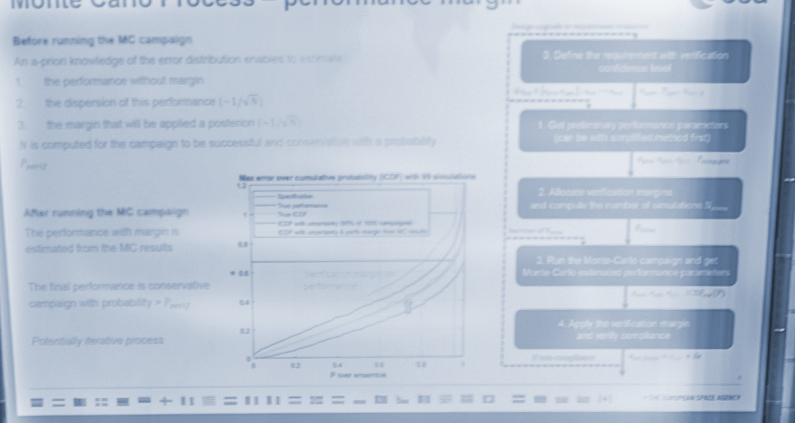
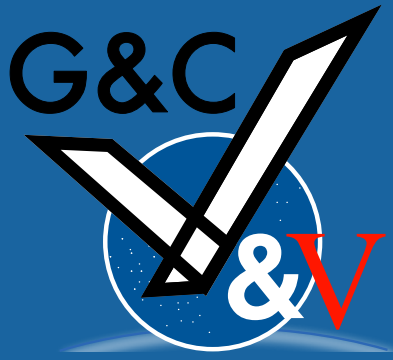




The Outcomes of the Second Inter-Agency GNC V&V Workshop

Findings, Observations and Recommendations for the
GNC Engineering Community of Practice



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SUMMARY

This report presents the outcomes of the Second Inter-Agency GNC Verification and Validation (V&V) Workshop held in July 2025 in Toulouse, France. The workshop brought together participants from space agencies, industry, and academia to exchange experience, discuss current challenges, and identify future directions for GNC V&V. Key themes included the growing complexity of GNC systems, the need for earlier and more integrated V&V processes, and the importance of combining classical and emerging methods such as robustness analysis, AI/ML approaches, and hardware-in-the-loop testing.

Across all sessions, a strong consensus emerged that no single V&V method is sufficient. Instead, a layered approach combining analytical tools, simulation, and testing is required. The workshop also highlighted the importance of collaboration across organizations and disciplines, as well as the need for improved toolchains, benchmarks, and training to enable adoption of advanced methods in practice.



INTRODUCTION AND WORKSHOP MOTIVATION

Many Guidance, Navigation, and Control (GNC) practitioners, both in industry and at the space agencies, face daunting challenges in identifying critical-need areas and developing effective strategies to prepare for upcoming demanding robotic science and crewed space exploration missions.

One specific and concerning trend that stands out in today's environment is the increasing level of complexity encountered in the GNC systems of modern space systems, both in the spacecraft themselves and their launch vehicles. When space mission needs are pushed to new limits in performance, cost and schedule, complexity becomes a dominant attribute that must be directly dealt with. In this context, complexity can be characterized by greater levels of system interactions and interdependencies (i.e., system entanglements in closed-loop dynamics and among the various algorithmic elements of flight software) as well as increased non-linear coupled dynamic behaviors.

Moreover, this complexity is driven by multiple types of system uncertainties as our space missions push into operational regimes that not only occur in harsh or extreme environments but

also are not well-characterized, which can lead to unpredictable interactions between the spacecraft and the operational environment. Some researchers have attempted to overcome the problems of complexity through the use of advanced control techniques [1]. To directly address system complexity, the GNC community of practice will need to develop modern ways of managing the GNC system complexity and potential unintended interactions with the system dynamics and environment as part of the design process.

This could include reformulating design synthesis as an optimization problem spanning multiple engineering disciplines. This approach will be a tremendous contrast to the current classical control system practice of iterative system tuning by the controls engineer. The underlying primary purpose of the GNC V&V process will be to identify and resolve, early in the design process, undesirable closed-loop system dynamic behaviors, especially those that cross traditional engineering discipline boundaries. For example, consider an undesirable controls-structures interaction (CSI) issue involving a flexible appendage vibration mode and the attitude controller bandwidth, or a destabilizing propellant slosh dynamics issue.

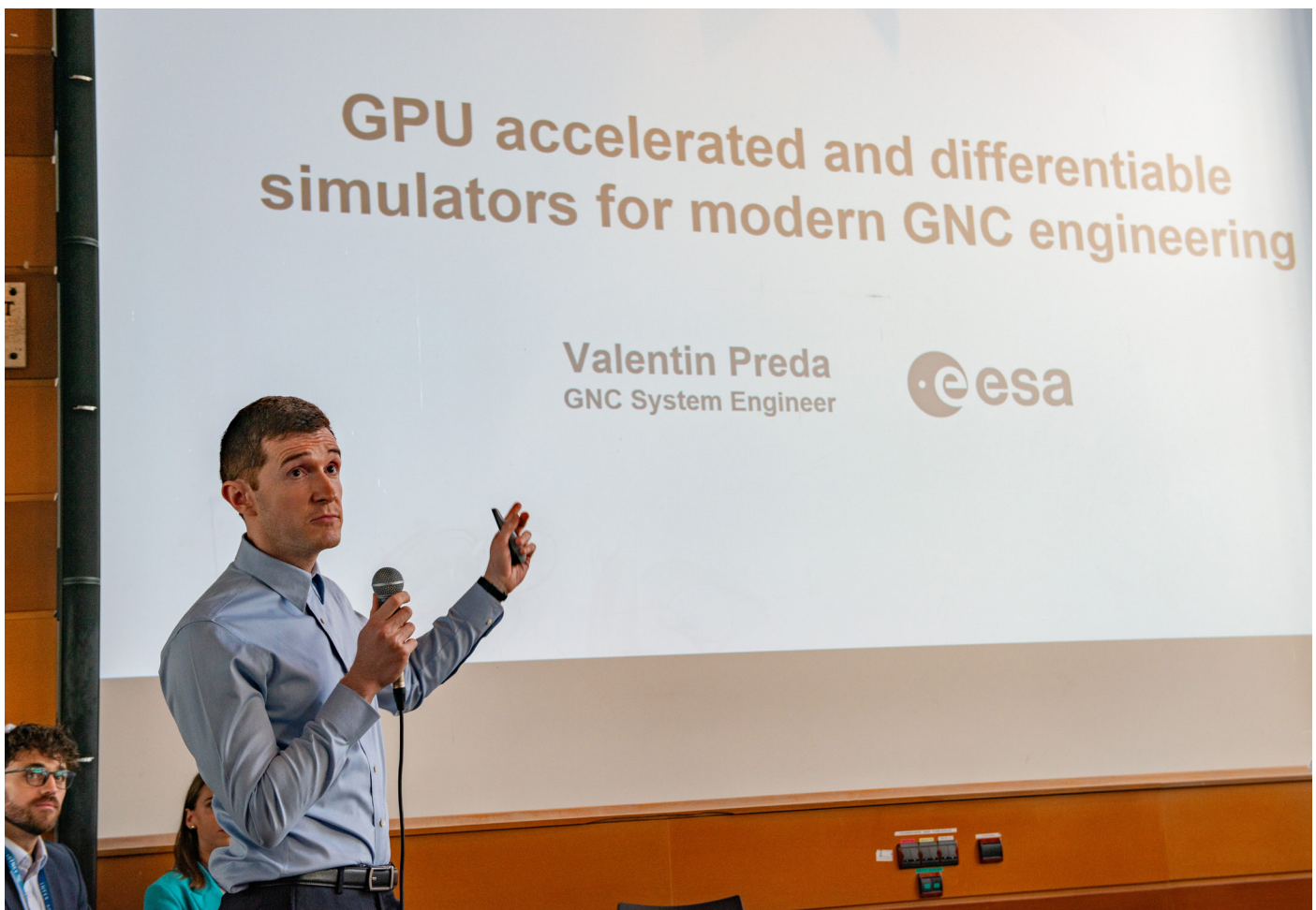
Obviously, the earlier in the design process the system-level closed-loop stability and performance issues can be resolved, the lighter the impact will be on project cost and schedule. Attention is needed to address the challenges and issues of increasing GNC system complexity in future spaceflight systems. In particular, GNC engineers will need to create robust and resilient system architectures that, in a cyclic manner, structure and integrate emerging technologies across multiple disciplines.

A very relevant current example of that is the application of onboard Artificial Intelligence/Machine Learning (AI/ML) based autonomy. The next generation of GNC engineers will benefit from design methods and tools that allow the convergence of a multidisciplinary design optimization process. Model-based design synthesis approaches that can simultaneously satisfy multiple dynamic system stability and performance requirements will likely be at the heart of the solution process.

Currently there is a significant gap in Verification and Validation (V&V) methods, processes, and tools to manage and flight-certify increasingly complex

GNC system architectures with multiple interacting layers of flight software algorithms. This is especially true for systems where robustness is at a premium and autonomous adaptive algorithms are part of the solution. One can envision employing local on-board autonomous decision-making algorithms to improve robustness and potentially reduce the complexity of advanced GNC system architectures.

This comes with the attendant cost of performing the necessary V&V to reduce uncertainty; assess and manage risk; and ultimately certify safe, reliable, and efficient GNC system operation. The cost of performing sufficient V&V on advanced GNC systems could be prohibitive, since a majority of project resources are spent on pre-launch verification. Clearly, there is a need for V&V tool development and education to manage increasingly complex GNC system instantiations.



Spacecraft and launch vehicle GNC systems are naturally complex since they interact with many other systems—e.g., avionics, software, propulsion, power, ground systems, structures, aerodynamics, payload, communications, thermal, and, in some cases, the on-board crew. Trends in GNC point towards even more complex systems. GNC engineers are increasingly encountering highly networked, cyber-physical dynamic systems.

Machine learning is increasingly being applied to control problems, and machine perception and optimization are leading to autonomous decision-making. We are increasingly encountering highly networked, cyber-physical dynamic systems. A trend towards increasing formalization of software, design architectures, and optimization is leading to treating these as dynamic systems. This results in yet another complexity:

The GNC engineering team now needs expertise in many domains, including artificial intelligence, software, avionics, optimization, and cyber-

physical dynamic systems. Not to mention (but we will) a practical working knowledge of advanced V&V techniques and methods. The in-space GNC engineering discipline is also trending towards increased online adaptation and optimization.

In the outer control loop, the trend has moved from Fault Detection, Isolation and Recovery (FDIR) to robust and adaptable path planning and onward to autonomous path planning and integrated health-management systems. In the inner loop, control systems have evolved from precomputed (on the ground) adaptation and robustness (gain scheduling) to fully online optimized adaptation and robustness.

This has resulted in advanced control and improved embedded capabilities, which of course require advanced V&V techniques. The trend towards increasing formalization of software, design architectures, and optimization is leading to treating these as dynamic systems.



This results in yet another complexity for our community of practice:

GNC engineers will increasingly need to possess expertise in many other non-GNC domains, including artificial intelligence, software, avionics, optimization, and cyber-physical dynamic systems. Ever more advanced systems can lead to gaps in the verification process. These can manifest as a difference between increasing V&V efforts aggravated by system complexity.

This is important because conducting V&V efforts (i.e., the performance requirements verification campaign and associated iterative tuning process) is an expensive undertaking for a project.

It is estimated that in a typical project, approximately 15-20% of total design and development phase time is spent in actual design synthesis with the remaining 80-85% being devoted to iterative tuning, analysis, and the performance verification campaign efforts [6]. Thus, there is an urgent need to develop efficient processes, tools, and testing capabilities to manage,

especially in the industrial setting, complexity and uncertainty within the trifecta of robustness, adaptability, and autonomy.

Therefore, the compelling importance of GNC V&V was the Inter-Agency Working Group's prime motivation for convening the July 2025 2-day GNC V&V Workshop in Toulouse, France that is the subject of this report. This report summarizes those Workshop proceedings, which were organized in the form of seven individual technical tracks held over the 2-day duration of the workshop.

A concise summary of the key findings, observations, and recommendations for closing this GNC V&V gap that emerged from each of the seven workshop technical tracks will be provided at the end of the paper, as well as some general conclusions.

The workshop contributors' hope is that sharing the outcomes of the GNC V&V Workshop will provide a basis for further discussions on this critical subject within the global GNC community of practice.



BACKGROUND ON THE INTER-AGENCY GNC V&V WORKING GROUP

European and American space agencies have a strong interest in GNC algorithm research and development (R&D) and the subsequent infusion of these advanced algorithms into engineering practice by their industry partners.

Beyond the R&D aspects, they share the challenging responsibility of architecting, designing, developing, launching, and operating spaceflight systems for human and scientific exploration. As space systems grow more complex a critical area has emerged and requires immediate attention: namely the V&V of GNC systems.

The concern is that current V&V approaches and processes may not be adequate to cope with the evolving GNC architectures and topologies being driven by autonomy but also by requirements for resiliency, reconfigurability, adaptability, and mission cost-benefit balance.

Observing these ongoing trends, and in a proactive effort to quantify and address this V&V gap, the

National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and other European space agencies have formed an informal collaborative working group to better understand the GNC V&V challenges and identify a way forward for the future of space system GNC V&V.

Specifically, the Inter-Agency GNC V&V Working Group's partner organizations include NASA, ESA, the French Space Agency (CNES), the German Aerospace Center (DLR), the Italian Space Agency (ASI), the French Aerospace Lab (ONERA), and the ISAE-SUPAERO University. Several members of the Inter-Agency GNC V&V Working Group at the completion of the workshop are pictured in Figure 1.

Between 2020 and 2025, this working group has been investigating the following two fundamental questions relevant to the future GNC V&V challenges:

1) How can the GNC engineering community of practice best prepare for the coming challenges in performing the GNC V&V for evolving GNC architectures that are driven by demanding requirements for autonomy, resiliency, reconfigurability, adaptability, and mission cost-benefit balance?

2) How can the space agencies help to bridge the GNC V&V gap between the GNC researchers and the GNC practitioners in industry?

Initially the Inter-Agency GNC V&V Working Group sponsored a series of technical seminars and also a first (virtual) workshop, presented over the period from autumn 2020 to spring 2021. The results of the virtual workshop on advanced GNC V&V tools, techniques and methods were subsequently documented in an AAS GNC Conference paper in 2022 [2]. Figure 2 highlights the three major themes that emerged for this first (virtual) GNC V&V workshop.

Following that first (virtual) workshop the Inter-Agency GNC V&V Working Group published a “Call to Action” Position Paper in February 2024 proposing a comprehensive set of recommended actions for all the GNC V&V stakeholders: space agencies, researchers, and industry [3].

This Position Paper discussed the needs for developing new and advanced GNC V&V tools and techniques, enhancing the education and training of the GNC workforce (especially in industry), and realistic benchmark problems for the GNC community of practice. Figure 3 highlights the key points of the 2024 Position Paper.

Figure 1. Members of the Inter-Agency GNC V&V Working Group



WORKSHOP OVERVIEW (2025)

In July of 2025, the Inter-Agency GNC V&V Working Group planned and executed another GNC V&V Workshop which was hosted by the ISAE-SUPAERO University at their campus in Toulouse, France. This workshop was conceived by its organizers to establish a common understanding of the critical GNC V&V issues and advancements between academia and industry and among the various government space agencies. Specifically, this second GNC V&V workshop had two major objectives:

- *Raise awareness about GNC V&V challenges and issues within our global GNC community of practice*
- *Provide an informal interactive forum for knowledge sharing and learning on the topic of advancing our collective GNC V&V capabilities*

Professor Daniel Alazard and Professor Francesco Sanfedino served as the local hosts at ISAE-SUPAERO University. The workshop

facilities were excellent and were well able to accommodate the 150 workshop registered participants. Figure 4(a) provides a word cloud depiction of the participant feedback on their country – note that over twenty different countries were represented at this workshop.

Figure 4(b) is breakdown of workshop participant occupations and reveals that there was a nice balance between researchers, space agencies and industry participants. The engagement of so many students did much to enhance the tone of the workshop. This workshop was purposefully not structured as a typical technical conference. For example, full technical papers were not required; instead, only a very few summary-level presentation charts were needed from each selected speaker to highlight their key talking points.

This in-person workshop, consisting of seven (7) individual technical tracks, was conducted in a series of very brief “lightning talks”, each of 8-minutes duration.

The workshop used an open-source audience engagement and live polling tool called Menti-meter*. A significant amount of time was devoted specifically for post-talk interactive discussion and Menti-meter polling among the workshop audience was also intentionally built into each track.

At the start of each track the co-chairs identified for the audience several relevant 'Talking Point' questions that served to focus this interactive discussion period which occurred after completion of the short talks. The Inter-Agency GNC V&V Working Group members believed that would be the best approach to have the type of informal forum conducive to group technical interactions, learning, and knowledge sharing that we desired.

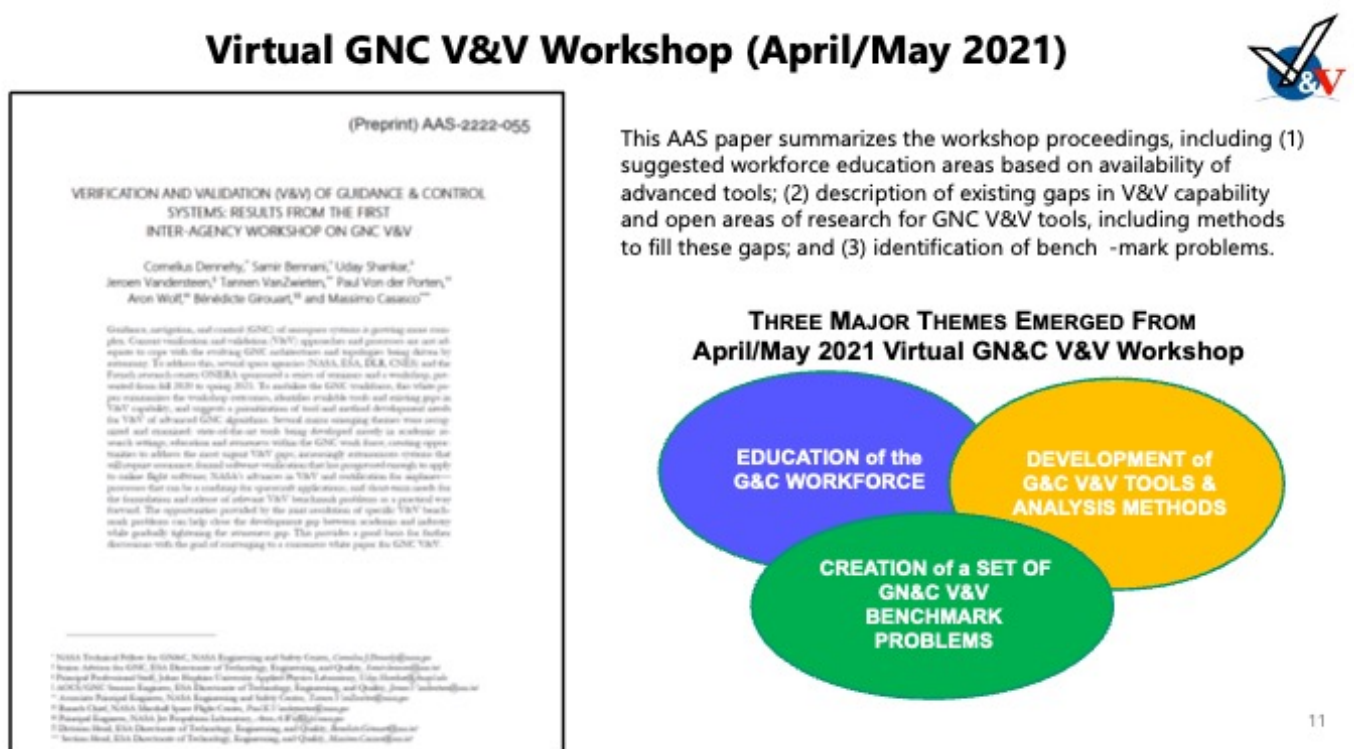
Each of the 7 technical tracks focused on a specific aspect of the overall GNC V&V challenge as depicted in Figure 5. A poster track (Track 8) showcasing innovative student research was also held as a part of the workshop along with two featured keynote addresses and two special

longer-duration "invited" talks. A total of 33 'lightning talks' were given during the course of the workshop and 13 student posters were on display.

Also, a post-workshop special seminar (i.e., effectively Track 10 of the workshop) was held on 11 September 2025 to provide a forum for 6 additional GNC V&V lightning talks from the NASA Jet Propulsion Laboratory (JPL). These 6 JPL talks were originally planned and scheduled to be given at the Workshop in Toulouse but owing to some unfortunate circumstances JPL representatives could not participate and their talks had to be postponed. A comprehensive list of all the workshop talks and posters is provided in the Appendix.

*Mentimeter is an interactive audience engagement tool that was particularly effective in stimulating the desired real-time interactive discussions in each of our seven technical tracks at the GNC V&V Workshop. Mentimeter can generate dynamic word clouds (see Figure 3a), support live and instant polling (see Figure 3b), and host entertaining and engaging quizzes. More information on Mentimeter can be found at: <https://www.menti-meter.com/>

Figure 2. Themes for the First (Virtual) GNC V&V Workshop (April/May 2021)



The first keynote address on the morning of Day 1 was given by a local representative from CNES, which covered the topic of orbital rendezvous. In this keynote the relevant flight experiences of the Prototype Research Instruments and Space Mission technology Advancement (PRISMA) rendezvous and formation flying two-spacecraft technology testbed mission were highlighted.

PRISMA, built by the Swedish Space Corporation, with CNES and DLR contributions, performed in-orbit validation of relative navigation sensors and associated GNC algorithms for closed-loop formation flying using the two spacecraft as flying testbeds.

The second keynote address on the morning of Day 2 was given by a representative of Airbus Defense and Space (Dr. Stefan Winkler). Dr. Winkler's keynote was entitled "Engineering Passion to Face the Real World! Research, Benchmark, Industrial Process, Efficiency" [6]. The point was made that

it is essential to fully understand the requirements to be verified before embarking upon a V&V campaign. In this talk the highly relevant topic of identifying and applying new advanced V&V technologies to improve industrial cost/schedule/performance efficiency in the deployment of future Attitude and Orbit Control Subsystems (AOCS) for spacecraft was discussed.

It was estimated that the combination of GNC system design and tuning is around 20-40% of the overall project cost indicating that there is cost reduction potential in these areas. In terms of the V&V, only the tuning costs can be reduced while design costs are already minimized by relying on a product-based industrial approaches already in place. In summary, Dr. Winkler mentioned how European research, industry and space agencies have teamed up to prepare for the future by conducting an ESA-sponsored General Support Technology Programme (GSTP) study called "Efficient V&V for AOCS" [4].

Figure 3. Highlights of the Inter-Agency Position Paper (February 2024)

"Looking to the Future: A Call to Action for Advanced GNC Algorithm Verification and Validation"



Looking to the Future:
A Call to Action for Advanced GNC Algorithm
Verification and Validation

8 February 2024
Version 1.0



Prepared by:
The Inter-Agency Guidance, Navigation, and Control
Verification and Validation Working Group (GN&C V&V WG)

- **Our WG focus has primarily been on addressing the GN&C V&V challenges that arise as drivers for more autonomy appear and system complexity increases.**
- **Purpose of this document was to capture the findings and recommendations of the WG and lay out future directions (a vision for the future) for Agency investments in V&V methods and tools for the most promising advanced GN&C algorithms**
- **Initially written as an impactful InterAgency "White Paper" type document intended to educate and influence organizational decision makers.**
- **Now document is more tailored towards a conference paper. Working Group members plan to roll out this paper internally within our respective organizations and across the GN&C community of practice**



Figure 4a

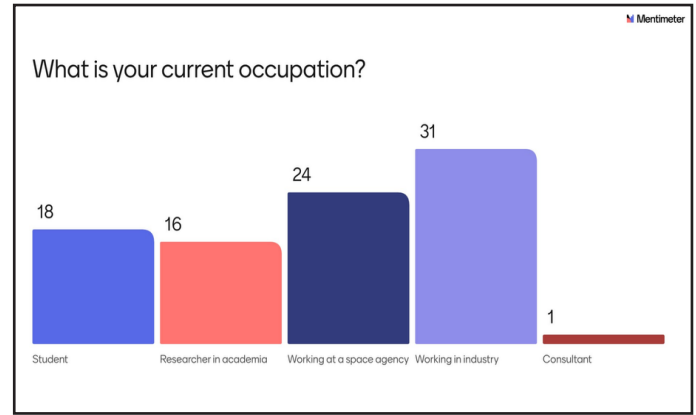


Figure 4b

Workshop Technical Tracks:

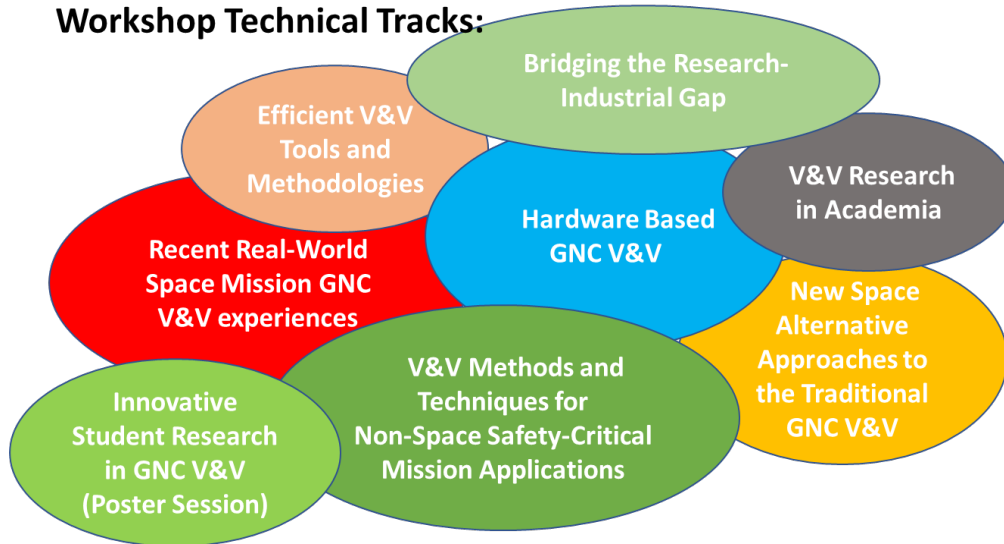


Figure 5

The first 30-minute invited talk was from ISAE-SUPAERO which provided a detailed discussion of the European Pointing Benchmark Problem that will soon be released to the community of practice as part of an open competition [5].

This benchmark problem, and the upcoming competition, are intended to help overcome the innovation gap of the GNC design process between research and industrial practice. The second 30-minute invited talk was from NASA and focused on the V&V process employed for the pre-launch certification of the Adaptive Augmenting Control (AAC) flight control system flown on NASA's Space Launch System (SLS) for Artemis I.

As described (by NASA speakers John Wall and Dr. Tannen VanZwieten) the SLS AAC algorithm was initially verified through a series of F-18 aircraft flight tests, and subsequently validated through Monte Carlo, evaluation of stressing cases, time-domain stability margin assessment, describing function analysis, Lyapunov stability

analysis, and hardware-in-the-loop testing. Early integration into the SLS high-fidelity flight control simulation environment and rigorous V&V led to receptive program adoption, confident flight readiness, and a successful first flight.

Each of the workshop tracks emphasized a different aspect of the GNC V&V problem, as listed in Table 1. These tracks are summarized and their findings outlined in the following sections.

Track	Subject	
1	Recent real-world space mission GNC V&V Experiences	Tracks in the workshop
2	Efficient V&V Tools/Methodologies for Systems Using Modern GNC Technologies	
3	Bridging the Research–Industrial Gap	
4	Benchmark Problems	This track was removed
5	V&V Research in Academia	Tracks in the workshop
6	New Space Alternative Approaches to the Traditional GNC V&V Process	
7	Non-traditional techniques for GNC algorithm V&V for non-space applications	
8	Posters: Innovative student research in GNC V&V	This was a posters-only session
9	Hardware-based GNC V&V	Track in the workshop
10	JPL GNC V&V Special Seminar Talks	JPL staff were not able to attend the workshop. Their talks were presented separately in an online seminar post workshop on 11 Sept 2025.

WORKSHOP TRACK SUMMARIES AND OUTCOMES

Within this section, a subsection is dedicated to summarizing the key themes and findings for each track.

TRACK 1 – RECENT REAL-WORLD SPACE MISSION GNC V&V EXPERIENCES

This track, the first of the workshop, focused on recent space missions, the associated limits and constraints of the current GNC algorithm V&V methods and lessons learned.

The interactive discussion on this topic could potentially identify where practical GNC algorithm V&V process improvements could be made, especially in ways that would be compatible with an industrial setting. This track hosted a total of four talks, all of them from industry.

The key themes that emerged from these talks included:

Incremental and Modular Validation Approaches:

Spaceflight projects like the European Robotic Orbital Support Services (EROSS), the Mars Sample Return Earth Return Orbiter (MSR-ERO) and the European Advanced Reusable Satellite (EARS) all highlighted incremental validation (Software-in-the-Loop, Model-in-the-Loop, Hardware-in-the-Loop on Avionics Test Bench) to ensure robustness and reduce early risks before final integration.

One approach was to introduce a lighter simulator to test GNC architectures before the full Functional Engineering Simulator was ready, reducing validation time and costs and enabling early hardware tradeoffs. Validation-oriented design ensures that software and hardware constraints are aligned early in the development process.

Standardization and Reusability: Standardized tools (e.g., generic post-processing tools and test bench used for EARS project) allow efficiency by pooling common resources across multiple missions. Model-Based Design (MBD) eases algorithm reusability,

reducing validation efforts in future projects. Failure Detection, Isolation, and Recovery (FDIR): A best practice would be to keep the FDIR algorithms as simple as possible to facilitate validation.

Overly complex FDIR designs can make the validation unfeasible. Recent experiences indicate that close collaboration between the GNC, systems engineering, flight software and avionics teams is essential for defining FDIR constraints and ensuring adequate system-level validation.

Robustness and Sensitivity Analysis: Linear Fractional Transform models reduced simulation complexity, enabling faster robustness analysis, as demonstrated by the Laser Interferometer Space Antenna (LISA) mission's Drag-Free and Attitude Control System (DFACS) team.

Sensitivity analysis allows for the identification of key uncertainties and reduced order model size, thus reducing system tuning iteration time.

Some of the key questions (talking points) discussed in the post-talk Track 1 interactive discussion included:

- *What are the current approaches to simulation model validation? (e.g., rendered images, sensor models, LISA extreme physics) Any recommendations, experiences, lessons learned?*
- *How do we gain confidence in the completeness of our V&V? For missions that we have never done before, how do we know what to test for?*
- *What is the relationship between the level of criticality of a project and the level of representativeness required during the V&V process?*



Key Findings from Track 1

Key findings from the interactive discussion and polling included the following:

1. A project can achieve a payoff from having an established GNC System Architecture using model-based design with reusable algorithms.
2. There is value in having an established V&V methodology since standardization promotes reuse and reduces costs/time.

Consider reuse of test benches from prior projects and previously validated plug-and-play models to cut performance verification campaign time.

3. Sensitivity analysis is critical to identifying key system uncertainties – for example, it was determined with sensitivity analysis that only 10 out of 200 uncertainties drove the LISA DFACS design.

4. Linear Fractional Transform (LFT) models for uncertainties can serve as a complementary approach to Monte Carlo. The LISA DFACS illustrated LFT usage for the system which would have required extremely long duration Monte Carlo simulations because of the combination of both high-frequency and low-frequency dynamics.

5. V&V benefits can be accomplished by using a 'Design for Testability' approach (e.g., employ simple FDIR).



TRACK 2 – EFFICIENT V&V TOOLS/METHODOLOGIES FOR SYSTEMS USING MODERN GNC TECHNOLOGIES

This track, which took place on the second day of the workshop, was the largest one with a total of ten talks split into two parts. The focus was on exploring emerging Verification and Validation (V&V) methodologies, tools, and techniques tailored for modern GNC technologies.

This includes V&V methodologies that would be appropriate for adaptive flight control, real-time trajectory optimization, AI/ML-based learning systems, optical navigation, fault management, and advanced modeling of dynamic systems like flexible structures and fuel slosh.

Novel V&V methods were presented that address the complexity and uncertainty in modern GNC systems.

The main objectives of Track 2 were to:

- Highlight innovative, practical GNC V&V tools and techniques
- Assess their current technology readiness for industrial deployment
- Identify unmet V&V needs for future mission-critical applications
- Provide roadmaps to mature V&V technologies to higher Technology Readiness Levels (TRLs)

Interactive discussions took place between the speakers and the audience after each of the two-part sessions. Some of the key questions discussed in the post-talk Track 2 interactive discussion included:

- *Despite recent progress, what are the main limitations of robustness-analysis-oriented tools for a more efficient GNC V&V process? Can these limitations be treated in a near future or can we think about alternative or complementary approaches to derive new multi-tools methodology? What are the most*

promising tools to be further developed and possibly integrated in the aforementioned methodology?

- *In this V&V process, what are the typical difficulties raised by modern GNC involving data-base, adaptive, AI-ML techniques?*

Polls revealed that most industrial partners were ready to adopt the presented tools. However, progress is still required. As an example: How can robustness analysis tools be advanced to take nonlinearities into account or manage systems with a large number of dimensions?

Among possible solutions the use of Graphics Processing Units (GPUs) could be an option to accelerate Monte Carlo based analysis, worst-case optimization, and Semi-Definite Programming (SDP) based approaches such as Integral Quadratic Constraints (IQC) analysis. The development of challenging benchmarks to generate competitions is also an excellent way to promote new and more efficient V&V tools.

Key Findings from Track 2

During the discussions after each talk and the wrap-up of this track several relevant questions were raised and interesting findings made, among them the following:

1. V&V should start early and integrate continuously with development, rather than postponing it to the end.
2. Process matters as much as algorithms. There is a need for clear workflows, automation, traceability, and having a Continuous Integration/Continuous Delivery (CI/CD) process in place are all essential.
3. Iterative and lightweight assurance is possible. Tailored processes and pragmatic tool choices can meet assurance needs even with small teams.
4. Multi-layer V&V strategies can be beneficial: employing fast, low-fidelity tools for

early screening and high-fidelity simulations for final validation.

5. Analysis beyond worst-case robustness is important: for example, sensitivity analysis can reveal which requirements are critical and what drives risk.
6. Incremental and targeted testing uncovers hidden failures: edge cases and stressing, off-nominal scenarios are crucial, especially for autonomous perception systems.
7. Robustness analysis and Monte Carlo and robustness analyses are complementary V&V techniques: Monte Carlo analysis is excellent for understanding system performance and robustness across a well-defined set of uncertainties, but struggles at very high confidence levels. Robust analysis tools are powerful when modeling is accurate (i.e., limited



model uncertainty). Robustness analysis can identify which combination of parameters results in worst cases, and perhaps can then guide targeted Monte Carlo simulations, and reduce over-design early in development.

8. Currently Monte Carlo cannot be replaced, only accelerated. GPUs (or other parallel computing methods) combined with automatic differentiation can reduce turnaround time, potentially by orders of magnitude, and enable realistic, large-scale tuning and verification efforts.

9. GPU parallelization can help robustness analysis, especially for frequency-by-frequency μ analysis.

10. On the tension between early validation and innovation, two viewpoints were identified: (1) early validation can reduce late-stage iterations and redesign, but (2) excessive early constraints may slow exploratory research. Multi-layer V&V strategies can be helpful for managing

these competing objectives: employing fast, low-fidelity tools for early screening and high-fidelity simulations for final validation

11. On AI / ML in GNC Verification the main difficulties that were identified are: robustness guarantees, scalability, the knowledge gap between AI and AOCS (GNC) communities, certification, and reliability.

However, black box concern on these methods is partially misleading: ML components are mathematically well-defined, and the difficulty lies in understanding interactions, not in opacity. The major open issue is the mismatch of semantics and metrics:

AI uses loss functions and statistical metrics, AOCS uses stability margins, eigenvalues, deterministic guarantees.

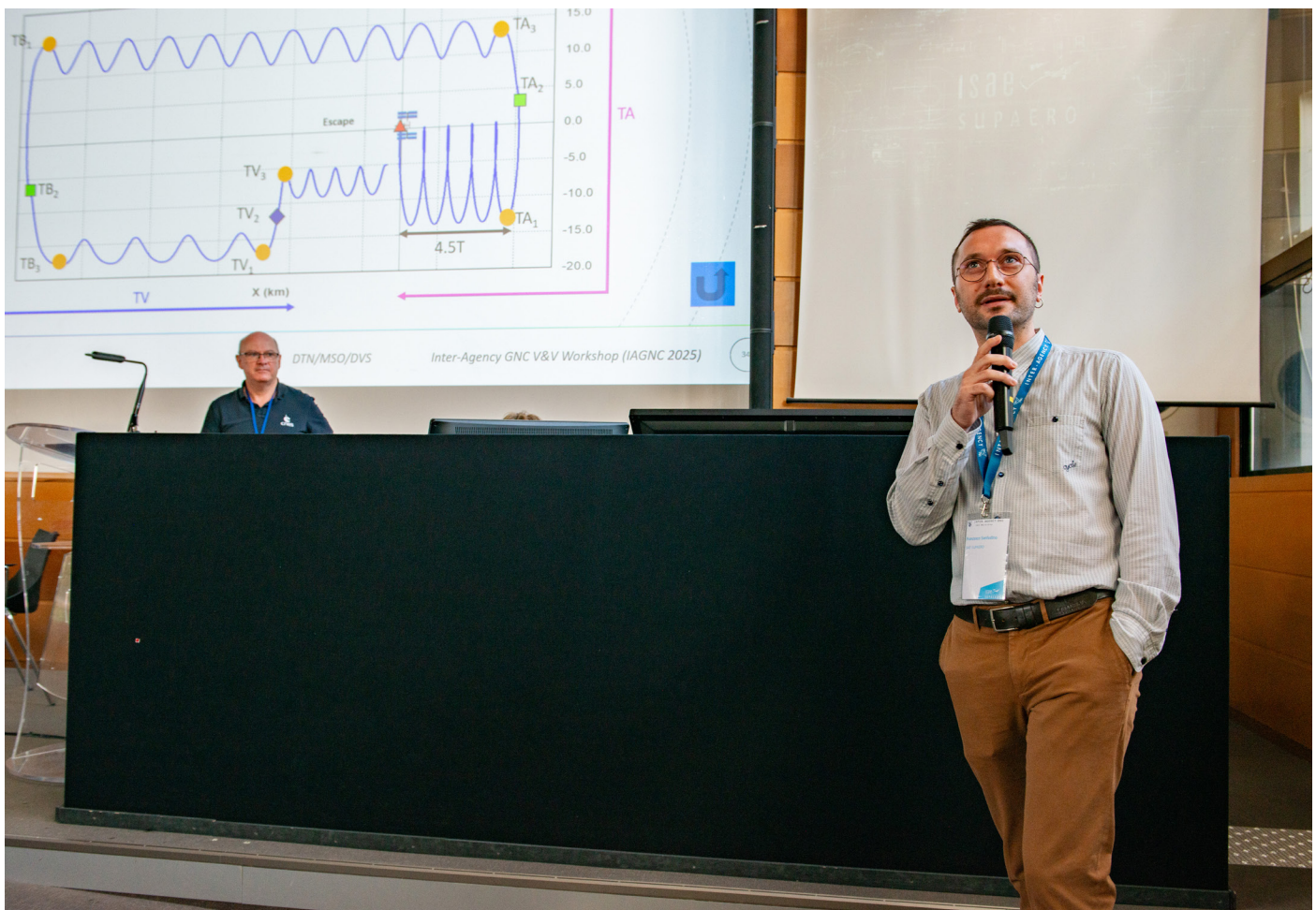
We need new or hybrid performance metrics that bridge between AI standards and GNC V&V standards for space systems.



12. Classical space system dynamics which impact GNC design are often dominated by linear behaviors. However, saturations, actuator nonlinearities, and software complexity all introduce significant nonlinear behaviors and must be adequately captured in the late-stage high-fidelity simulators.

13. V&V results can sometimes force late mechanical design changes. This is highly undesirable and costly. Sensitivity and robustness analysis can precede Monte Carlo analysis and can prevent late redesign by helping to efficiently identify critical parameters early.

14. Organizations expressed readiness to adopt new V&V tools. Identified barriers to adoption include: infrastructure readiness, training and expertise, tool sustainability and maintenance. Some identified enablers include: open-access libraries, community-supported tools, integration into existing workflows.



TRACK 3 – BRIDGING THE RESEARCH-INDUSTRIAL GAP

This track addressed the challenges of transferring new Guidance, Navigation, and Control (GNC) methods from academic research into industrial practice, especially regarding Verification and Validation (V&V).

The five talks and interactive discussions covered several relevant areas of research: iterative design methodologies, safety filters, sensitivity analysis, CFD-based approaches for fuel sloshing, and probabilistic methods for robust performance. Key topics to provoke group discussion in this track included:

- Reliance on Monte Carlo simulations in industry and the potential need to incorporate advanced verification methods.
- Model-based design challenges and how to validate increasingly complex models

- Understanding the trade-offs between cost and robustness in V&V campaign.
- Agency roles in adapting standards, enabling New Space practices.
- Identifying and/or creating transfer pathways: developing mechanisms for how academic methods can realistically enter industrial practice.
- Considerations regarding the scalability of academic methods must be considered to ensure they are viable for large, complex industrial applications.
- Training and knowledge transfer are essential: new methods must not only be publishable, but also teachable, learnable, and usable by industry engineers. For instance, long and complex user manuals may create an entry barrier: having tools with good GUIs could potentially aid in breaking this barrier.



Some of the key questions discussed in the post-talk Track 3 interactive discussion included:

- *Industry still relies almost exclusively on Monte Carlo simulations. Where are the new methods, and why aren't they used?*
- *What are the model-based design & validation challenges?*
- *V&V Cost vs. Robustness: What's the Right Trade-Off?*
- *How can Academic methods be transferred into Industry Practice?*
- *What are your main lessons learned in using modern V&V Techniques/Tools?*
- *New Space: Is it the Fast Lane of Integration?*
- *Do Agency standards need to be updated to allow/support adoption of „emerging V&V techniques“?*

On the topic of over-reliance on Monte Carlo methods (versus other advanced methods), it is worth noting that the context can aid in selecting an appropriate method (e.g., in case of requirements with low confidence levels, it is difficult to beat the simplicity of Monte Carlo).

Also, Monte Carlo with adaptive importance sampling is quite effective to estimate small probability of failure. Some advanced methods (namely μ -analysis) can be readily used early in a lifecycle to invalidate a design, but it is more difficult to rely on this analysis for proving out a design.

Risk management (level of risk that can be accepted) also plays a role in selecting the most appropriate V&V techniques.

The space agencies have a key role in supporting the transfer of knowledge, by fostering education, training initiatives (including via shared common benchmark problems), and standards that make academic innovations accessible to practitioners.



Space agencies can support the creation and evolution of standards which can then play a role in fostering the emergence of advanced methods, as observed in the aviation domain.

Key Finding from Track 3

The consensus takeaway from this track was that academic methods show promise, but simplicity, traceability, scalability, training, and standards are critical for adoption in industry.

Agencies have the opportunity to facilitate both the transfer and the practical uptake of these academic methods.

TRACK 4

Readers should please note that the originally planned Track 4 (Benchmark Problems) was removed from the initial workshop program and that Track 9 (Hardware-based GNC V&V) was substituted in its place.

However, as mentioned above, there was an invited workshop talk by ISAE-SUPAERO describing the European Pointing Benchmark Problem that will soon be released to the GNC community of practice as part of an open competition [5].

It is envisioned that some of the most promising solutions to the European Pointing Benchmark Problem emerging from this upcoming competition will be presented at the 2026 ESA GNC Conference in Seville, Spain.



TRACK 5 – V&V RESEARCH IN ACADEMIA

This track welcomed a total of four talks on recent research results and focused on how to further integrate academic research into government and industry V&V of GNC algorithms. This field is often thought to be the responsibility of space agencies and industry, as it is a pre-liminary phase to certification.

A positive trend observed is that the emergence of AI in GNC applications, the increasing utilization of multidisciplinary/multiphysics co-simulations, and the application of co-design* approaches are all reviving academic interest in the V&V field. Some of the key questions discussed in the Track 5 post-talk interactive discussion included:

- *What kind of specific V&V topics does the emergence of AI in GNC applications raise?*
- *Which framework should be optimally chosen to deal with V&V topics such as*

modelling and quantifying uncertainties, which require even more coordination between academic researchers and industry?

- *What are the industry's main expectations of the contributions to be made by academic researcher in V&V? (e.g., are methodological developments preferred over theoretical developments?)*

*Co-design, also sometimes referred to as participatory design, is an integrative and collaborative design activity. Co-design spans not only the technical integration of multiple disciplines but also the interactive technical negotiation perspectives critically important to comprehensively address complex system engineering challenges. Co-design is closely linked with multi-physics co-simulation which is a supporting information system to advance engineering design methods. Co-simulation provides a technical foundation for co-design activities on which participating engineering disciplines can explore and define the problem from their different perspectives.



During the discussions after each talk and during the wrap-up of the track, multiple findings and observations emerged, including the following:

- Modular simulation platforms and robust control frameworks enhance V&V efficiency for complex GNC systems. Evidence was presented that shows academic research emphasizing autonomy and realism in simulation, and the development of techniques for evaluating GNC strategies across varying levels of detail to address current and future challenges in space exploration.
- Analytical methods (e.g., IQCs, OvertPoly^{*}) complement traditional Monte Carlo simulations, improving scalability and precision.
- Optimization algorithms, such as those used in Model Predictive Control (MPC) and Successive Convexification (SCvx), are increasingly being deployed in real-time, embedded GNC systems. While first-order methods offer computational efficiency and

predictable convergence, their theoretical guarantees often fail to translate reliably into real-world implementations. Academic research has yielded a methodology that ensures that theoretical guarantees (e.g., convergence, stability) are preserved in the implemented code. This work bridges the gap between theoretical models and practical implementations, enhancing the reliability, robustness, and efficiency of optimization-based GNC systems.

- Given the trend for neural network controllers becoming more widely used in safety-critical space mission applications, V&V methods for ensuring their safe operation are essential. Existing methods struggle with scalability and precision for nonlinear systems. This area would benefit from future academic research.

^{*}OvertPoly is a combinatorial algorithm for verifying nonlinear neural feedback systems. Based on the resolution of mixed-integer linear programs, the algorithm computes tight polyhedral over-approximations of the forward-reachable set of the nonlinear system. Refer to Reference 7 for details on the OvertPoly algorithm.



- In some mission applications such as the LISA* Drag-Free and Attitude Control System (DFACS) great challenges are encountered to perform accurate V&V at very low frequencies. A key finding therefore was the critical importance of combining analytical methods with high-fidelity nonlinear simulations for certain design cases such as this one.
- Early integration of novel algorithms, rigorous testing, and stakeholder buy-in are critical for certifying advanced control systems like the Artemis I Adaptive Augmenting Control (AAC) flight control system.
- Bridging the gap between academia and industry in GNC V&V calls for addressing real problems, standardizing benchmarks, and managing Intellectual Property (IP) challenges. This discussion reaffirmed the need for realistic and representative benchmark problems for the academic community to grapple with.

One of the talks in this track discussed the V&V experiences from a LISA mission study. The scientific objective of this mission requires maintaining free-flying test masses on precise geodesic trajectories, necessitating a robust DFACS. Of particular interest here are the challenges faced by the DFACS V&V process due to the need for very long-run duration time-domain simulations to accurately estimate low-frequency spectral densities.

The talk provided information on the Astrophysical Parameters Inference System (Apsis) project, funded by ESA, which explored new control designs and architectures to meet LISA's stringent scientific requirements. A robust control synthesis methodology was proposed that uses Linear Fractional Transformation (LFT) modeling and structured H_∞ control synthesis, which provided analytical insights into the LISA DFACS performance.

*LISA is a joint ESA/NASA space-based gravitational wave observatory scheduled for launch in 2037.



The proposed control architecture was validated through Monte Carlo campaigns using a high-fidelity nonlinear simulator. The results obtained showed good agreement between analytical predictions and long-run duration simulations, and highlighted the challenges of accurate V&V at very low frequencies and the importance of combining analytical methods with simulations.

The track underscored the importance of researchers developing innovative V&V approaches to tackle emerging GNC challenges while maintaining and fostering productive collaboration between academia, industry, and regulatory bodies.



TRACK 6 – NEW SPACE ALTERNATIVE APPROACHES TO THE TRADITIONAL GNC V&V PROCESS

This track examined the current New Space trend that is especially prevalent in the commercial space market. In this context the term “New Space” is used to refer to this time of unprecedented growth in the space community and to indicate the greatly expanded scope of what is now possible for launchers, spacecraft, and landers. Thus, there has been a great deal of movement away from the 1960s/1970s traditional model of centralized, big government-led space projects towards a new model that increasingly exploits the commercial space market in ways not previously done in order to obtain cost and schedule advantages.

This trend exhibits fundamental philosophical changes from the traditional GNC V&V process and increasingly exploits new techniques and methods of doing business. This track investigated

whether there has been a reduction in the GNC system V&V and thus a diminished level overall system reliability in the process of obtaining these New Space cost and schedule benefits.

The counterpoint to this issue was also examined and discussed, namely: have the New Space companies developed alternative, less costly and time-consuming approaches to performing flight system GNC V&V work that the space agencies and their industrial partners could benefit from.

The overall intent of this track was to better understand how space agencies and industry can manage the associated risks of alternative GNC V&V approaches and also how to leverage the new opportunities to increase the number of missions flown and to potentially develop new capabilities. Unfortunately, very few talks were received which could shed light New Space alternate approaches, and forming a collaborative relationship with New Space organizations is an objective of the working group.



There is a New Space mindset which is driven by market needs (cost/schedule reduction) more than platform size. This mindset represents a shift from pure science missions by space agencies to more commercial/sellable products.

One critical challenge that was identified in this track was the trade-off between the need for full compliance with the European Cooperation for Space Standardization (ECSS) standards to satisfy high reliability requirements and the New Space demands that place a high priority on low cost and fast delivery turnaround.

One New Space example emphasized a rigorous software framework with auto-coding and extensive V&V (model-in-the-loop to hardware-in-the-loop) to balance ECSS standards compliance with New Space market demands for rapid delivery and lower cost systems. Some of the key questions discussed in the Track 6 post-talk interactive discussion included:

- *To what extent are the ECSS standards still relevant for New Space missions? What recommendations do you have for tailoring? What recommendations do you have regarding the trade of reducing cost versus accepting higher risk?*
- *What are your experiences with autocoding, and what is the impact on the V&V efforts?*
- *What are the impacts of New Space methods, not only on reliability, but also on robustness and performance?*

KEY FINDINGS FROM TRACK 6

The key findings that resulted from the open interactive discussion and the interactive polling in this Track 6 included the following:

1. New Space Philosophy: CubeSats and multi-sat constellations shift the V&V process towards iterative, in-orbit testing, prioritizing market needs and cost/schedule over strict V&V requirements.
2. Auto-coding usage: There is roughly a 50/50 split between dominant auto-coding and manual coding in recent projects; general agreement is that auto-coding it reduces costs.
3. Most costly V&V aspects: Hardware testing is the dominant cost driver; The documentation effort also drives cost, especially for ESA projects where demand for documentation is more than for commercial customers. Simulation development and engineering labor hours are also two other significant cost drivers.

4. Greatest cost-saving opportunities: Sharing/reducing hardware tests & facilities; automation (processes, dataset generation, documentation); reuse of tools/models; continuous integration/development pipelines; access to better tools.
5. Trade-offs in small platforms (SmallSats/CubeSats/NanoSats):
 - a. Tight margins and complex miniaturization often can lead to reduced performance.
 - b. Observed trend is the shift from very small (e.g., 3U) to slightly larger platforms for better controllability and performance.
 - c. Constellation philosophy: Requirements less rigid; early missions serve as in-orbit tests for iterative improvement ("launch, learn, reiterate") rather than "get it perfect first time."

Some final thoughts and ideas that emerged from Track 6 included the following:

- a. Strong automation tools and co-location between design and verification teams enable rapid iteration and continuous testing.
- b. Need for robust equivalence testing (model vs. generated code) — borrow best practices from other non-aerospace industries.
- c. Testing frameworks should verify requirements compliance, not just 100% equivalence.
- d. Reuse and automation can free engineers from repetitive tasks to focus on mission-specific innovation.

This New Space track closed on an optimistic note emphasizing automation, reuse, and process integration as key enablers for cost-effective, yet reliable GNC V&V in the New Space era.



TRACK 7 – NON-TRADITIONAL TECHNIQUES FOR GNC ALGORITHM V&V FOR NON-SPACE APPLICATIONS

This track explored how non-space domains such as aviation, automotive, and AI/ML can contribute methods, standards, and practices to improve GNC V&V in space missions. Speakers from both academia and industry presented perspectives on formal methods, iterative processes, certification lessons, and AI/ML safety.

Discussions emphasized how “spin-ins” from non-space sectors can address the increasing complexity of autonomous space systems. This track had a total of four talks. Similar to the situation with Track 6, the organizers were somewhat surprised to receive only a few abstracts addressing non-space domain GNC-related V&V experiences.

The lessons learned here for future GNC V&V workshops was for the organizing committee to cast a wider net well outside the GNC

community of practice for relevant non-space V&V experiences. In the coming year the working group plans to make it a priority to more fully engage with GNC practitioners in non-space domains in an effort to understand where the most potential for fruitful cross-pollination lies.

Some of the key questions addressed in the post-talk Track 7 interactive discussion included:

- *How can cross-pollination between non-space and space V&V domains be effective?*
- *Which non-space domain standards (e.g., DO-178C, ISO 26262 – Road Vehicles Functional Safety, and ISO 21448 - Safety Of The Intended Functionality or SOTIF) are most relevant to space applications?*
- *What practical spin-ins (e.g., formal methods, objective certification, simulation-based scenarios) can be transferred?*
- *How to certify AI/ML for autonomous GNC systems?*

- Should requirements and metrics used by space agencies be reformulated or adapted, taking inspiration from other domains?

Key Findings from Track 7

The key findings that resulted from the open interactive discussion and the interactive polling in this Track 7 included the following:

1. Appropriate audience mix for this track: Out of 55 participants polled, 18 had worked in non-space domains (automotive, aviation, underwater vehicles) and 11 had experience in both space and non-space.
2. Cross-pollination: A large majority (54 out of 62 votes) agreed or strongly agreed that cross-pollination between space and non-space V&V techniques would benefit the GNC community.
3. Spin-ins: Positive examples included formal methods from aviation (Airbus adoption),

automotive metrics and simulation, DO-178 certification processes, CI/CD, and autocoding. Reported benefits were largely very positive (8) or somewhat positive (4), with no negative experiences.

4. AI/ML probes: Efficiency gains (e.g., anomaly detection) were noted, but risks remained in verification (e.g., unknowns addressed by SOTIF). Hybrid approaches combining classical and ML methods were suggested. Polling captured strong interest in AI/ML as a gamechanger, albeit risky due to black-box behavior and high data requirements.

5. Getting started: Suggested steps included academia–industry co-location, benchmarks and competitions, starter kits and GUI-based tools, and practical education.

6. Requirements and metrics adaptation: Agencies may need to revise how requirements are defined and adopt metrics inspired

by non-space industries to enable efficient and comparable verification practices.

The consensus reached at the end of this track was that non-space practices provide valuable templates for improving GNC V&V in the space domain. The transfer requires adaptation, simplification, and institutional support, with agencies playing a central role in enabling uptake. Requirements and metrics will be central levers in making this transfer practical and effective.

TRACK 8 – POSTERS: INNOVATIVE STUDENT RESEARCH IN GN&C/V&V

The Inter-Agency FNC V&V Working Group, recognized that the academic community is home to a wide variety of multi-disciplinary engineering research related to GNC and that university students represent the next generation of GNC engineers. Some of the most innovative thinkers at universities are conducting research that relates to developing modern

and efficient GNC V&V methods and tools.

As such, the Working Group had a strong interest in engaging university graduate-level students in the Workshop. The Workshop organizers belief was that there is value in providing both a showcase for student research and an interactive forum for students to better understand the real-world GNC V&V challenges being discussed at the workshop.

The Working Group therefore solicited posters from both MS and PhD candidates which highlight their current academic research and its potential impact on GNC V&V challenges. A total of 13 posters from several prestigious universities were on display during the dinner gathering at the end of Day 1.

Figure 6. Posters Displaying Innovative Student Research in GN&C/V&V



TRACK 9 – HARDWARE-BASED V&V

This Track described and examined some specific examples and instantiations of innovative Hardware-in-the-Loop (HITL) test facilities in order to better understand the unique value (and any barriers) of hardware-based testing, versus pure software simulation, to the overall GNC V&V process.

The technical attributes of certain GNC HITL test facilities were highlighted along with the procedures used. An objective of this Track was to identify practical lessons learnt from using hardware-based test facilities in the support of GNC V&V.

The inclusion of this Track 9 represented a scope expansion to the Workshop content by our algorithm-focused Inter-Agency GNC V&V Working Group, in response to the several hardware V&V related abstracts received from the community. This track fostered interactive technical dialogue,

aligning with the conference's emphasis on practical industrial-compatible V&V advancements. Some of the key questions addressed in the Track 9 post-talk interactive discussion included:

- *What are the practical lessons learned from using hardware-based test facilities in the support of GNC V&V?*
- *What are the barriers to using hardware-based test facilities?*
- *Which aspects of a GNC system are more easily/readily simulated rather than tested with hardware?*

Key Findings from Track 9

The key findings that resulted from the open interactive discussion and the interactive polling in this Track 9 included the following:

1. Practical Improvements: HITL testing offers developers practical improvements: early HITL testing reduces late risks (e.g., to identify sensor deviations, processor overloads). Allows detection of unforeseen, by analysis alone, behaviors.

An example was provided of a CubeSat HITL test which identified the potential for star tracker outages (earlier than predicted from just an analysis of tracker specifications). It was noted that Monte Carlo simulation can help to identify what HITL tests are needed and it can help to design those tests.

Because simulation cannot cover everything, all testing, including HITL testing, are necessary and are both supplementary and complementary to simulation, including Monte Carlo.

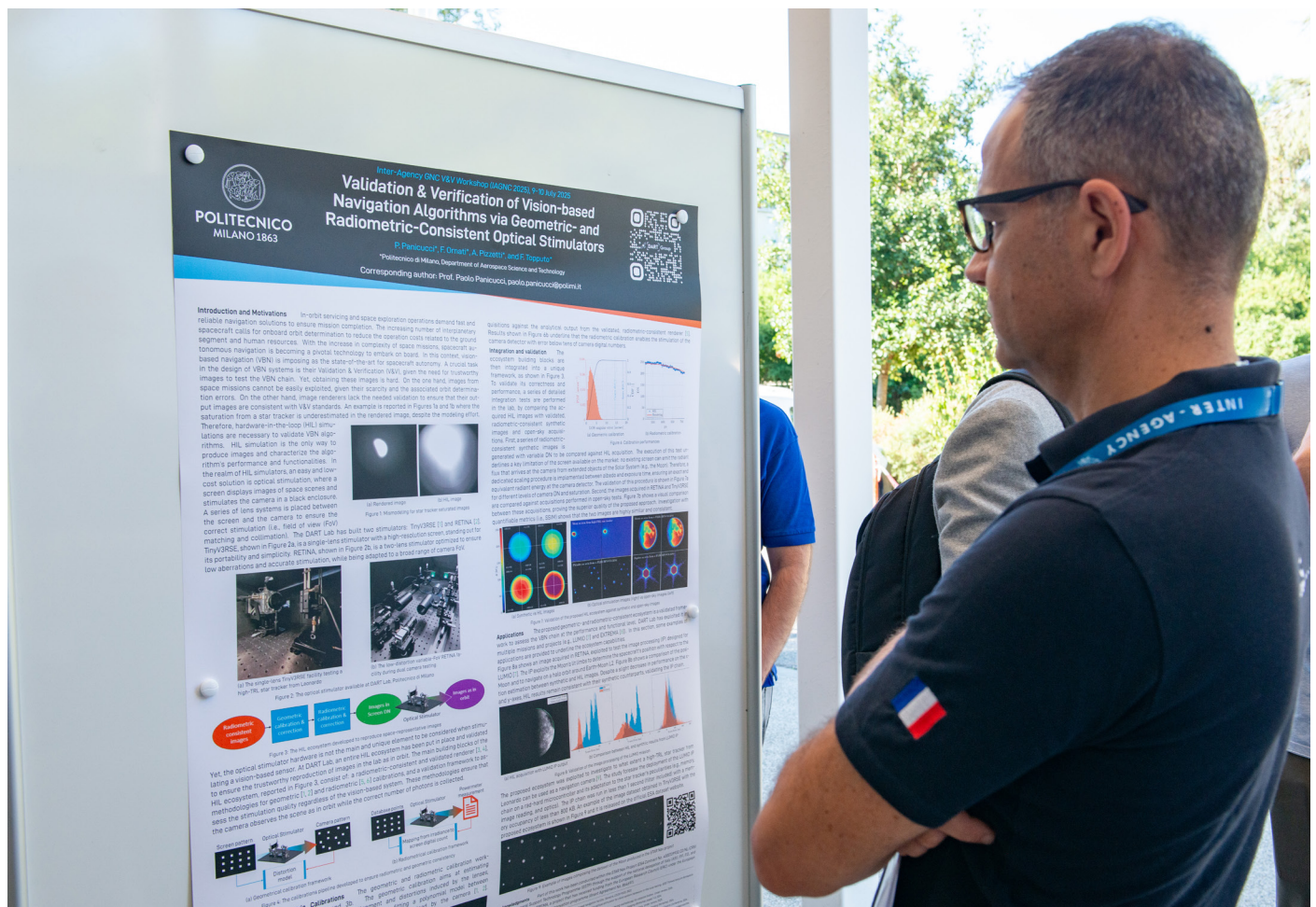
2. Plan for Evolution of Testbed: Needs evolve but should start HITL testbed development early (Phase B) for complex algorithms (e.g., Vision Based Navigation (VBN) algorithms hosted on flight processors).

3. Challenges: the cost/time for HITL testbed setup clearly motivates reuse; HITL testbeds provide excellent support for flight operations, especially anomaly investigations and resolution; it is critical to take steps for ensuring testbed representativeness; for example, the calibration of hardware elements is essential.

4. Future Directions: Broader interagency focus on HITL; Standardization/reusability cuts costs. SmallSat/CubeSat industrial providers embracing HITL testing; open datasets/tools; Important to consider that HITL testbeds can generate realistic sensor data sets for Machine Learning (ML) training. Balancing realism for ML (e.g., domain gap quantification).

There were several audience questions concerning data flows for VBN and attitude control data flows. A wide-ranging general discussion of HITL testing advantages also took place touching on the following: Close-to-flight conditions, interface handling, surprise prevention.

Can draw inspiration from robotics hardware testing; "test" vs. "validate"; quantify domain shift via characterization (real materials, calibration, ground truth); certification of HITL testbed for users.



TRACK 10 – JPL GNC V&V SPECIAL SEMINAR TALKS (POST-WORKSHOP)

A special online GNC V&V Seminar was held by the Inter-Agency working group on 11 September 2025 to showcase a set of JPL lightning talks that we were unable to hear at the July workshop.

Five of these six JPL talks were originally intended to be included in Track 1 of the Workshop (Recent Real-World Space Mission GNC V&V Experiences) and the remaining sixth talk entitled “JPL’s Evolution of the GNC V&V Process” was to have been included in Track 6 (New Space Alternative Approaches to the Traditional GNC V&V Process).

As described by several of the JPL speakers there were some lessons learned from JPL’s recent GNC V&V experiences include:

- Advantages can be obtained by performing basic end-to-end closed loop GNC, Flight Software (FSW), and Testbed functionality

using multiple different test venues. These were described as “quick and dirty sanity checks for debugging, and correction of errors”. Test venues include engineering workstations, avionics test benches, hardware in the loop system testbeds, and system-level Integration and Test (I&T).

- In this manner GNC V&V “shakeout” testing is completed in venues with gradually increasing complexity, starting in workstation testbeds, then avionics/system testbeds with increasing HWIL configurations and complexity. All of which enable, in a combined fashion, system level V&V.
- Upon initial shakeout completion in all test venues, a “GNC checkout” procedure is formalized and executed in I&T before every system-level test to verify GNC readiness for GNC closed-loop V&V testing in the system-level test environment.

- A practice employed as part of the Psyche V&V campaign was the completion of thousands of GNC subsystem Monte Carlo simulations, with randomly dispersed values for thrust vectors, mass, attitude, body rates, thrust level, swirl torque, hardware biases, etc. This typical V&V process was then subsequently followed by running a handful of carefully selected simulations at the system level on the Psyche Flight Software Testbed. This JPL lesson learned aligned with a very similar finding from Track 9 where it was also noted that adding a few carefully selected HITL cases could well complement a traditional Monte Carlo simulation campaign.

- Having a formal plan and multi-stage incremental process for model certification provided benefits to the V&V process, especially for planetary Entry, Descent, and Landing (EDL) applications. The four stages of JPL’s model certification process are: 1) model functional definition, 2) physical model

validation, 3) mathematical model verification, and 4) plug-in verification.

In regard to the future, the fundamental JPL message centered around the complex and diverse GNC developments anticipated for JPL’s proposed missions. Therefore, JPL is motivated to find ways to reduce the GNC implementation and associated V&V costs in their future developments by reducing I&T issues early. JPL is studying next generation autonomous GNC architectures which will depend on distributed computing and power.

These ambitious missions are characterized by, among other things, high accuracy pinpoint landings on Mars based on computer vision and GNC for aerial mobility which entails on-board autonomy, Terrain Relative Navigation (TRN) and hazard avoidance. These types of complex missions thus serve as the motivating drive for JPL to find ways to reduce GNC system implementation and V&V costs in future developments by reducing integration & test issues as early as possible.

The JPL GNC engineering team is preparing for future missions in which will feature autonomy for increased robustness during mission critical events, vision-based algorithms, and high precision landing using intensive on-board optimization. These factors will combine to present significant GNC V&V challenges. Part of their solution set is to use highly integrated multi-disciplinary teams that span and cover GNC, systems engineering, flight software, avionics, and power.

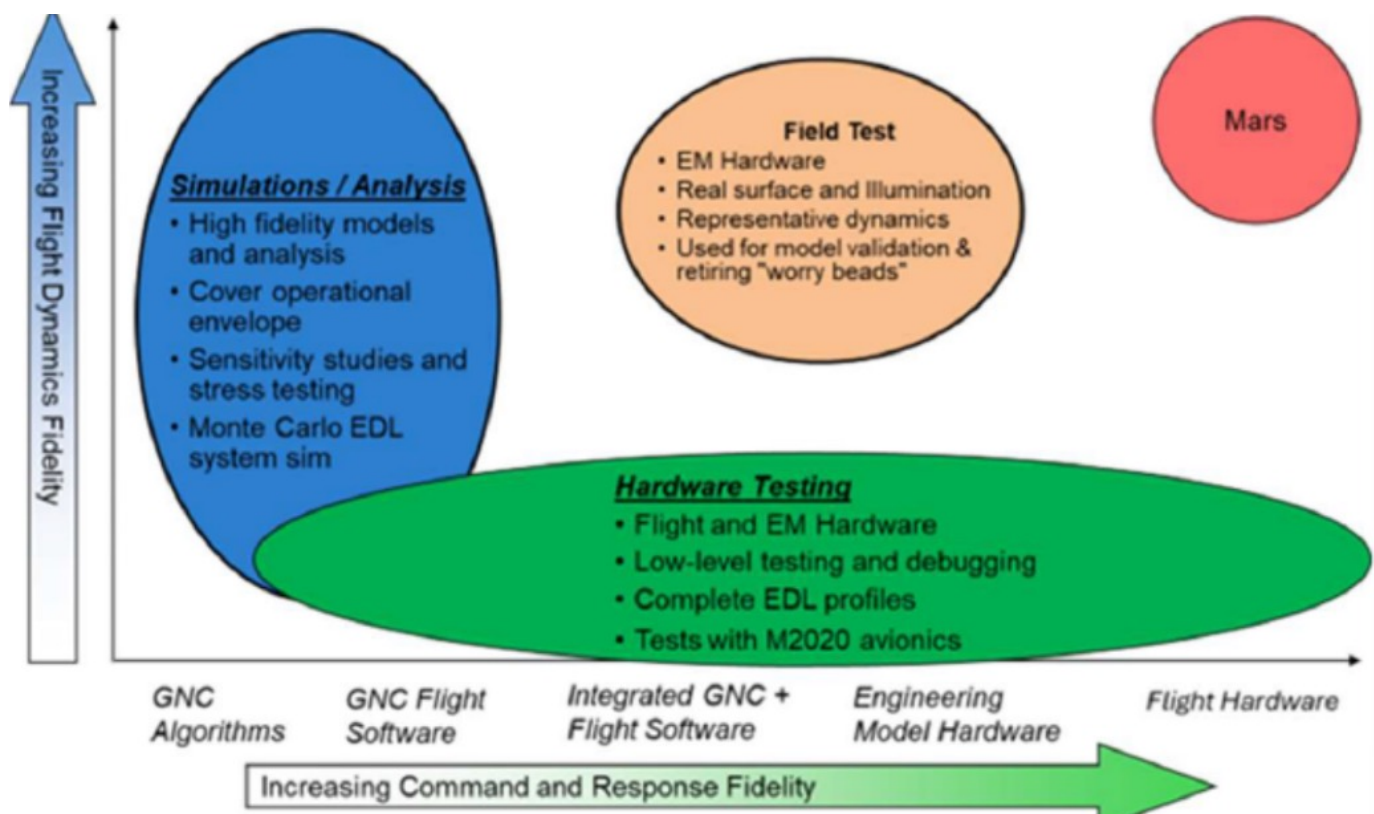
This would be a paradigm shift away from the current traditional practice used at JPL (and also at many other organizations) in which the actual integrated hardware/software verification testing of GNC sensors, algorithms, and actuators does not occur until spacecraft system-level I&T, which occurs relatively late in the design and development process. The proposed shift involves performing GNC verification testing and the resolution of system integration issues earlier in the design and development process in a HITL environment. As described in one of the

JPL talks the value proposition of this dedicated HITL verification testing approach would be:

- 1) it would allow the GNC engineering team to focus on GNC integration issues and verification testing in isolation from other spacecraft system issues,
- 2) the GNC team would have more flexibility to solve problems and push boundaries, and
- 3) GNC would have greater opportunity to de-risk and infuse new technology into flight systems.

Moreover, with common subsystem elements (i.e., flight computer, interconnect, software base) this envisioned shift to a HITL testing approach can have a low per-project cost/schedule impact which is something that would benefit both NASA and JPL. The overall JPL V&V approach is illustrated in Figure 7, which they refer to as the “L-curve”. It depicts how JPL combines, over time as the GNC system evolves, increasing levels of command and response fidelity

Figure 7. Overall JPL V&V Approach (the “L-curve”).



through hardware testing with increasing flight dynamics fidelity through simulation/analysis. This V&V approach also includes elements of Field Testing, at least for their Mars missions, to more closely emulate the 'real world' and to support model validation and risk retirement.

WORKSHOP KEY FINDINGS

After careful consideration and discussion of all the material presented at the Toulouse workshop the Inter-Agency GNC V&V Working Group formulated the following set of overall workshop findings:

1. It is essential to fully understand the requirements to be verified before embarking on a V&V campaign.
2. Sensitivity analysis is critical to revealing and understanding which uncertain parameters are dominating system performance, stability, and risk.
3. Robustness analysis is largely standardized but there is work to be done to standardize the process of sensitivity analysis.
4. It is a very beneficial practice to adopt an 'integrated verification' approach where GNC V&V efforts start early in a project lifecycle. Integrated verification involves doing quick V&V iterations, using reduced order models, as part of each design and analysis cycle. A suite of verification

tools of increasing fidelity can be used to cover the entire design and development activity.

Lower fidelity verification tools can be used early on to gain design insights. This can be followed by the use of the highest fidelity tools and models for the final 'run for the record' V&V activities that constitute the formal compliance proof needed prior to launch/first flight.

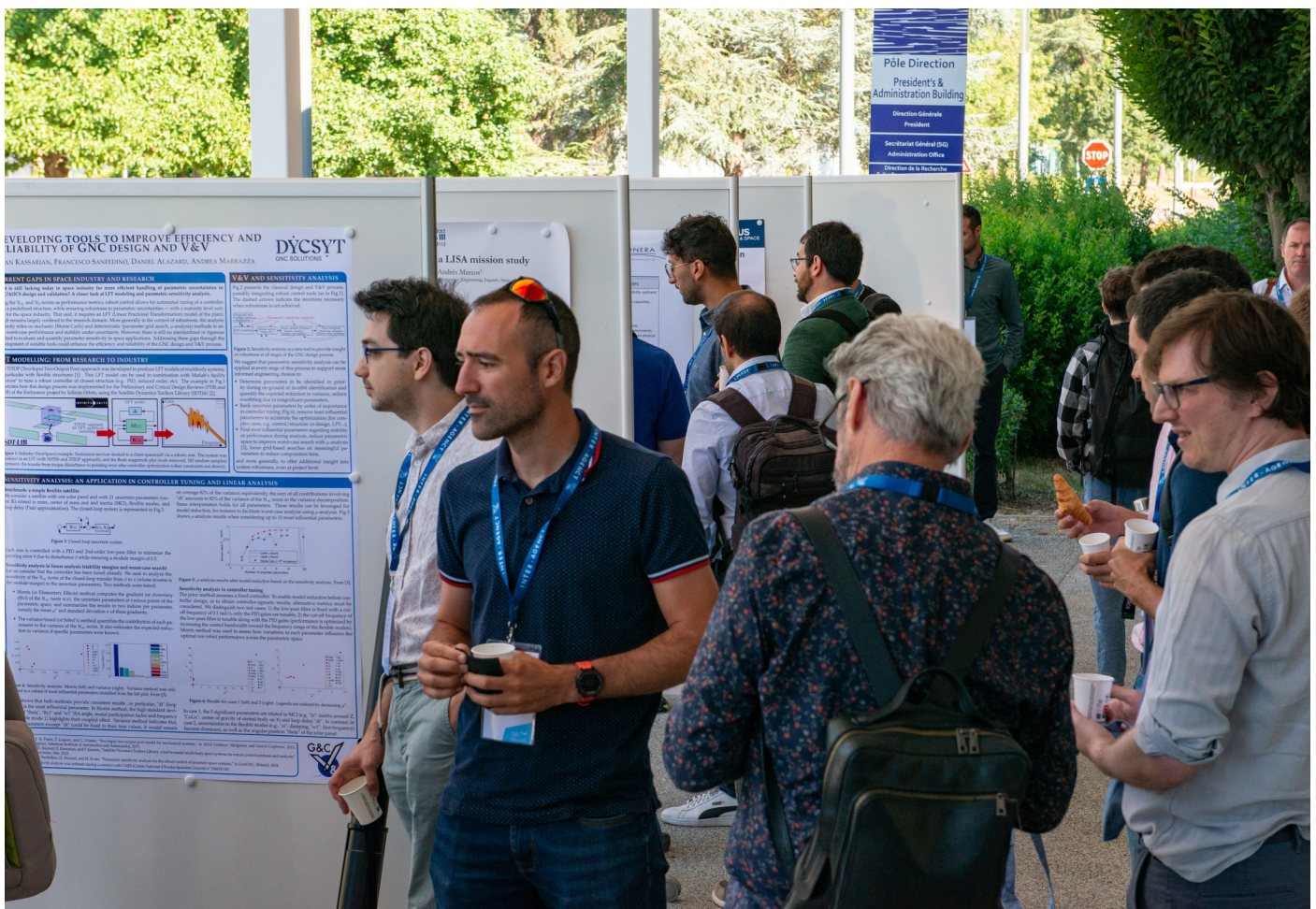
5. Monte Carlo simulation is still the 'Gold Standard' to prove compliance with performance requirements. There is no new verification technique (or combination of techniques) that can broadly replace Monte Carlo verification. (However, see discussion about LFTs below).

6. No single tool seems to cover all needs. Most tools have limitations and are complemented by Monte Carlo simulations. The LISA DFACS example presented at this workshop demonstrates that new tools can enable novel V&V analyses.

7. Industry needs new tools for more efficient (i.e., faster than typical Monte Carlo) verification processes. The Monte Carlo approach cannot be replaced, but the process can be accelerated. New techniques and approaches are needed to reduce turnaround time by orders of magnitude and enable realistic, large-scale verification and tuning.
8. The Linear Fractional Transform (LFT) models for uncertainties can serve as a complementary V&V technique to Monte Carlo: the LISA DFACS example cited above stands out as an excellent example of this.
9. There is an emergence of AI in GNC applications. The data-driven methods of AI/ML are here to stay. The use of these algorithms offers promising potential research areas for the benefit of GNC V&V but are not without their challenges.
10. There is a trend towards the increasing use of multidisciplinary, multi-physics and co-design approaches in simulation. Examples of this include

structural dynamics modeling and Computational Fluid Dynamics (CFD) modeling integrated into closed loop GNC simulations. These multi-physics and co-design approaches appear to be reviving an academic interest in the V&V field.

11. The use of GPUs for computational parallel processing is an advantageous option not only to accelerate Monte Carlo based simulation, but also to accelerate worst-case optimization and SDP-based approaches such as IQC analysis.
12. Industrial organizations can benefit from having reusable standardized V&V processes.
13. Robustness analysis and Monte Carlo and robustness analyses are complementary V&V techniques: Monte Carlo analysis is excellent for understanding system performance and robustness across a well-defined set of uncertainties, but struggles at very high confidence levels. Robust analysis tools are powerful when modeling is accurate (i.e., limited model uncertainty).



Robustness analysis can identify which combination of parameters results in worst cases, and perhaps can then guide targeted Monte Carlo simulations, and reduce over-design early in development

14. There may be benefits obtained from shifting from Worst Case Requirements to Probabilistic Requirements.

15. Bridging the gap between academia and industry in the area of GNC V&V calls for easily accessible tools, realistic problems, and knowledge transfer (e.g., starter kits, competitions, conference session and workshops for education and training). The knowledge transfer opportunity provided by the July 2025 workshop was a good step in the right direction taken by the working group, as it the upcoming European satel-lite benchmark problem competition.

16. Academic researchers would benefit from having benchmark problems grounded

in the real-world mission applications.

17. Model-based V&V is fundamentally at the core of GNC V&V since Hardware-in-the-Loop testing cannot typically reproduce the required precision nor match the ability of simulations to do large numbers of runs with a wider coverage of anticipated dispersions. Extensive, comprehensive, and rigorous model validation is therefore a critical necessity prior to the verification campaign.

18. Techniques for the often very necessary step of large-order model reduction, and for the subsequent validation of the reduced order model, are typically critical elements in the GNC V&V process.

19. Non-space domain V&V practices can provide valuable templates for improving GNC V&V in the space domain. The transfer requires adaptation, simplification, and institutional support, with agencies playing a central role in enabling the uptake of these non-space V&V practices. However, the space domain industrial



practitioners will need clear and understandable requirements and metrics in order to make this transfer across domains practical and effective. The space agencies may need to revise how requirements are defined and adopt metrics inspired by non-space industries to enable efficient and comparable verification practices.

20. Hardware-based V&V (i.e., HITL testing) was frequently mentioned and appears to be becoming more prevalent, especially for CubeSat/Nanosat platforms and also for vision-based navigation systems. Establishing testbeds for hardware-based verification testing is costly and time consuming but increasingly critical. Monte Carlo simulation can help to identify what tests are needed and it can help to design the tests. Because simulation cannot cover everything, all testing, including HITL testing, are necessary and are both supplementary and complementary to simulation, including Monte Carlo simulation.

21. V&V benefits can be accomplished

by using a 'Design for Testability' approach (e.g., employ simple FDIR architectures).

22. Industry appears ready to adopt new V&V tools pioneered by academia but organizational infrastructure barriers exist. The scalability of academic methods and tools must be carefully considered to ensure they are viable for large, complex industrial space-flight mission applications.

Having long-term, responsive support from a stable entity is essential when adopting a new tool, as a company requires reliable support services for upgrades/bug fixes for every key tool in its design and development process work-flow.

23. A consensus takeaway was that academic V&V methods show promise, but simplicity, traceability, training, and standards will be key for adoption in industry. The space agencies can play a central role in enabling both the transfer and the practical uptake of these academic methods.



KEY RECOMMENDATIONS FROM SECOND GNC V&V WORKSHOP

Based on the aforementioned key overall workshop findings identified in the previous section, the Inter-Agency GNC V&V Working Group recommends the following courses of action:

Recommendations to the Space Industry

1. Adopt the best practice of including GNC V&V steps from the start of a project using a suite of verification tools of increasing fidelity to cover the entire design and development activity.
2. Investigate ways to extend and/or speed up the typical Monte Carlo verification process. GPUs should be considered as an option to accelerate the Monte Carlo based simulations. Consider investigating advanced methods for conducting Monte Carlo simulations [8].
3. Investigate broader use of LFT models for uncertainties which can complement traditional Monte Carlo simulation-based verification.

4. Industry should examine the cost/benefits trade of establishing largely reusable, efficient, and standardized V&V processes. Recommendations to Space Agencies

5. Adopt the best practice of including GNC V&V steps from the start of a project using a suite of verification tools of increasing fidelity to cover the entire design and development activity. (Also recommended to the Space Industries.)

6. Consider how to shift from imposing worst case requirements to levying probabilistic requirements

7. Serve as a vital bridge between academia and the space industry. This can include providing academia realistic benchmark problems (and facilitating benchmark problem open competitions), along with real-world models, and actual test/flight data. The challenges in sharing these types of information are more of the non-technical administrative aspects than



the technical ones (e.g., managing IP constraints, conforming to export control regulations, etc.).

8. Support industry in their adoption of new V&V tools by working to overcome the identified infrastructure barriers that hamper their integration into existing industrial workflows. This would entail the development of awareness and readiness education/training, making specialized expertise available, and creation of V&V tool sustainability and maintenance best practices. Workshop discussions identified key enablers such as open-access libraries, training starter kits, benchmark problems, community-supported tools, and the establishment of new standards to make academic innovations accessible to industrial practitioners.

9. Focus, jointly with academia and industry, on resolving the mismatch of semantics and metrics associated with the application of AI in space GNC systems. AI uses loss functions and statistical metrics whereas GNC engineers typically use

stability margins, eigenvalues, and deterministic guarantees. New, perhaps hybrid, performance metrics are needed now to bridge between the AI standards, semantics, and metrics and the traditional GNC V&V standards for space systems.

10. Explore further where and how the non-space domain V&V practices can provide value for improving GNC V&V in the space domain, especially in cases where AI/ML technology is employed. This includes the definition of clear and understandable new requirements and encouraging the adoption of V&V metrics inspired by non-space industries to enable efficient and comparable verification practices.

11. Formulate a standard (or standards) providing guidelines for the planning and execution of a formal model certification process as part of the overall V&V process. This standard should be tailorable and could potentially leverage the sequential multi-stage model certification steps used by JPL which are:

- 1) model functional definition,
- 2) physical model validation,
- 3) mathematical model verification, and
- 4) plug-in verification.

Recommendation to Space Researchers in Academia

12. Further investigate the practical use of AI/ML based methods for GNC V&V applications. This is a potentially rich source of interesting, intellectually challenging, and relevant graduate research activities to be conducted in collaboration with industry/space agencies.

To close the knowledge gap between the AI and GNC communities, beneficial research topics should include establishing robustness guarantees, scalability, reliability metrics, and practical certification processes.

Joint Recommendation for the Space Industry, Space Agencies, and Academia

13. Collaborate on implementing a program where academic researchers are embedded (i.e., physically co-located) within either an industrial setting and/or within a space agency. The experiences gained by this type of program will increase mutual understanding (e.g., develop a common terminology), facilitate knowledge transfer, foster a better understanding of mission applications, and allow for more efficient use of V&V tools/methods.





CONCLUSIONS

This report summarizes the outcomes of the July 2025 GNC V&V Workshop held in Toulouse, France, along with key findings and recommendations.

The workshop contributors hope that sharing the outcomes of the GNC V&V Workshop in this way will provide a solid basis for further discussions on this critical subject within the global GNC community of practice. There were 7 technical tracks over two days with lightning talks (8 minutes each), dedicated Q&A and interactive discussions with live Mentimeter polling, two powerful keynote addresses, and two special invited presentations. Topics spanned rendezvous maneuvers, launchers, reentry vehicles, swarms, formation flying, and other challenging applications.

The workshop organizers were very pleased to host such a diverse, balanced mix of individuals from the space industry, academia, and agencies (and many different countries). It was an environment where the speakers were very accessible, lively discussions were taking place

and there were many networking opportunities. It would be fair to describe it as an "amazing crowd" with many enthusiastic bright minds tackling unsolved problems and inventing new approaches.

The workshop interactive discussions revealed a passionate and enthusiastic community of subject matter experts eager to share their knowledge and help prepare for the future. There was a strong positive participant response to the workshop's non-traditional format featuring the brief lightning talks coupled with the extended duration interactive discussion/polling period.

There was clear feedback from the workshop participants that GNC V&V is an important and interesting topic. The vast majority of participants expressed a strong interest in having a future workshop. The workshop was deemed a success in fostering collaboration, sharing ideas, and advancing GNC V&V. On a cautionary note, the more we, as a GNC community of practice, delay V&V research and

development efforts that will support complex GNC systems for space applications, the more we will be hampered in implementing modern autonomous system architectures and designs. Without proper V&V, it is harder to identify brittle architectures and design shortcomings early in a project life cycle.

Consequently, it will be more difficult and expensive to introduce corrective actions into designs late in the project flow.

The criticality of the V&V process was reinforced by discussions at the Inter-Agency seminar series and workshop. It is important for us all to embrace V&V as not simply an academic exercise, but rather a safety-critical process.

The ultimate goal is to have the required tools and methods to verify emerging technologies, such as AI/ML, in order to strike the correct balance between safety and innovation.

Our Inter-Agency GNC V&V working group will continue its efforts to engage in community discussions such as the workshop forum described herein – most importantly our intention is to maintain the momentum of the Toulouse workshop going forward.

For example, the European satellite benchmark problem competition has been kicked off in February 2026 and a GNC V&V focused conference session (similar to the one held here at the 2026 AAS GNC Conference) is planned for the upcoming ESA GNC Conference to be convened in Sevilla, Spain (28 September–2 October 2026).

The Inter-Agency GNC V&V Working Group also has preliminary plans to convene a third GNC V&V Workshop in 2028. The workshop contributors welcome technical feedback, from the global GNC community of practice, on the GNC V&V topics addressed at the workshop and summarized in this report.



ACKNOWLEDGMENTS

Fondation
ISAE - SUPAERO



All the members of the Inter-Agency GNC V&V Working Group would like to recognize here the support received during the process of planning and executing this workshop in Toulouse. The success of our workshop clearly stems from the dedication, cooperation, and generous contributions of many individuals and organizations. We therefore wish to express our sincere gratitude to the following organizations, whose invaluable support made this workshop possible.

L'Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), a world leader in aerospace innovation and education, deserves special recognition for serving as our gracious workshop host. The meeting facilities, as well as the other accommodations and services, provided to us were perfectly suited to our workshop and we benefited greatly from their campus location in Europe's aeronautics and space capital, Toulouse. The Inter-Agency GNC V&V Working Group mutually shares with ISAE-

SUPAERO the spirit of scientific and technological excellence, focused on serving the future needs of the space agencies and our industry partners.

In particular we acknowledge the generous contribution to the workshop budget from the Fondation ISAE-SUPAERO (<https://fondation-isaie-supaero.org/>). We also wish to acknowledge the support of the CNES-affiliated Communities of Experts, more generally known as COMET, for co-sponsoring our workshop. Created by CNES in 1998, the COMET organization serves to federate the different spheres of aerospace expertise through integrated networks.

COMET is currently composed of 20 communities bringing together more than 3,000 experts from the academic, industrial and institutional disciplines. DYCSYT, a GNC Solutions company, is also to be acknowledged and thanked for organizing the two-day tutorial short course that preceded the workshop covering 'Modeling, Control, Analysis, and V&V Applied to Robust Attitude Control of a Large Flexible Spacecraft'.



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We especially must recognize and express our enthusiastic thanks for the outstanding diligence, dedication, and attention to detail of Professor Francesco Sanfedino for his lead role in organizing the Toulouse workshop at the ISAE-SUPAERO campus.

More broadly speaking we certainly appreciate the support of the international GNC community of practice for embracing the need to better prepare ourselves for the future and for their open spirit of collaboration as together we all attempt to build a modern GNC engineering ecosystem that includes new approaches, methods, tools, and technologies for GNC V&V.

Lastly, we all wish to emphatically acknowledge the early fundamental contributions made by Samir Bennani (PhD, retired ESA GNC Specialist) in initially identifying the GNC V&V concerns raised in this report and his instrumental role in establishing the Inter-Agency GNC V&V Working Group. [Well done all.](#)

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APPENDIX: GNC V&V WORKSHOP LIGHTNING TALKS (LISTED BY TRACK)

Track 1: Recent Real-World Space Mission GNC V&V Experiences

T1.1 - Recent Real-World Space Mission GNC V&V experiences - Amphi 2 Chair: Jeroen Vandersteen (ESA), Miguel Morere (CNES), Neil Dennehy (Consultant)	
Validation approach for a rendezvous GNC bi-compatible with Vision and LIDAR sensing	Vincent DUBANCHET (TAS); Romain MORA (TAS); Davide CASU (TAS); Angelo AUSIELLO (TAS)
Reusable V&V methodology for GNC algorithms with application to EARS satellite re-entry	Adolfo Molina Delgado (DEIMOS); Giuseppe Edoardo Addario (DEIMOS); Giovanni Medici (DEIMOS); Javier Herrero Martin (DEIMOS); Valentina Raimondi (CNR-IFAC)
Validation of Guidance, Navigation & Control on-board architecture for Mars Sample Return Rendezvous	Alexandre Falcoz (Airbus DS); Benjamin Charbaut (Airbus DS); Marc Jacquiau (Airbus DS); Keyvan Kanani (Airbus DS); Alex Marchand (Airbus DS); Pierre Blanc-Pâques (Airbus DS); Leila Lorenzoni (ESA); Paul Duteis (ESA)
USA DFACS Robustness Analysis	Martin Maurice (Airbus DS)

Track 2 – Efficient V&V Tools/Methodologies for Systems Using Modern GNC Technologies

T2.1 - Efficient V&V Tools and Methodologies for Systems Using Modern GNC Technologies - Amphi 2 Chair: Jean-Marc Biannic (ONERA), Francesco Sanfedino (ISAE-SUPAERO), Hélène Evain (CNES)	
GNC Flight Software Development and Verification: A process, its evolution, and the challenges involved.	Leonardo Borges Farconi (DLR)
Feasible and safe CONOPS analyses for Close Proximity Operations - Use-case of EROSS project	Vincent DUBANCHET (TAS); Romain MORA (TAS); Davide CASU (TAS); Angelo AUSIELLO (TAS)
Combining Sensitivity and Robustness Analyses for AOCs Verification and Validation	Maurice Martin (Airbus DS)
Validation of the DLR Crater Navigation System for Autonomous Precise Lunar Landing	Eleonora Andreis (DLR); Hans Krüger; Stephan Theil (DLR)
GPU accelerated and differentiable simulators for modern GNC engineering	Valentin Preda (ESA)
T2.2 - Efficient V&V Tools and Methodologies for Systems Using Modern GNC Technologies - Amphi 2 Chair: Jean-Marc Biannic (ONERA), Francesco Sanfedino (ISAE-SUPAERO), Hélène Evain (CNES)	
Conservative and compliant Monte-Carlo simulation campaigns by design	Nicolas Deslaef (ESA); Francois Benoit du Rey (ESA)
IQClab: An IQC based toolbox for robustness analysis and control design - updates and new features	Joost Veenman (Novantec)
Validation of Autonomous Orbit Control of a swarm in a system simulator	Cécile DECHOZ (CNES); Irene Valenzuela Molina (CNES); Marie-Claire CHARMEAU (CNES); Bernard PONTET (CNES); Julien GALIZZI (CNES); Yoan GREGOIRE (CNES); Felipe ALVES SUANA (CNES)
Verification and Validation of Fault Detection and Diagnosis algorithms for launch vehicle TVC systems	Stefano Fari (DLR); David Seelbinder (DLR); Stephan Theil (DLR); Pedro Simplicio (ESA)
Robust H2-Norm Analysis of Uncertain Space Systems	Tommaso Casati (ONERA)

Track 3 – Bridging the Research–Industrial Gap

T3 - Bridging the Research-Industrial Gap - Amphi 2 Chair: Massimo Casasco (ESA), Stephan Theil (DLR), Simone Giabuschi (ASI)	
Framework for Systematic Control Design and Verification in Drag-Free Missions	Francesco Basile (TAS); Carlo Novara (POLITO); Vinicius Marchioli (POLITO); Mattia Boggio (POLITO); Michele Pagone (POLITO)
On-board Safety Filters for Thrust Vector Control of Launchers	Aitor Gomez (Aalborg University); João Belfo (DEIMOS); Jose Vasconcelos (DEIMOS); Pedro Simplicio (ESA); Massimo Casasco (ESA); Jakob Stoustrup (Aalborg University)
Developing tools to improve efficiency and reliability of GNC design and V&V: from research to industry	Evan Kassarian (DYCSYT); Francesco Sanfedino (ISAE-SUPAERO); Daniel Alazard (ISAE-SUPAERO); Andrea Marrazza (DYCSYT)
Closed-loop CFD simulator for fuel sloshing mitigation V&V	Michael Fogel (Rutgers University); Laurent Burlion (Rutgers University)
Probabilistic Robust Performance based on Linear Fractional Transformations and Polynomial Chaos Expansion	Harald Pfifer (TU Dresden); Mario Izquierdo Serra (Airbus DS); Maurice Martin (Airbus DS); Stefan Winkler (Airbus DS)

Track 5 – V&V Research in Academia

T5 - V&V Research in Academia - Amphi 2 Chair: Daniel Alazard (ISAE-SUPAERO), Christelle Cumer (ONERA), Valentin Preda (ESA)	
Advancements in Autonomous Space Robotics at Onera : Control Frameworks and Co-Design Strategies for On-Orbit Servicing and Assembly	Sofiane Kraïem (ONERA); Mathieu Rognant (ONERA); Sérgio Waitman (ONERA)
GNC V&V experiences from a LISA mission study	Diego Navarro-Tapia (UC3M); Andres Marcos (UC3M)
Verifying the implementation of optimization algorithms via Integral Quadratic Constraints	Alexandre Chapoutot (ENSTA); Pierre-Ioic Garoche (ENAC)
OvertPoly: An Algorithm for Scalable and Precise Verification of Nonlinear Neural Feedback Systems	Samuel Akinwande (Stanford University); Chelsea Sidrane (KTH); Mykel Kochenderfer (Stanford University); Clark Barrett (Stanford University)

Track 6 – New Space Alternative Approaches to the Traditional GNC V&V Process

T6 - New Space Alternative Approaches to the Traditional GNC V&V Process - Amphi 2 Chair: Jeroen Vandersteen (ESA), Géraldine Constant Filaire (CNES), Stefan Winkler (Airbus DS)	
Experimental verification and validation of the CubeSpec mission high-precision pointing system	Leonardo Peri (KU Leuven); Dirk Vandepitte (KU Leuven)
Attitude Determination and Control System Development for Nanosats with Focus on Performance, Robustness and Reliability	Mikel Samson (arcsec); Rhimas Van de Putte (arcsec); Wim De Munter (arcsec)

Track 7 – Non-Traditional Techniques for GNC Algorithm V&V for Non-Space Applications

T7 - Non-Traditional Techniques for Conducting GNC Algorithm V&V for Non-Space Applications - Amphi 2 Chair: Stephan Theil (DLR), Neil Dennehy (Consultant)	
End-to-End Development and Validation of GNC Algorithms: Towards an Iterative and Automated Process	Jose Luis Redondo Gutierrez (DLR); Ansgar Heidecker (DLR); Marco Sagliano (DLR); Andreas Wenzel (DLR); Leonardo Borges Farconi (DLR); Macés Hernandez Jose Alfredo (DLR); Henrik Harms (DLR); Francesco Marchetti (DLR); Stefano Fari (DLR); David Seelbinder (DLR); Stephan Theil (DLR)
Leveraging robust control tools for code-level formal verification of GNC algorithms	Elias Khalife (Virginia Tech); Mazen Farhood (Virginia Tech); Pierre-Ioic Garoche (ENAC)
Bridging Non-Space V&V Practices to Enhance Space GNC Systems	Stephan van Beek (MathWorks); Ossi Saarela (MathWorks); Jean-Paul Marcade (MathWorks)
Verification, Validation and Safety Assessment of Machine Learning Airborne Applications	Konstantin Dmitriev (MathWorks)

Track 8 – Posters: Innovative Student Research in GN&C V&V

COCKTAIL DINNER + T8 - Poster session for Innovative Research in GNC/V&V - Cafeteria	
The CubeSat attitude V&V air bearing facility installed at ESA-ESTEC	Andrea Curatolo (Università di Bologna)
Towards a Verifiable Linear Programming-based SCVx Algorithm	Daniil Berrah (ENSTA); Damien Hoareau (ENSTA); Alexandre Chapoutot (ENSTA)
Formal verification of artificial intelligence in guidance, navigation and control systems	Céline Bellanger (ENAC); Pierre-Loïc Garoche (ENAC); Matthieu Martel (Université de Perpignan); Céilia Picard (ENAC)
Gaussian process-based grid point allocation for robust control	E. Javier Olucha (Eindhoven University of Technology); Valentin Preda (ESA); Amritam Das Eindhoven (University of Technology); Roland Tóth (Eindhoven University of Technology)
Methodologies, algorithms and processes for the development of Thrust Vector Control for aerospace applications	Luca Palombi (AVIO)
Collision avoidance maneuver computation and validation for long-term space encounters	Matthieu Masson (LAAS-CNRS); Christian Artigues (LAAS-CNRS); Denis Arzelier (LAAS-CNRS); Fabrizio Dabbene (CNR-IEIT); Mioara Joldes (CNR-IEIT); Martina Mammarella (CNR-IEIT); Federica Paganelli-Azza (AIKO)
A Bottom-Up Approach for Radiometric Validation of Synthetic Imagery	Andrea Pizzetti (POLIMI); Paolo Panucci (POLIMI); Francesco Toppoto (POLIMI)
Modular Attitude Determination and Control System Approaches for a Broad Range of Nano-Satellites	Lisa Elsner (ZfT); Vijay Nagalingesh (ZfT); Klaus Schilling (ZfT)
Certifying Quantized Neural Networks for Autonomous Control -- a Robustness-based Approach	Wahiba Bachiri (Abou Bakr Belkaid university); Pierre-Ioic Garoche (ENAC); Yassamine Seladji (Abou Bakr Belkaid university)
Counter Optimization: Worst-Case Optimization for Validation and Verification of Complex Black-Box Systems	David Braun (TUM); Patrick Piprek (ESA); Florian Holzapfel (TUM)
LFT Modeling of closed kinematic chains	José Afonso de Oliveira Moreno Neves (ISAE-SUPAERO); Francesco Sanfedino (ISAE-SUPAERO); Daniel Alazard (ISAE-SUPAERO)
Robustness Guarantees for Nonlinear Trajectory Planning Applied to Orbital Robots Tasks	Caroline Specht (DLR)
Pyxis: A highly predictable toolchain for FPGA circuit production of advanced GNC algorithm	Inès Winandy (ENAC); Arnaud Dion (ISAE-SUPAERO); Pierre-Loïc Garoche (ENAC); Florent Manni (CNES)

Track 9 – Hardware-based V&V

T9 - Hardware-based V&V - Amphl 2	
Chair: Bénédicte Girouart (ESA), Jeroen Vandersteen (ESA), Neil Dennehy (Consultant)	
Validation & Verification of Vision-based Navigation Algorithms via Geometric- and Radiometric-Consistent Optical Stim	Paolo Panicucci (POLIMI); Fabio Omati (POLIMI); Andrea Pizzetti (POLIMI); Francesco Toppato (POLIMI)
Streamlining Laboratory Dataset Generation for Training and Verification of Vision Based Navigation in Space	Sebastian Rimmer (ESA); Ane Morkemo (ESA); Joris Belhadj (ESA); Irene Huertas Garcia (ESA); Djordje Lepir (ESA)
Hardware-in-the-Loop Testbeds for Attitude Control in Distributed Networks Composed of Small Satellites	Timon Petermann (ZfT); Lisa Elsner (ZfT); Klaus Schilling (ZfT)
V&V of Autonomous Spacecraft Proximity Maneuvers Leveraging HIL Lab Facilities: Standardization & Benchmark Problem	Marcello Romano (TUM)

Track 10 – JPL GNC V&V Post-Workshop Talks (at 11 Sept 2025 Special Seminar)

Track 10 - JPL GNC V&V Talks	
11 September 2025 GNC V&V Seminar	
JPL's Evolution of the GNC V&V Process	Oscar Alvarez-Salazar (JPL) and Carl Christian Liebe (JPL)
Europa Clipper GNC V&V	Paul Brugarolas (JPL), et al
GNC V&V For the Psyche Low Thrust Deep Space	Paige Arthur (JPL)
Verification and Validation for Mars Entry Descent and Landing	Swati Mohan (JPL), et al
MSL/M2020 Field Test V&V	James Montgomery (JPL) and Andrew Johnson (JPL)
Research and Development Path to Flight in Guidance and Control Satellite Autonomy Testbed	David Sternberg (JPL), et al