the aircraft states and governing the translational movements along the longitudinal, lateral and vertical axes are:

\[
\frac{d\phi}{dt} = \frac{V \cos \gamma \sin \chi + V W \phi}{R_M + h}
\]

(4)

\[
\frac{d\lambda}{dt} = \frac{V \cos \gamma \cos \chi + V W \lambda}{\cos \phi (R_H + h)}
\]

(5)

\[
\frac{dh}{dt} = V \sin \gamma + V W h
\]

(6)

\[
\frac{dv}{dt} = \frac{\Delta f}{m} - g \sin \gamma
\]

(7)

\[
\frac{dy}{dt} = \frac{g (\cos \phi - \cos \gamma)}{V}
\]

(8)

\[
\frac{d\chi}{dt} = \left( \frac{N \phi}{V} \right) \left( \frac{\sin \phi}{\cos \gamma} \right)
\]

(9)

\[
\frac{dm}{dt} = -c(P, V, h) T(P, V, h)
\]

(10)

\[
\Delta f = T(P, V, h) - D(L, V, h)
\]

(11)

The above Differential Algebraic Equations (DAEs) incorporate three control variables $u = (P, n, \phi)$ where $P$ is the engine power setting, $n$ is the load factor and $\phi$ is the bank angle. These form the inputs of the dynamic system. The seven state variables are described as $x = (m, \phi, \lambda, h, V, \gamma, \chi)$, the derivatives of which are presented in the Equations of Motion (EOM), where $m$ is the aircraft mass, $\phi$ is the geodetic latitude, $\lambda$ is the geodetic longitude, $h$
is the altitude, $V$ is the true air speed, $\gamma$ is the flight path angle, $\chi$ is the heading, $R_M$ is the meridional radius of curvature, $R_T$ is the transverse radius of curvature, $W$ is the wind velocity and $g$ is the acceleration due to gravity of the Earth. Assumptions considered are a rigid body aircraft, nil wing bending effect, rigidly mounted aircraft engine on the vehicle body, zero thrust angle, the location of the aircraft mass in the aircraft centre of gravity, varying mass only as a result of fuel consumption, no sideslip and uniform gravity. Wind effects are considered along the three translational axes of the 3-DOF EOM. The geodetic coordinate reference system used is the World Geodetic System of year 1984 (WGS 84). Error modelling is performed to determine the effects of uncertainties on the 4D trajectories generated. The random errors, which are unpredictable, are quantified to estimate the overall error associated with the position of the aircraft. The system states are modified with the addition of the stochastic term, $e(t)$ and are given by:

$$\dot{x}(t) = f[x(t), u(t), e(t), t]$$  \hspace{1cm} (12)

The errors associated with the position of the aircraft (both manned and unmanned) are dependent on the standard deviations of the ADM parameters given by:

$$\sigma_V = \sqrt{(\frac{-g \cos \gamma}{V^2})^2 \sigma_{\dot{V}}^2 + \left(\frac{U_{\text{norm}}}{m}\right)^2 \sigma \tau^2}$$  \hspace{1cm} (13)

$$\sigma_h = \sqrt{(\frac{\sin \gamma}{V^2})^2 \sigma_{\dot{V}}^2 + \sigma_{\dot{W}_h}^2 + (\frac{V \cos \gamma}{V^2})^2 \sigma \gamma^2}$$  \hspace{1cm} (14)

$$\sigma_\dot{\chi} = \sqrt{\left(\frac{-N \sin \phi}{V \cos \gamma V^2}\right)^2 \sigma_{\dot{V}}^2 + \left(\frac{N \sin \phi}{V \cos \gamma V}\right)^2 \sigma_\phi^2 + \left(\frac{-g \sin \gamma}{V^2}\right)^2 \sigma_\dot{\gamma}^2}$$  \hspace{1cm} (15)

$$\sigma_\dot{\chi} = \sqrt{\left[\frac{1}{(R_M+h)^2}\right]^2 \sigma_{\dot{W}_\phi}^2 + \left[\frac{-V \sin \gamma \sin \chi + V \dot{W}_\phi}{(R_M+h)^2}\right]^2 \sigma h^2 + \left[\frac{-V \sin \gamma \sin \chi}{(R_M+h)}\right]^2 \sigma_\gamma^2 + \left[\frac{\cos \gamma \sin \phi}{(R_M+h)}\right]^2 \sigma_\chi^2}$$  \hspace{1cm} (16)

$$\sigma_\dot{\lambda} = \sqrt{\left[\frac{\cos \gamma \cos \chi}{\cos \phi (R_T+h)^2}\right]^2 \sigma_{\dot{V}}^2 + \left[\frac{-V \cos \gamma \sin \chi}{\cos \phi (R_T+h)^2}\right]^2 \sigma \phi^2 + \left[\frac{\sin \phi \cos \phi (R_T+h)}{(\cos \phi (R_T+h))^2}\right]^2 \sigma_\chi^2 + \left[\frac{-\cos \phi (V \cos \gamma \chi + V \dot{W}_\lambda)}{(\cos \phi (R_T+h))^2}\right]^2 \sigma h^2 + \left[\frac{-V \sin \gamma \sin \chi}{\cos \phi (R_T+h)}\right]^2 \sigma_\lambda^2}$$  \hspace{1cm} (17)

$$\sigma_\dot{\lambda} = \sqrt{\left[\frac{-\cos \gamma \cos \chi}{\cos \phi (R_T+h)^2}\right]^2 \sigma_{\dot{V}}^2 + \left[\frac{-V \cos \gamma \sin \chi}{\cos \phi (R_T+h)^2}\right]^2 \sigma \phi^2 + \left[\frac{\sin \phi \cos \phi (R_T+h)}{(\cos \phi (R_T+h))^2}\right]^2 \sigma_\chi^2 + \left[\frac{-\cos \phi (V \cos \gamma \chi + V \dot{W}_\lambda)}{(\cos \phi (R_T+h))^2}\right]^2 \sigma h^2 + \left[\frac{-\cos \phi (V \cos \gamma \chi + V \dot{W}_\lambda)}{(\cos \phi (R_T+h))^2}\right]^2 \sigma_\lambda^2}$$  \hspace{1cm} (18)

Simulation Case Study

A stochastic analysis is performed to evaluate the potential impact of system uncertainties on the trajectory generation. The introduction of uncertainties on all the nominal parameters, with ranges equal to the standard deviations as provided in [17] allows transforming the EOM into stochastic differential equations that are then treated with the Monte Carlo sampling technique and solved using the deterministic optimizer for 150 samples. The absolute lateral deviation of the 4D trajectories (affected by uncertainties), with respect to the reference track are calculated for all flight phases. Considering these results, the two-sigma confidence region, corresponding to 1.85 NM for the simulation case, falls well inside the RNP requirements. This holds true also for the cruise phase and for the descent phase case study (including stochastic wind), in which the performances obtained are within the RNP threshold values. Table 4 summarises the performance values obtained for various flight phases considered in our research with the RNP threshold values defined by ICAO.
<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Performance Obtained [NM]</th>
<th>RNP Threshold [NM]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climb</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>Cruise</td>
<td>3.2</td>
<td>4</td>
</tr>
<tr>
<td>Descent</td>
<td>1.6</td>
<td>2 / 1</td>
</tr>
</tbody>
</table>

### Conclusion

The Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM) and Avionics (CNS+A) systems performance parameters for improving safety and integrity were identified. Based on the elicited requirements, mathematical models were developed for estimation of the performance parameters, which are then implemented as software modules in the NG-FMS software. Future research will explore the potential of Avionics Based Integrity Augmentation (ABIA) to enhance the operation of NG-FMS in a Performance Based Operations (PBO) environment [24-27]. Data driven architectures and networked System of Systems (SoS) concepts for implementing the NG-MMS are also currently explored. Improved stochastic analysis using additional error distributions and propagation models are envisaged. Additionally, data link bandwidth requirements in high density air traffic scenarios would be considered, including the associated trajectory data descriptors and negotiation/validation protocols.

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