# Challenge Problem Overview for the Certification by Analysis Uncertainty Quantification Discussion Group

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**Aircraft Certification by Analysis is a broad term that describes the process by which engineering analysis tools are used to supplement flight testing to demonstrate compliance with regulatory requirements. For each requirement that is to be met through this process, the analysis tools must be sufficiently accurate to ensure that an equivalent level of safety is obtained as if the aircraft to be certified had been flight tested for the requirement. In recent decades, the ability of analysis tools to accurately predict aircraft performance has improved dramatically, leading to increasing interest and limited early adoption of Certification by Analysis across the aerospace industry. However, rigorously demonstrating the credibility of analysis tools remains a challenge for many types of certification requirements, yet is necessary for widespread adoption of Certification by Analysis approaches in the future. The field of uncertainty quantification is well-suited to address this problem, but will require substantial advances in order to achieve the ambitious industry goals for Certification by Analysis. The objective of this paper is to introduce a Challenge Problem focusing on a relevant Certification by Analysis task including uncertainty quantification. In particular, an antenna radome is added to the upper fuselage surface of the NASA Common Research Model, and participants in the Challenge Problem are requested to develop verification, validation, and uncertainty quantification frameworks to assess how the design complies to certification regulations. Specific details regarding the geometry, computational fluid dynamics, structural analysis, and sources of uncertainty are discussed throughout this paper. Challenge Problem deliverables and logistics are also discussed.**

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# I. Introduction

As of today, aircraft certification, no matter if for minor modifications or completely new parts or designs, is fundamentally built upon physical testing. The ambition of Certification by Analysis (CbA) is to selectively reduce the amount of certification flight or structural testing required for new aircraft by supplementing it with analysis-based results, while maintaining an equivalent level of safety as if a flight test had been performed [1]. This goal, if achieved, will enable faster time-to-market, reduced development costs, and more innovative designs, which will in turn lead to higher-quality aircraft for the airlines and a better overall experience for the flying public. CbA is fundamentally built upon flight modeling, which is a term that covers a variety of methods, including analyses based on wind tunnel results, numerical methods such as Computational Fluid Dynamics (CFD), Computational Structural Mechanics (CSM), and Computational Aeroelasticity (CA), as well as Flight Dynamics Simulation (FDS).

The idea of reducing physical testing through the usage of analysis methods is neither new nor limited to aircraft certification. In fact, various activities are ongoing in different industries with the same or similar ambitions, even if the naming convention differs [2, 3]. One example is the nuclear industry, where certification is already commonly done by analysis, due to the high risks and costs associated with testing [2]. Simulation in general is not new to the aerospace industry, and in fact contributes significantly to every modern aircraft program throughout the design cycle, using tools from many disciplines at varying levels of fidelity. Within recent years, increased performance and availability of computational resources combined with the development of sophisticated simulation tools has increased the desire and plausibility of using simulations more rigorously during aircraft certification.

In 2021 the AIAA published the *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, in which a set of practices are outlined when flight modeling is being developed, proposed, and used to reduce flight testing relative to established aircraft certification practices [1]. The field of uncertainty quantification (UQ) has been identified as being crucial to achieve the CbA goals, but is not as far developed as necessary. Hence, significant advances in the field of UQ and its integration with aerospace models and processes are needed to achieve the ambitious goals of CbA. This has initially been acknowledged within the Recommended Practice [1] as well as the NASA Guide on CbA [4], in which an explicit UQ technology development track is present. In 2024, a position paper [5] was published by Boeing, DLR, NASA, and Airbus that highlights programmatic shortcomings and technical impediments that need to be addressed. These challenges are sorted into four main categories below:

- Mindset & Awareness
- Tools & Capabilities
- Data and Benchmarks for Verification & Validation (V&V)
- Applied Research & Established Processes

The position paper was accompanied by a panel discussion during the AIAA SciTech 2024 conference with representatives from industry, government, and academia. One of the key points highlighted in the position paper as well as during the panel discussion is the need for an industrial relevant CbA Challenge Problem that can be leveraged to further advance the CbA and UQ state-of-the-art. Additional background on the challenges and opportunities for CbA is included in Appendix Appendix A.

The purpose of this paper is to introduce a multi-disciplinary CbA Challenge Problem with elements of V&V and UQ that are relevant to industrial aircraft certification applications. The problem is based on the addition of an antenna fairing to the upper surface of the fuselage of an existing configuration; specifically, the NASA Common Research Model (CRM) [6] is used as the baseline aircraft geometry. First, the goals of the AIAA Certification by Analysis Community of Interest (CoI) are stated in Section II, followed by the envisioned high-level deliverables from Challenge Problem participants in Section III. Afterwards, a thorough discussion of the Challenge Problem details is made in Section IV, including an overview of certification requirements that have to be fulfilled to obtain certification for such an alteration to an existing configuration. Details on geometry, flight envelope, aerodynamic modeling, and structural modeling are also provided. An introduction to many CbA-relevant sources of uncertainty is given in Section V, along with some discussion on their relevance for the Challenge Problem. The logistics and timeline for the Challenge Problem are described in Section VI, and finally the paper concludes with a short summary in Section VII.

## II. Goals of the CbA CoI

The goal of the AIAA CbA CoI is for the aerospace community to develop V&V and UQ frameworks applicable to CbA. This will involve an understanding of (1) multi-disciplinary sources of uncertainty; (2) how those sources are categorized and quantified; (3) how to propagate heterogeneous sources of uncertainty; and (4) what the impacts of the relevant uncertainties are for the purposes of demonstrating compliance to aircraft certification regulations. In order to execute this goal, the CbA CoI organizing team is issuing a Challenge Problem for which participants will be required to address each aspect above.

The CbA CoI organizing team recognizes that large antenna installations have been certified by analysis since the early 2000s. However, previous Airbus A330-200 series [7] and Boeing 737-8 series [8] examples focused on CFD analysis only and did not contain a multidisciplinary component, such as the inclusion of structures. In general, bird strike, vibration, thermal effects, and fail-safe conditions are critical for the antenna assembly design – not the aerodynamic loads to be considered by participants of the Challenge Problem described herein. The structures aspect of the Challenge Problem is purely academic because there are already approved Methods of Compliance (MOCs) that support CbA for antenna installations. Nevertheless, the V&V and UQ frameworks that Challenge Problem participants will necessarily define and exercise in their submissions are expected to be applicable to future certification applications which do not currently have approved CbA MOCs.

## III. Expected Deliverables from Participants

Participants in the CbA CoI Challenge Problem are expected to deliver the following artifacts, either in a conference paper or in another appropriate form at the AIAA SciTech 2027 conference in January 2027:

1. An assessment of structural margin for the antenna radome mounting structure (pin connections) computed for the range of operational conditions and relevant structural failure criteria, and including an estimate of total uncertainty based on the sources of uncertainty described in Section V. Details on each of the involved disciplines are provided in Section IV. The assessment will involve the calculation of the following:

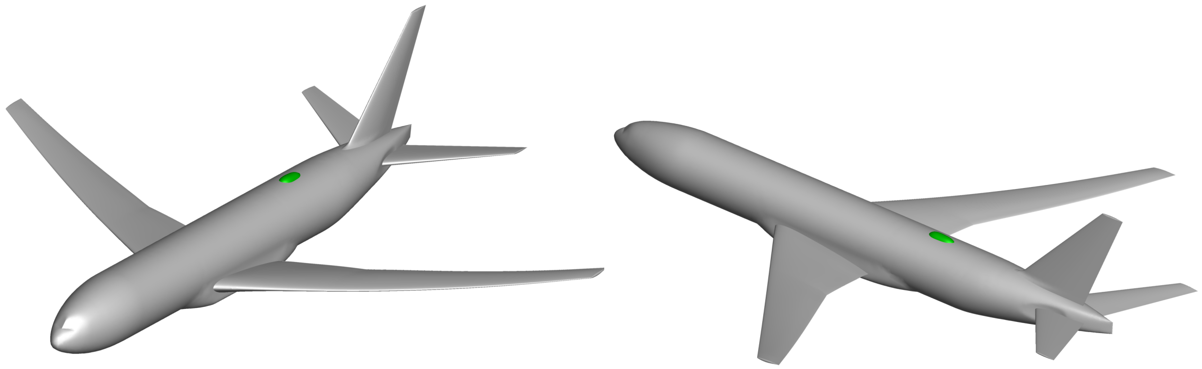
   (i) External aerodynamic pressures on the radome for a range of operating conditions
   (ii) Associated structural attachments loads
   (iii) Structural reserve factors for the relevant failure modes, including a check against requirements

   These tasks can be performed using either a simplified or detailed structural model, as described in Section D; participants should report their chosen structural model in their submissions.

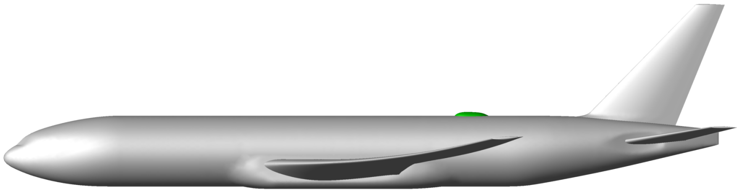
2. A detailed description of the V&V and UQ framework that was employed to facilitate the calculations required for the item above, including all assumptions, advantages, and identified limitations of the framework for all steps involved.

As stated in Section II, the main goal of this Challenge Problem is the development of V&V and UQ frameworks applicable to CbA. Therefore, participants are encouraged to provide as much detail as possible in their delivery of item 2. The CbA CoI organizing team envisions that high-level flowcharts may be an effective way to describe V&V and UQ frameworks, coupled with text descriptions of each component within the process. Solutions to the Challenge Problem will necessarily require some level of pragmatism and engineering judgment, so a potential exercise at SciTech 2027 and beyond could be to compare different participants' approaches to overcoming limitations in data, physical modeling, computational cost, etc.

For the purposes of the Challenge Problem the final expected analysis deliverable will be the quantified confidence of meeting the identified certification requirements. It is recognized that for an industrial application of an overall V&V and UQ framework a key required element will be the quantification of the acceptable levels of confidence required to demonstrate certification compliance and achieve an equivalent level of safety. This is out of the scope for this Challenge Problem as it will require significant further alignment and discussion with the certification authorities. However, the results from this Challenge Problem are seen as an important step towards establishing a common understanding and framework for the future exploitation of UQ for certification by analysis. Nevertheless, participants are encouraged to share their thoughts and recommendations on the future challenges towards full exploitation. Especially the point of potentials for further reducing the amount of testing data needed should be mentioned in this regard.



(a) Front isometric view. (b) Rear isometric view.



(c) Side view.

**Fig. 1. Graphical representation of the NASA CRM with VTP and with a notional antenna radome shown in green.**

## IV. Detailed Challenge Problem Description

As described by Vassberg et al. [9], the NASA Common Research Model (CRM) is based on a transonic civil transport configuration designed to fly at a cruise Mach number of 0.85 with a nominal lift coefficient of 0.5. The wing has an aspect ratio of $AR = 9.0$ and taper ratio of $\lambda = 0.275$. Various configurations of the CRM have been studied extensively in the AIAA Drag Prediction Workshop (DPW) Series [10, 11], as well as in the AIAA High-lift Prediction Workshop (HLPW) Series [12, 13]. Given its intentional similarity to real commercial aircraft, broad community interest, and extensive past and future wind tunnel test campaigns, the CRM is an excellent choice as the starting point for an AIAA CbA Challenge Problem.

To this end, the CbA Challenge Problem will assume that the NASA CRM represents an existing in-service aircraft, and that an Original Equipment Manufacturer (OEM) wishes to create a variant of the CRM which has an antenna radome added to the upper fuselage. The idea of an antenna radome addition to a previously-certified aircraft was previously been suggested as a CbA use case in the aforementioned AIAA Recommended Practice [1] and NASA Guide on CbA [4]. A graphical depiction of an antenna on the CRM is included in Fig. 1.

The addition of an antenna radome to the upper fuselage of an aircraft requires compliance to many regulatory requirements. A sample of relevant U.S. Federal Aviation Administration (FAA) regulations is included in Table 1. This list contains elements of 14 CFR Part 25 Subparts B (Flight) and C (Structure), and is not exhaustive. An equivalent set of regulations is also provided from the European Union Aviation Safety Agency (EASA). It would be infeasible for an AIAA community Challenge Problem to request that participants demonstrate compliance of a radome addition to each of these regulations; instead, the focus of the CbA Challenge Problem will be limited to the prediction and compliance demonstrations of steady-state aerodynamic loading and its impact on the structural integrity of the radome addition and surrounding structure. This scope most closely aligns with the regulations described in §25.301(b) and §25.321, which are available on the U.S. Code of Federal Regulations website [14].

Challenge Problem participants will be provided with geometry for a NASA CRM configuration with and without the addition of the antenna radome. They will also be provided with specific 14 CFR Part 25 regulations and will be tasked to determine – using engineering analysis tools – whether or not the addition of the radome would result in a successful or unsuccessful passing of the regulations according to technical metrics contained therein. Simulations using CFD and CSM at multiple flight conditions will likely be

**Table 1. Sampling of FAA 14 CFR/EASA CS regulations relevant to the addition of an antenna radome to an aircraft.**

| Part | Subpart | Paragraph(s) | Description |
|---|---|---|---|
| 25 | B | 25.251(b)(d) | Vibration and buffeting |
| 25 | B | 25 25.253 | High-speed characteristics |
| 25 | C | 25.301(a)(b) | Loads (cover paragraph for validated aircraft model) |
| 25 | C | 25.305(a)(e) | Strength and deformation (buffeting Loads) |
| 25 | C | 25.307(a) | Proof of structure |
| 25 | C | 25.321 | Flight loads |
| 25 | C | 25.365(e) | Pressurized compartment loads |
| 25 | C | 25.471 | Ground loads |
| 25 | C | 25.571(a)(b)(e) | Fatigue and damage tolerance, bird strike |
| 25 | C | 25.629 | Aeroelastic stability |

required, including simulations at dive Mach speed and both zero and non-zero angle of sideslip. In order to make a pass/fail determination, participants will need to establish the Predictive Capability of their analysis tools, which is formally defined as [15, 16]:

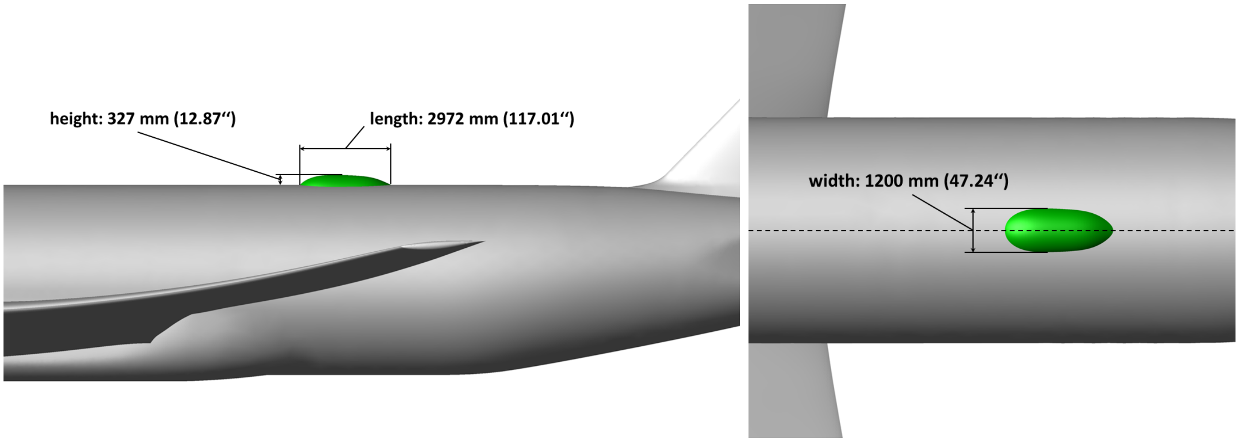
> *Predictive Capability:* The use of a computational model to fortell the state of a physical system, including relevant uncertainties, under conditions for which the computational model has not been validated.

Predictive Capability necessitates the use of concepts from V&V and UQ. It is a fundamental component of successful CbA endeavors by OEMs because the "conditions for which the computational model has not been validated" will be the flight conditions for which CbA efforts wish to reduce or replace flight test with computational model results.

Lastly, an important aspect of any community Challenge Problem is that it simultaneously be (1) achievable by Challenge Problem participants without extraordinary effort and (2) relevant to technical shortcomings that the aerospace community recognizes need to be solved. The AIAA CbA CoI organizing team believes that certification-focused engineering simulations of an antenna addition to the CRM will meet both of the objectives. The likely government, academic, and industry participants in the problem have already established some V&V and UQ processes for CFD and CSM tools, but more work is needed to integrate these approaches into a rigorous V&V and UQ framework with a focus on Predictive Capability for CbA. The proposed problem also addresses some of the key challenges described in the AIAA CbA UQ Position Paper [5], including an emphasis on applied research and a multi-disciplinary UQ component (fluids + structures). Moreover, the organizing team believes that by leveraging the existing NASA CRM ecosystem, the aerospace community will rally around this problem with huge importance to the future of CbA.

### A. Geometry Overview

As shown in Fig. 1 and as stated in Section IV the reference aircraft geometry to be used in this Challenge Problem is the NASA CRM geometry, including a vertical tailplane as provided by the French aerospace lab ONERA [17]. The geometry of the antenna radome is deliberately held generic, but still representative in shape and size for typical products found on commercial airliners today. As shown in Fig. 2 the radome features a height of 327 mm (12.87"), a length of 2972 mm (117.01"), and a width of 1200 mm (47.24"). In real applications these radomes are typically mounted either upstream or downstream of the wing root. The radome in this geometry is positioned downstream of it. The reader shall be reminded here that the objective in defining and modeling the geometry did not consist in reverse-engineering an existing radome shape as closely as possible, e.g. to compute performance data. Instead, a representative, but at the same time sufficiently generic geometry shall be provided as a CbA-related test case for the novel V&V and UQ frameworks to be developed in support of the Challenge Problem.



(a) Side view details. (b) Top view details.

**Fig. 2. Closeup views of the notional antenna radome shown in green mounted on the upper fuselage of the NASA CRM.**

**Table 2. Flight conditions where analysis is to be performed.**

| Group | Case | Altitude [FL] | Mach | EAS [kt] | Q [N/m$^2$] | $C_L$ | $n_z$ | $\beta$ [deg] |
|---|---|---|---|---|---|---|---|---|
| 1 | MCR | 350 | 0.85 | 273.1 | 12092 | 0.4 to 0.6<br>($\Delta C_L = 0.05$) | 0.8 to 1.2 | 0 |
| 2 | MCR | 350 | 0.85 | 273.1 | 12092 | 0.5 | 1.0 | 0 to 5<br>($\Delta\beta = 1$) |
| 3 | MMO | 350 | 0.89 | 286.0 | 13257 | 0.46 | 1.0 | 0 |
| 4 | VD | 0 | 0.56 | 370.0 | 22191 | 0.0 | 0.0 | 0 |
| 5 | VD | 0 | 0.56 | 370.0 | 22191 | 0.27 | 1.0 | 0 |
| 6 | VD | 0 | 0.56 | 370.0 | 22191 | 0.68 | 2.5 | 0 |
| 7 | VD | 0 | 0.56 | 370.0 | 22191 | 0.27 | 1.0 | 0 to 5<br>($\Delta\beta = 1$) |
| 8 | MD | 300 | 0.96 | 346.0 | 19411 | 0.31 | 1.0 | 0 |

MCR: Cruise Mach number
MMO: Maximum operating Mach number
VD/MD: Dive Speed / Mach number

## B. Flight Envelope

In the frame of this Challenge Problem the antenna radome mounted on the CRM as described in subsection A shall be analyzed for a set of flight conditions (see Table 2). There are two cases at nominal cruise conditions covering both effects of angle of attack and sideslip angle. Case 3 covers the effect of increasing the speed at level flight up to the maximum operation Mach number. Cases 4 to 7 are introduced to cover maximum speed and therefore maximum dynamic pressure, varying nz from 0 to 2.5 and assessing the effect of sideslip. The last case is located at the VD/MD corner, i.e., maximum speed and dynamic pressure while at the same time achieving the maximum Mach number. The conditions have been selected to cover relevant parts of the flight envelope. They are however not an exhaustive list of cases that might be required for the certification of an antenna radome on a real aircraft.

## C. CFD Problem Details

Appropriate methods have to be chosen by each applicant to compute the aerodynamic loads on the radome at the flight conditions specified in Table 2. Such methods need to be able to capture the relevant physical effects in transonic flow. Some guidance can be found in the AIAA Recommended Practice document [1] where it is stated that

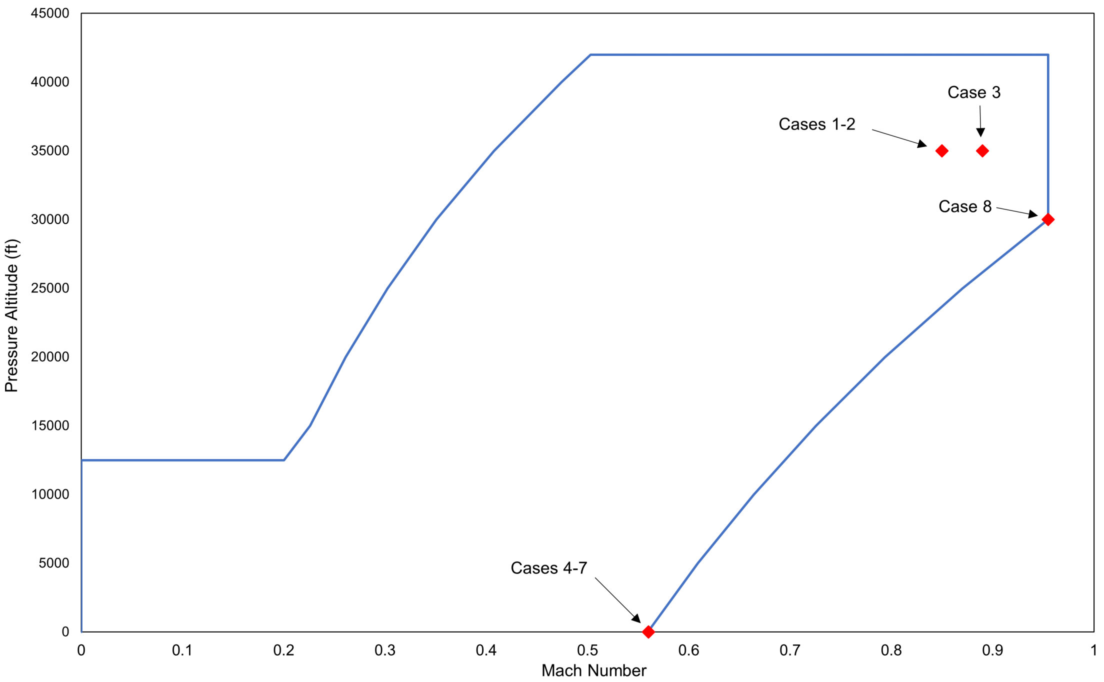


**Fig. 3. Flight envelope with selected cases for analysis.**

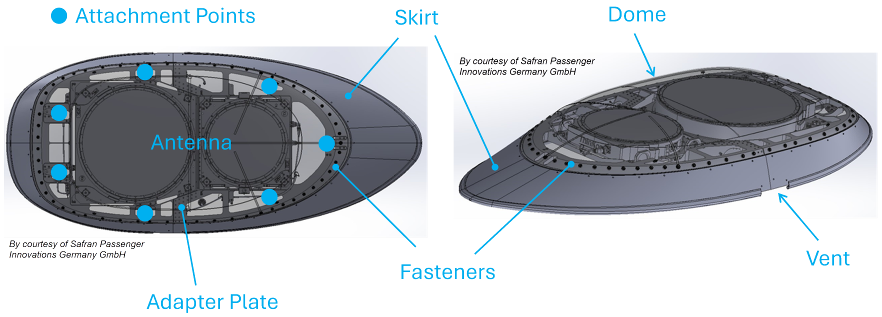
> *EASA and the FAA have accepted CFD analyses as an acceptable means to show that the addition of a radome on the fuselage of a previously certified airplane would not affect the original compliance demonstration for CS/14 CFR 25.251(b).*

Further insight on the "appropriateness" of CFD tools for this specific regulation for a generic radome installation can be found in an Equivalent Safety Finding and Interpretive Material proposed by EASA [18], where it is stated that "*...a full Navier-Stokes code with robust turbulence modelling is needed for such an analysis.*" It needs to be kept in mind, though, that this wording is addressing §25.251(b) only, for which the applied CFD method must be able to identify potential sources of vibration arising from shocks, flow separation or other unsteadiness in the flow. Although the task in this CbA Challenge Problem is slightly different, focusing more on determining the aerodynamic loads as an input to subsequent structural analyses for showing compliance with §25.301(b) and §25.321 instead of assessing the flow field in detail as required by §25.251(b), participants are nonetheless expected to utilize computational codes based on solving the Reynolds-Averaged Navier-Stokes equations. Steady simulations, assuming a rigid radome geometry, are considered sufficient. A potential CFD approach could therefore look like this:

- Based on the provided Computer-Aided Design (CAD) geometry: generate CFD meshes with the tool of your choice following best practices for meshing
- Run steady CFD computations with the method of your choice and your best practices w.r.t. numerical settings and turbulence model, while assuming a rigid geometry
- Determine the aerodynamic loads on the radome for all conditions specified in Table 2 and proceed with structural analysis.

## D. Structural Problem Details

Structural certification of an antenna radome on an airplane involves many regulations as pointed out in PS-AIR-25-17 [19], and also the consideration of several different loading conditions with various underlying sources. An example of a critical load case that usually ends up sizing the antenna radome is a bird strike event, which induces large dynamic loads on the structure. However, for the present Challenge Problem the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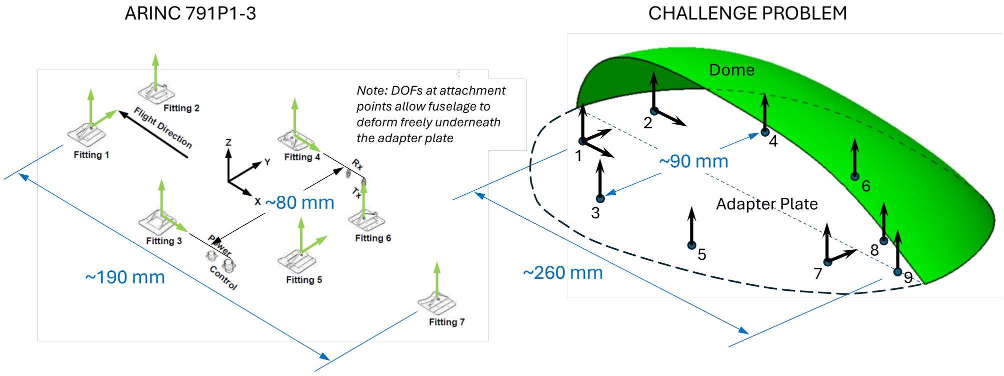
By courtesy of Safran Passenger Innovations Germany GmbH

**Fig. 4. Example of an antenna radome and its individual parts**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*Note: DOFs at attachment points allow fuselage to deform freely underneath the adapter plate*

**Fig. 5. Attachment interface between the adapter plate and fuselage.**

scope is limited to aerodynamic loads, in particular resulting from the flight conditions shown in Table 2. Also, the certification aspects will be limited to certain details of the alteration project associated with the addition of the antenna radome.

Delving into structural aspects of an antenna radome and its installation on a fuselage requires an examination of its anatomy first. Typically, an antenna radome structural assembly consists of two main parts: the dome (or radome), which is the aerodynamic fairing that protects the antenna equipment from the environment, and the adapter plate (which is often actually a frame) with provisions for mounting antenna equipment. The dome attaches to the adapter plate via removable fasteners; the adapter plate transfers the dome loads to the fuselage through several discrete interface points. The dome is typically fabricated from a quartz fiber laminate due to favorable dielectric properties required for an optimal functioning of the antenna, while a high-strength aluminum alloy (such as a 7000-series) is used for the adapter plate. An example of an antenna radome with its constituent parts is shown in Fig. 4.

The attachment to the fuselage is generally in the form of pin joints (lug and clevis configuration, where the lug is on the fuselage and the clevis on the adapter plate), enabling a relatively easy installation process. Strength calculation methods for these types of joints are available from a variety of publicly available sources (e.g., Refs. [20, 21, 22, 23, 24]). Each individual interface point is carefully designed to react loads only in certain directions to allow free deformation of the underneath fuselage without being restricted by the antenna assembly (Fig. 5). An example plus more detailed description of the interfaces can be found in Attachment 1 of the ARINC 791P1-3 standard [25].* Note that addition of lugs to the airplane requires some level of modification to the local crown structure of the fuselage, such as the addition of intercostals to align with interface points, and reinforcements to frames and skin in order to mitigate the cut-outs for wire routing and the increased loading because of the antenna radome installation.

The goal of employing CbA in the context of the current Challenge Problem may be formulated as follows: develop a simulation of the structural failure of an antenna radome installation on the fuselage of a commercial airplane which has demonstrated credibility to be accepted as a means of showing compliance

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*This standard is also showing a total of seven attachment points; due to the Challenge Problem antenna radome being larger, a total of nine attachments points will be adopted as shown in Fig. 5.

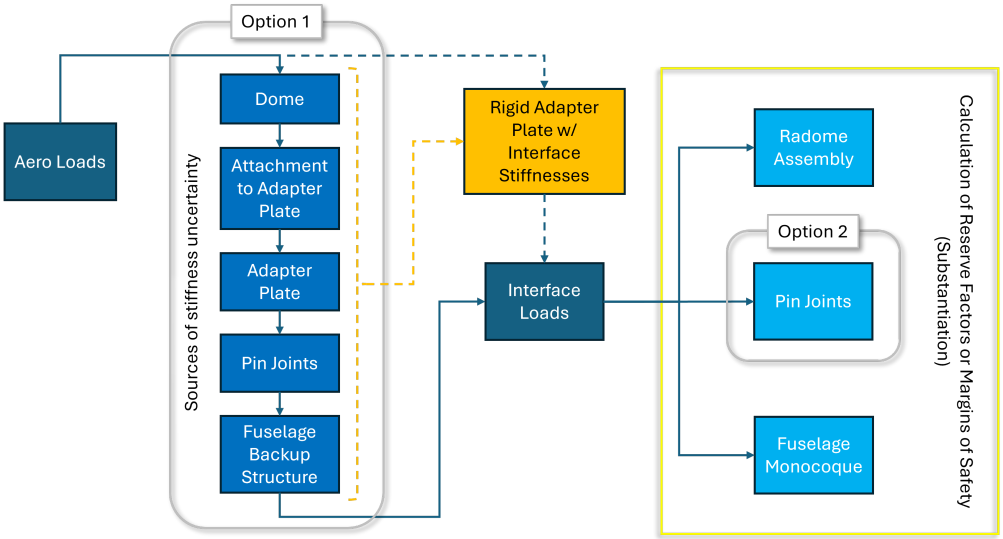

**Fig. 6. Path from load application to structural substantiation of radome assembly, fuselage interfaces, and local fuselage monocoque structure. Also illustrated are the domains for Options 1 and 2 defined for the Challenge Problem.**

with the relevant airworthiness regulations. Essential to this effort is following a rigorous, structured, and risk-informed process that results in demonstrating credible simulations (where credibility is in the eye of the certification authority). Such a process may be referred to as a Credibility Assurance Framework (CAF). There are currently two standards in work (that the authors are aware of) which intend to provide a CAF for CbA of aerospace structures specifically: one is a proposed Certification Memorandum by EASA [26] (which is accessible from the EASA website), the other by the ASME VVUQ-90 subcommittee (scheduled to be published in the near future). Characteristic for a CAF for structures CbA is the utilization of a so-called testing & analysis pyramid, which constitutes a bottom-up, hierarchical building block approach where model V&V and UQ starts at a small scale (e.g., coupon level) and gradually progresses towards larger scale testing domains (e.g, coupon → part → component → (sub-)assembly → full-scale).

The flow chart in Fig. 6 depicts the path followed by the aerodynamic loading before being "absorbed" by the fuselage. Air flow around the radome manifests itself as a pressure distribution exerting forces and moments on the dome, which are then transferred to the adapter plate via the fastener connection. Once in the adapter plate, the loads are distributed to the individual interface points, which subsequently discharge them into the fuselage backup structure through the pin connections. Each of these elements on the path of the applied loading has a certain stiffness – with associated uncertainties – which affects the distribution of the reaction forces at the attachment points. Once the interface loads are known, a static equilibrium exists allowing for the strength substantiation (i.e., calculation of *reserve factors* or *margins of safety*[†]) of the pin connections, the fuselage backup structure, and the antenna radome assembly itself.

For the structural aspects of the current Challenge Problem, participants can choose between the following two options, each focusing the V&V and UQ activities on a different aspect and with a different level of effort:

- **Option 1** focuses the V&V and UQ activity on the various contributions to the total stiffness of the antenna radome assembly structural system and its boundary conditions, with the goal of developing the interface loads—with quantified uncertainty—at the nine discrete attachment points. This effort requires a detailed FEM model of the antenna radome assembly (such as shown in Fig. 7b), featuring the main elements (radome; attachment of radome to adapter plate; adapter plate; attachment of adapter plate to fuselage; and fuselage backup structure) as defined in Fig. 4. UQ will have to be performed on each of these five total stiffness contributors but note that each individual one is actually a collection of several lower-level uncertainties. Concerning the applied loading, this option requires the mapping of the CFD pressures onto the FEM representation of the dome. When obtained from a credible simulation, the interface loads may be deemed compliant with 14 CFR §25.301(a) by the

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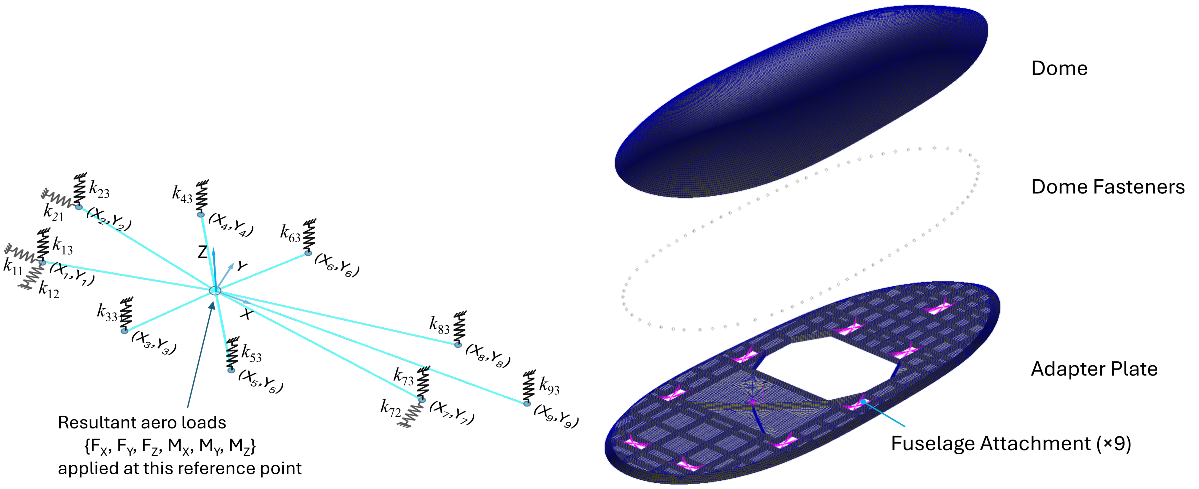
[†] The reserve factor is the ratio of strength to operating load or stress, and must be $\geq 1$; the margin of safety is equivalent, but subtracts one from this ratio (i.e., margin of safety = reserve factor - 1) and must therefore be $\geq 0$.



(a) Simple model.

(b) Detailed FEM model.

**Fig. 7. Structural models associated with Options 1 & 2 of the Challenge Problem (detailed FEM and simple model, respectively).**

airworthiness authorities and can be consumed as limit loads by downstream analysis for the further substantiation of structure affected by the antenna radome installation. For the current Challenge Problem, participants are asked to calculate reserve factors based on the interface loads and an established pin joint analysis method, supporting a showing of compliance to 14 CFR/CS 25.301(a)(b), 25.303, 25.305(a)(e), 25.307(a), 25.619, and 25.625.

- **Option 2** calls for the development of a credible analysis method or simulation to establish reserve factors for the lug-pin-clevis connections.[‡] In this case, the focus of the V&V and UQ activity is on predicting structural strength (or an *allowable*) with an associated quantified uncertainty. Fig. 8 provides a sketch of a typical lug and clevis joint and the uncertainties that are involved in the strength calculation. The interface loads required to compute reserve factors are obtained from a simple structural model which features a rigid adapter plate attached to grounded, linear springs located at the interface points, representing the stiffness (and associated uncertainties) of the antenna radome assembly and fuselage backup structure (Fig. 7a). The aerodynamic load resultants with their uncertainties (obtained from CFD analysis) are specified at some reference point and are from there on distributed to the individual attachment points via the stiffness matrix of the structural model. The result is a set of interface loads with quantified uncertainty which can then be used as limit loads in conjunction with the calculated pin joint strength values to show compliance to 14 CFR/CS 25.301(a)(b), 25.303, 25.305(a)(e), 25.307(a), 25.619, and 25.625.

The premise for Option 2 is that the stiffness of the antenna radome assembly (with uncertainties) is accurately represented by the spring elements. It essentially bypasses the work required for Option 1 and treats the antenna radome assembly system as a black box. For the purpose of the Challenge Problem, values of the stiffnesses $k_{\mathrm{ij}}$ in Fig. 7a – including the uncertainties – and the stiffness matrix will be provided to the participants. Furthermore, a detailed FEM model for Option 1 will be made available for download. (located on NASA website). Participants are encouraged to follow the guidance in the proposed EASA standard [26] for their VVUQ activities related to the structural aspects of the Challenge Problem.

## E. Reference Data

One of the most important sources of uncertainty for CbA is model form uncertainty. This type of uncertainty arises when the equations being solved by a computational code (e.g., Reynolds-Averaged Navier-Stokes, Linear Elastic Models, etc.) do not match the true physical reality of the system being simulated – that is,

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[‡] Typically, OEMs will have their own validated pin joint analysis methods which address uncertainty by being reliably conservative and, therefore, would not try to perform simulations of these types of joints.

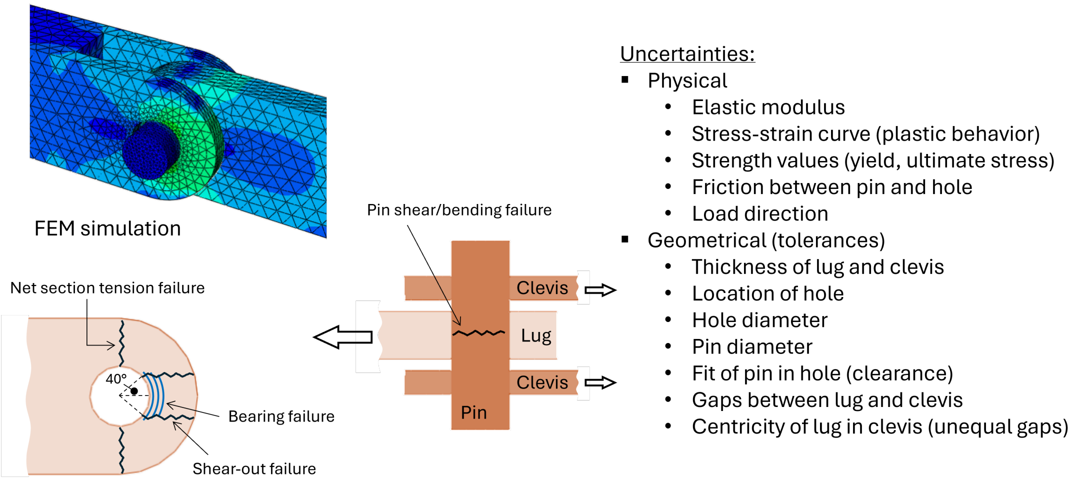

**Fig. 8. Pin joint (lug-clevis) geometry and associated uncertainties in determining a strength value (for Option 2).**

the mathematical form of the model is incorrect with respect to reality. The field of Validation attempts to quantify model form uncertainty; however, an important aspect of Validation is that it requires a comparison between computational results and some physical reference data.

For the purposes of the CbA Challenge Problem, there are three types of reference data that participants are encouraged to employ:

1. Data already available to participants through their organizations' own wind tunnel testing, structural testing, flight testing, or other internal experiments

2. Externally available data from AIAA or other activities such as the AIAA Drag Prediction Workshop (DPW) [10], AIAA High-Lift Prediction Workshop (HLPW) [13], Boeing Speed Bump [27], Virginia Tech Benchmark Validation Experiments for RANS and LES Investigations (BeVERLI Hill) [28], etc. A large amount of publicly available wind tunnel data for the NASA CRM is available, including surface pressure data for a range of conditions [6]. While these measurements are for the baseline aircraft, the data remain a useful reference for this exercise.

3. New wind tunnel, flight test, and/or structures test data to be generated specifically for the purposes of the CbA Challenge Problem

The AIAA CbA CoI organizing team is investigating avenues for the collection of reference data specifically for the CbA Challenge Problem, but at the time of this writing no firm commitments have been made. Challenge Problem participants will be made aware of developments in this area in future CbA CoI communications.

## V. Sources of Uncertainty

Uncertainties are an inherent part of every engineering analysis and managing them efficiently at the needed level of accuracy has been identified as a key consideration for a more widespread adoption of Certification by Analysis. Therefore, sources of uncertainty form a core component of the Challenge Problem proposed herein. This section will first outline potential sources of uncertainties for the previously introduced antenna radome case with a focus on the §25.301 and §25.321 regulations. Afterwards, a down-selection is performed which includes a detailed description of uncertainties that the CbA CoI organizing team believes should be accounted for when working on the Challenge Problem. Moreover, reasoning is provided for omitting other sources of uncertainties.

Table 3 lists various sources of uncertainty that the organizing team identified as possible considerations for the proposed antenna radome test case, with the specific focus on the §25.301 and §25.321 regulations. These uncertainties are grouped based on respective disciplines or modeling steps, such as geometry or structural modeling. Moreover, they span across all well-established uncertainty categories, e.g. parametric input uncertainties (No. 1, 2, 4, 6-8, 15), model form uncertainties (No. 3, 5, 10, 16, 17), and numerical

**Table 3. List of sources of uncertainties for the CbA benchmark problem with focus on the §25.301 and §25.321 regulations. If they should be accounted for in the participants analysis is indicated in the Challenge Problem column.**

| No. | Source of Uncertainty | Challenge Problem |
|---|---|---|
| | *Geometry Modeling* | |
| 1 | Difference between as-designed and as-built geometry | No |
| 2 | Omission of geometrical details, e.g. brackets, linkages, etc. | No |
| | *Aerodynamic Modeling* | |
| 3 | Mismatch between numerical results and physical reality (model form uncertainty) | Yes |
| 4 | Variations in freestream boundary conditions | No |
| | *Structural Modeling* | |
| 5 | Mismatch between numerical results and physical reality (model form uncertainty) | Yes |
| 6 | Internal pressure of the antenna radome | Yes |
| 7 | Variations in material properties, joint stiffnesses, and dimensions (e.g., manufacturing tolerances) | Yes |
| 8 | Differences between numerical and physical constraints | No |
| | *Coupling of Disciplines* | |
| 9 | Interpolation error when passing pressures between the disciplines with different discretizations | Yes |
| 10 | Validity of the employed coupling mechanism between aerodynamics and structure, i.e. accounting for aeroelastic couplings | No |
| 11 | Finite precision error when passing pressures between the disciplines | No |
| | *Numerical Approaches and Settings* | |
| 12 | Discretization error present in numerical solutions | No |
| 13 | Iterative convergence error in numerical solutions | No |
| 14 | Finite precision arithmetic of numerical solver | No |
| 15 | Selection of smoothing parameters, limiter thresholds, and other tunable solver parameters | No |
| | *Process-related* | |
| 16 | Uncertainty in referent data used for the computation of model form error | Yes |
| 17 | Performing model form error estimation for one flow type, e.g. flow over a simplified bump, but needing to assess predictive capability for another, e.g. flow over a bump on an aircraft | Yes |
| 18 | Surrogate model error if a surrogate model is used | Yes |
| 19 | Usage of a finite number of samples in uncertainty propagation | Yes |
| 20 | Interpolation / extrapolation error of model form uncertainty through flight envelope | Yes |
| 21 | Sampling error due to performing numerical simulations only at a fixed number of flight points | No |

errors (No. 9, 11-14, 18-21). Even though this is already an extensive selection, there is a possibility that one or more uncertainty sources have been overlooked; Challenge Problem participants are encouraged to bring such sources of uncertainty forward in their submissions. So-called "unknown-unknowns" and low-probability events (e.g. bird strike) have not been included in the list of uncertainty sources as they are typically accounted for by safety factors. Furthermore, including these sources more explicitly in simulation-based approaches may be impossible or computationally infeasible, so real certification applications might address them using physical testing and not engineering analysis.

The CbA CoI organizing team has identified a subset of uncertainties sources that are deemed of particular relevance for the antenna radome case. These are marked with a *Yes* in the *Challenge Problem* column of Table 3. Both aerodynamic and structural model form uncertainties (No. 3 and 5) are at the heart of the Challenge Problem. Aerodynamic reference data will be provided (see Section E) and determining the aerodynamic model form uncertainty with an appropriate methodology is part of each participant's responsibilities. Note that uncertainties in the reference data (see UQ source No. 16) should be accounted for during an estimation of model form uncertainty. For the structural model a fixed model form uncertainty will be provided for Option 2 (see Sec. D) at a later date; participants will be asked to compute their own estimates of model form uncertainty for Option 1. Given that validation data will not be available for all points of interest within the flight envelope, participants will need to interpolate/extrapolate model form uncertainties (No. 20). Moreover, participants might decide to use further reference data as detailed in Section E. If this is the case, uncertainty source No. 17 might also be relevant. With respect to the fluid-structure coupling process, the uncertainties introduced by passing results from one discretization to the other (No. 9) should be appropriately taken into consideration. If one or more surrogate models are used as part of the V&V and UQ processes, then the corresponding surrogate modeling errors (No. 18) should be reported and propagated. Moreover, reasoning should be provided if the number of samples used for uncertainty propagation is impacting the outcomes of the investigations (e.g., using a finite number of Monte Carlo samples for computational cost savings). Finally, parametric model inputs, such as variations in internal pressure of the antenna radome (No. 6) and structural stiffnesses (No. 7), should be propagated forward through the analysis. Since the internal pressure is generally unknown (or at least very difficult to establish), it has been practice to envelope the structural analysis using the minimum and maximum pressure coefficients at the vent locations (see Fig. 4) as obtained from the CFD analysis. In lieu of this enveloping procedure, participants may want to consider assuming some statistical distribution of the internal pressure based on engineering judgment. A similar argument can be made for the structural stiffness parameters (e.g., Young's modulus, joint stiffness) if validation test data is scarce or unavailable altogether. Participants should make reference to any assumptions made for the dependency of input uncertainties, assess the impacts of these assumptions, and provide any thoughts on practical approaches to better quantify the dependencies.

Besides the aforementioned sources of uncertainty that are relevant for the CbA Challenge Problem, Table 3 contains several additional sources. For some, such as No. 4, 8 and 21, acceptable means of compliance (AMC) are already in place between OEMs and certification authorities. Hence, such sources may not apply for Certification by Analysis, even if they do apply to more traditional certification using physical testing. For other sources of uncertainty (No. 11-15), established best practices exist that should be employed. Further sources of uncertainties are regarded as low-impact (No. 11 and 14) and are thus excluded from the recommended set to be addressed. Finally, the uncertainty sources No. 1, 2 and 10 have been identified as interesting by the organizing team but are deemed beyond scope for the CbA Challenge Problem. Note that Table 3 is not intended to be a one-to-one mapping of the existing AMCs but instead aims only to resemble considerations an OEM might make during the actual CbA process.

## VI. Logistics, Timeline, and other Administrative Details

The planning and execution of the CbA Challenge Problem is expected to be a multi-year effort, starting with the publication of this paper at the AIAA AVIATION conference in July 2025. A CbA CoI meeting will also be held in the evening at AVIATION 2025, offering potential participants their first chance to provide feedback on the Challenge Problem definition. By the end of December 2025, the CbA CoI organizing team expects to have identified reference data (or a plan to collect it) so that all participants will have the ability to estimate model form uncertainty. Additional community meetings will be held at the AIAA SciTech 2026 and AIAA AVIATION 2026 conferences, ultimately leading to one or more special sessions or a workshop with participant results at SciTech 2027. These milestones are included in Table 4 for reference.

**Table 4. Timeline of CbA CoI Events and Milestones.**

| Event | Date | Milestone or Agenda |
|---|---|---|
| AVIATION 2025 | July 2025 | Publish this paper, community engagement |
| Year-end 2025 | December 2025 | Identify reference data |
| SciTech 2026 | January 2026 | Community engagement |
| AVIATION 2026 | July 2026 | Community engagement |
| SciTech 2027 | January 2027 | Special session(s) or workshop with participant results |

To communicate in between the community engagements at AVIATION and SciTech, the organizing team will continue to leverage the AIAA Engage platform. AIAA Engage is a service available to all users who create an AIAA account. Useful features include discussion threads which can be used for Q&A or FAQ content, document libraries, virtual event scheduling, and more. To join the CbA CoI on Engage, navigate to `https://engage.aiaa.org/`, log into your AIAA account, and then search for the "Certification by Analysis Uncertainty Quantification" community.

As the name suggests, AIAA Engage is useful for engagement with the organizing team and with other Challenge Problem participants. However, it is not the most useful service for sharing the size and quantity of files that are typically required to run other AIAA workshops such as the previously mentioned DPW and HLPW series. To this end, the organizing team has established the website `https://aiaa-uq4cba.larc.nasa.gov/`, which may be used for sharing geometry, reference data, meeting information, participant submission forms, and more.

## VII. Summary

Certification by Analysis generally describes the process during which simulation tools used to supplement flight testing to demonstrate compliance with regulatory requirements and ensure a equivalent level of safety. In the past few years the field of uncertainty quantification has specifically been identified as a key enabler for a more widespread adoption of Certification by Analysis. However, a list of programmatic shortcomings and technical impediments hindering the more usage of uncertainty quantification exists, as has been previously reported. The AIAA Certification by Analysis Community of Interest has been actively working on identifying and highlighting these challenges while simultaneously trying to overcome them. This paper introduces a Challenge Problem with the goal for participants to develop V&V and UQ frameworks applicable to Certification by Analysis. The Challenge Problem is based on the NASA CRM high-speed configuration with an antenna radome added to the upper fuselage. For the addition of such a radome, compliance with multiple government regulations must be demonstrated. However, Challenge Problem participants should focus the impact of steady-state aerodynamic loads as defined in §25.301(b) and §25.321. Participants are expected to assess structural margins accounting for uncertainties while also providing detailed descriptions of their employed V&V and UQ framework. To facilitate execution of the Challenge Problem, this paper includes details for all involved disciplines as well as for relevant sources of uncertainties. Further information and data is available on the dedicated website `https://aiaa-uq4cba.larc.nasa.gov/`. Outcomes of the Challenge Problem are expected to be discussed during the AIAA SciTech2027 conference.

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# Appendix A. Challenges and Opportunities

Overall systematic increase using modeling and simulation techniques to support the showing of compliance with aircraft certification requirements offer reasonable opportunities:

- Faster time-to-market, reduced development costs, and more innovative design
- Robust planning for the final development and certification phase
- Increased testing and certification efficiency
- Safety, allowing for investigation by analysis where testing would be impractical or impossible [29] and by reducing number of flight tests with high risk
- Quality by systematically ensuring on-the-spot results and back-filling

In recent discussion on the increase of modeling and simulation for certification, one of the main attention items raised by Doeland [29] is about errors and uncertainties along with verification and validation aspects. Similarly, the AIAA Recommended Practice related to CbA [1] asks for justification that, for example, the flight modeling analysis results are adequate for the purposes of the particular compliance showing despite potential modeling errors and uncertainties. The same level of confidence as if compliance had been shown (exclusively) based on flight testing is postulated. Exemplarily, for rotorcraft comprehensive guidance is given by the Rotorcraft Certification by Simulation Community [30] to facilitate the development and define the constraints for the effective use of flight simulation, to support, augment, or replace flight testing in the demonstration of such compliance, without sacrificing the level of safety.

Coherently, the demonstration of adequate and systematic consideration of uncertainties and their propagation for the related multiphysics problem is mandatory to proceed and capitalize on the opportunities. Therefore it is in focus of the challenge: How to ensure an equivalent level of safety compared to the current certification process (often based on large testing)?

Concrete use cases for Certification by Analysis were outlined and discussed in the literature [1, 30] of which the *External Radome Addition on the Fuselage of a Previously Certified Airplane* is picked up for the present use case. Here, it is framed by Subpart C - Structure of the respective certification specifications / airworthiness standards for large / transport category aeroplanes.

As the need to identify best practices and develop guidance material for applying formal methods for uncertainty quantification to a typical multiphysics problem, which will facilitate the application of modeling and simulation for streamlining the certification process, was acknowledged [29], the learnings from this use case contribute to address the lack of standardization and guidance material in the field of aircraft certification. The CbA CoI has published a UQ position paper [5] that discusses the major technical and programmatic impediments that are preventing more widespread use of CbA. These challenges are broken into four categories, which are summarized below.

### Mindset & Awareness

A major challenge for successful adoption of UQ for CbA will be to change the mindset and increase awareness of UQ within all participating organizations involved in Aircraft design, manufacture, certification and operation. Within the current design and certification of new aircraft there is a strong reliance on using acceptable means of compliance and engineering judgment within the aircraft design, validation and calibration of models from test data. This creates some specific challenges in ensuring an "equivalent level of safety" to the existing certification process since we know there are many inherent and unquantified uncertainties in the process but we also know that we have many decades of evidence that the current certification rules and means of compliance result in safe aircraft. It is important therefore to establish a common language and technical understanding between academia, aircraft manufacturers and the certification authorities.

### Tools & Capabilities

Many of the key challenges for the tools and capabilities required for UQ are related to the ability to propagate uncertainties through the aircraft design process and associated simulation tools. These must rigorously and efficiently propagate both the aleatory (inherent, probabilistic) and epistemic (non-probabilistic, lack of knowledge) uncertainties through the relevant multi-disciplinary analyses. For the industrial applications it is also important to assess the computational needs associated with the uncertainty propagation through high fidelity (computationally expensive) analyses and the scalability impacts for increased numbers of uncertainties.

### Data & Benchmarks for V&V

V&V relies heavily on the availability of test data against which the results can be compared. Typical focus for OEMs is to ensure the V&V of the final product more than the V&V of the underlying analysis models themselves. In general industrial testing is focused on more deterministic testing with limited assessment for the uncertainties inherent in the overall testing process. The application of UQ for CbA will necessitate a greater need to be able to quantify the uncertainties in our underlying models (model form uncertainty). This provides many open questions relating to the quantification of testing uncertainties and impacts on testing scope (e.g. need for repeatability tests) combined with uncertainty on the “re-usability” of test data and model V&V from one aircraft design to the next. This is a particularly challenging topic when considered within the overall goals of CbA for reduction in overall testing.

### Applied Research & Established Processes

There have been significant advances in the application of UQ methods and approaches in aerospace, however there are still limited examples applied to the industrial scale and complexity for multi disciplinary design using high fidelity (computationally intensive) analysis tools with UQ methods.