Advances in Digital Avionics for Sustainable Aviation and Spaceflight Operations

DASC 44th Digital Avionics Systems Conference
Montreal, Canada - September 14-18, 2025

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Montreal (Canada), 15 September 2025

https://ieee-aess.org/tech-ops/avionics-systems-panel-asp

Outline

1. Introduction to the IEEE AESS Avionics Systems Panel	Giancarmine
2. Air and Space Transport Integration: Towards Multidomain Traffic Management	Rob
3. Aviation Noise Impact Assessment and Mitigation	Erik
4. ATM and Flight Management Systems	Erik / Alex
5. UTM, AAM, and Trusted Automation	Erik / Alex
6. Regulatory Considerations in the Era of AAM: Approaches to Technology Maturity and Standardization	Craig
7. Challenges and Advances in Space Domain Awareness and Space Traffic Management	Giancarmine

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Introduction to the IEEE AESS Avionics Systems Panel

Avionics Systems Panel

The Avionics Systems Panel (ASP) is composed of IEEE Associate or higher-level members who are representatives of industry, government laboratories, educational institutions, and professional societies and who are active in the domain of Avionics. Its main objectives are:

- Promote and support collaborative research initiatives in the domain of Avionics
- Develop and disseminate high-quality IEEE publications in the domain of Avionics
- Promote and support educational activities in the domain of Avionics
- Sustain and oversee the programs of the IEEE/AIAA Digital Avionics Systems Conference (DASC) and the Integrated CNS Conference; and contribute to other conferences and dissemination initiatives
- Manage the nomination and selection of candidates for IEEE Awards in the domain of Avionics
- Encourage submission of nominations for IEEE Fellows and Senior Members in the domain of Avionics
- Recommend and support new IEEE avionics standards or revisions of existing standards

ASP Committees and Regular Meetings

- The ASP relies on a diverse community of experts (currently from US, EU, UK and Asia), contributing to the work of five different committees. The panel holds regular monthly meetings addressing the following topics:
  - **Research and Innovation (R&I).** Participation to NASA UTM and AAM activities; connections/collaborations with NextGen in the US and SESAR in the EU; other national and international Avionics/ATM/UAS programs; Collaborations with JARUS, ICAO, IFATCA, and others
  - **Publications.** Editorial Board and reviewer contributions to the Transactions on Aerospace and Electronic Systems and AESS Systems Magazine; Special Issues on Avionics, UTM/UAM and Space Systems; joint journal publication initiatives (e.g., Avionics Systems for Trusted Autonomy, Multi-Domain Traffic Management, Avionics Education)
  - **Conferences.** IEEE/AIAA Digital Avionics Systems Conference (DASC); IEEE/AIAA Integrated Communications, Navigation and Surveillance Systems (ICNS) Conference; IEEE/AIAA/PHM Aerospace Conference; other conferences
  - **Education Activities.** AESS Distinguished Lecturers/VDL Program updates; Webinars, Tutorials and Short Course initiatives
  - **Industry Engagement and Standards.** UAS/Autonomy, AI, V2X Communications, Cyber Security, etc.
- Joint meetings with the Cyber Security Panel are also held

Current ASP Activities

- The ASP focuses on avionics systems for commercial, military, and general aviation applications. Relevant avionics functions include: communications; navigation; surveillance; command and control; manned/unmanned air traffic management; and space systems (launch vehicles, satellites, and other space platforms)
- The ASP monitors, analyzes and supports industry and government activities that impact the future of aviation and space operations, such as the ICAO, RTCA/EUROCAE and AEEC standardization initiatives, the FAA NextGen program, the SESAR program, the NASA UTM and Advanced Air Mobility (AAM) initiatives, the JARUS working groups, the UNOOSA and COPUOS activities, and the NOAA-OSC Space Situation Awareness and Space Traffic Management (SSA/STM) policy developments
- The ASP also supports research and education activities related to the social, environmental, and economic impact of aviation and space systems, with specific emphasis on the development and industry uptake of digital technologies. The ongoing transformations of the airspace (both low-altitude and high-altitude operations) and the increasing congestion of the near-Earth space environment are prompting the need to integrate legacy ATM with emerging UTM, AAM and STM systems
- The establishment of a Multi-Domain Traffic Management (MDTM) framework requires significant technological and regulatory advances, especially in the area of autonomous systems, trustworthy/certifiable AI, and cognitive human-machine systems. This next-generation of avionics systems will support safer and more efficient flight operations, offering an array of new services and supporting a more sustainable development of the aerospace sector

Recent ASP Publications

[1] G. Fasano, O. G. Crespillo, R. Sabatini, A. Roy, and R. Ogan, "From the Editors of the Special Issue on Urban Air Mobility and UAS Airspace Integration: Vision, Challenges, and Enabling Avionics Technologies." IEEE Aerospace and Electronic Systems Magazine, Vol. 38, No. 5, pp. 4-5, May 2023

[2] I. Majid, R. Sabatini, K. A. Kramer, E. Blasch, G. Fasano, G. Andrews, C. Camargo and A. Roy, “Restructuring Avionics Engineering Curricula to Meet Contemporary Requirements and Future Challenges.” IEEE Aerospace and Electronic Systems Magazine, 36(4): 46-58, April 2021.

[3] R. Sabatini, K. A. Kramer, E. Blasch, A. Roy and G. Fasano, "From the Editors of the Special Issue on Avionics Systems: Future Challenges." IEEE Aerospace and Electronic Systems Magazine, 36(4): 5-6, April 2021

[4] R. Sabatini, A. Roy, E. Blasch, K. A. Kramer, G. Fasano, I. Majid, O. G. Crespillo, D. A. Brown, R. Ogan, “Avionics Systems Panel Research and Innovation Perspectives,” *IEEE Aerospace And Electronics Systems Magazine*, 35(12):58-72, December 2020.

[5] E. Blasch, R. Sabatini, A. Roy, K. Kramer, G. Andrew, G. Schmidt, C. Insaurralde, and G. Fasano, "Cyber Awareness Trends in Avionics," 2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC), October 2019

Other ASP Publication Initiatives

- Currently discussing new position papers on industry-focused Avionics Research and Innovation (R&I) perspectives, and Avionics Systems Education
- The ASP is working on a book for the IEEE Series on Aeronautics and Astronautics Systems. The provisional title is ***"Advances in Avionics and Astrionics Systems."*** Current chapters include:
  - Chapter 1: Global Perspective in Avionics and Astrionics Systems Research
  - Chapter 2: CNS/ATM for future ATM
  - Chapter 3: Advances in PNT
  - Chapter 4: Communications and Data Networks
  - Chapter 5: UTM and AAM
  - Chapter 6: Surveillance Sensors and Systems
  - Chapter 7: Space Avionics
  - Chapter 8: Cybersecurity
  - Chapter 9: Interactive HMI
  - Chapter 10: Certification Challenges
  - Chapter 11: Education and Training Evolutions
  - Chapter 12: Future of Avionics

ASP Distinguished Lecturers

- Various ASP members serve as Distinguished Lecturers (DL) and are actively contributing to the AESS Distinguished Lecturer (DL) and Virtual DL (VDL) Webinar Series:
  - Roberto Sabatini – Intelligent and Autonomous Aerospace Systems
  - Erik Blasch – Multisensor Systems and Data Fusion
  - Kathleen Kramer – Navigation and Cyber-Security in Avionics
  - Giancarmine Fasano – Unmanned Aerial Vehicles
  - Carlos Insaurralde – Modelling and Decision Making for ATM





ASP Industry Engagement and Standards

❖ ASP members are contributing to the advancement of ICAO, RTCA, EUROCAE/SAE and AEEC avionics standards.

ICAO	RTCA / EUROCAE	AEEC
• Established by the 1944 treaty at Chicago Convention • Operates as a United nations constituency • Caters to prime objectives of global interoperability, uniformity & equitable service of aircraft over all UN countries • Defines system functional and interoperability requirements	• Specifies services, system & avionics concept of operations, safety and performance requirements • Specifies methods for requirements verification • FAA uses RTCA standards for US airworthiness certification • EASA/Europe uses EUROCAE standards for the same purpose • Other countries mostly follows either RTCA or EUROCAE standards	• Established by aircraft operators to specify avionics form, fit and functions supporting airline operations • Primary goal is for avionics vendors and aircraft manufacturer to have uniform equipment standards for line replacement

Future Standards

- The ASP is collaborating with ICAO, IFATCA, EASA, EUROCAE and SESAR initiatives to promote avionics research/innovation, education and the evolution of certification standards for UAS Traffic Management and Advanced Air Mobility
- ASP members contributed to weekly meetings of the JARUS (Joint Authorities for Rulemaking on Unmanned Systems) Working Group 7 – Automation Concept of Operations. Recent activities have focused on:
  - ATM and UTM Automation
  - Flight Rules for Autonomous Operations
  - Infrastructure, Aerodromes and Ground Equipment
  - Considerations for Technology Maturity
  - Automation and Trusted Autonomy Use Cases
  - Multiple Simultaneous Operations

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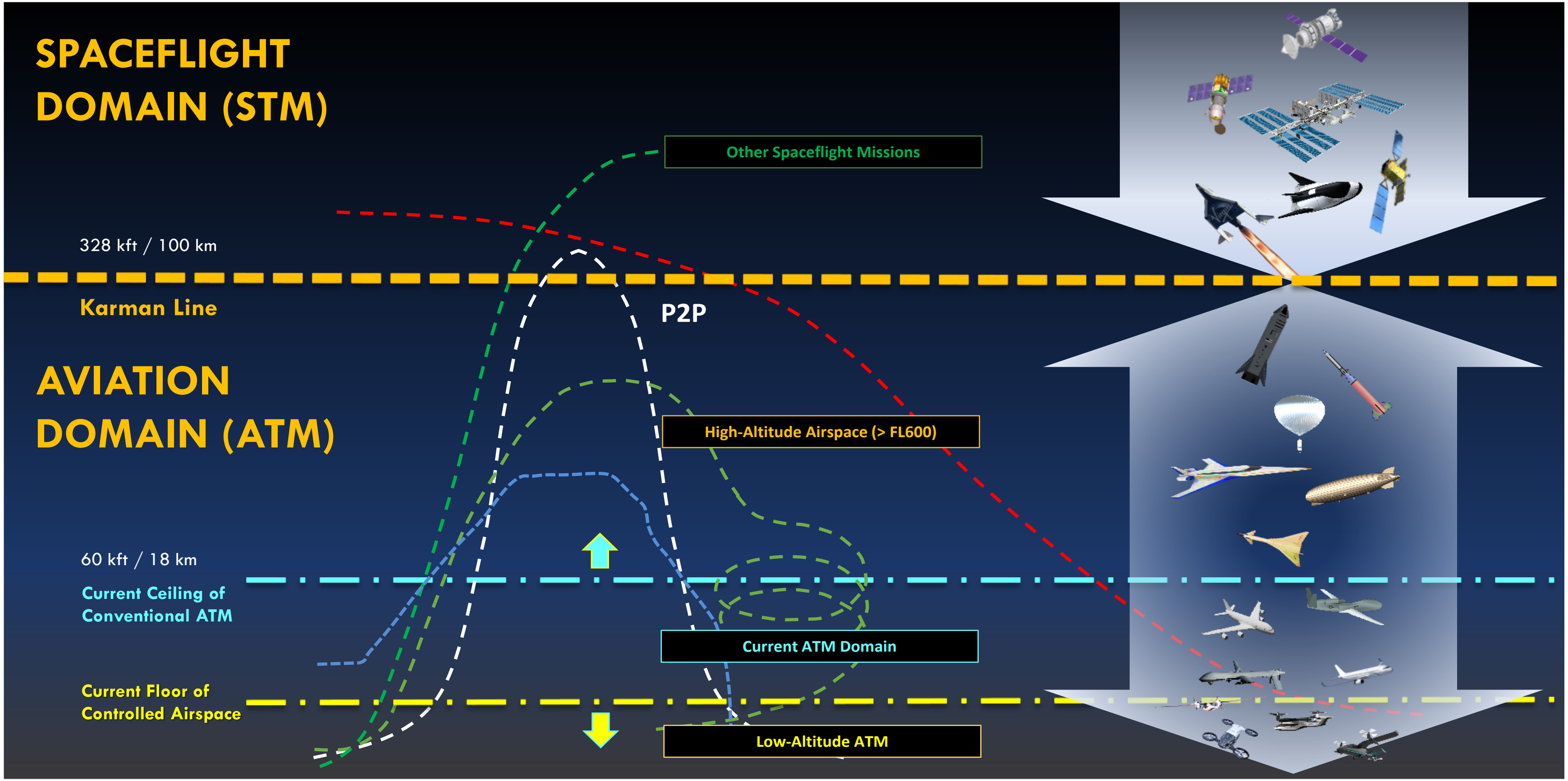
Air and Space Transport Evolutions: Towards Multi-Domain Traffic Management

Evolving Flight Domains



Global Air Transport Industry

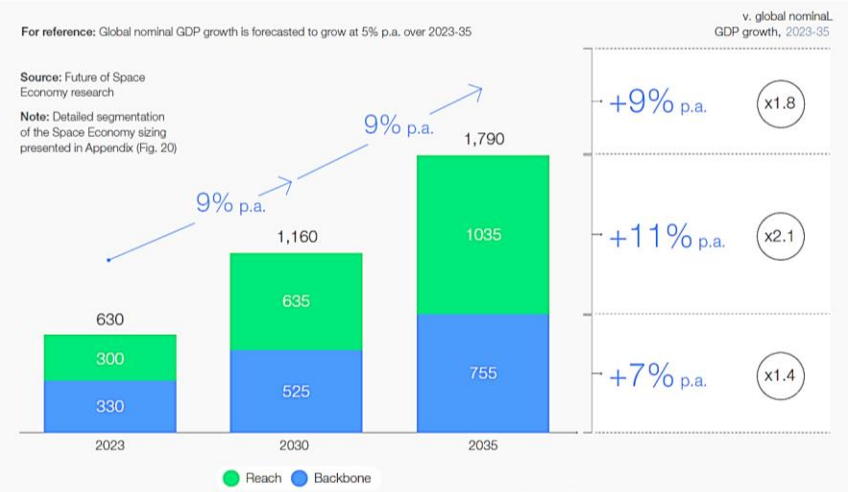
- The aviation industry plays an important role in the global economy. According to ATAG*, this sector contributed US$3.5 trillion to the world GDP (4.1%) and supports 87.7 million jobs globally

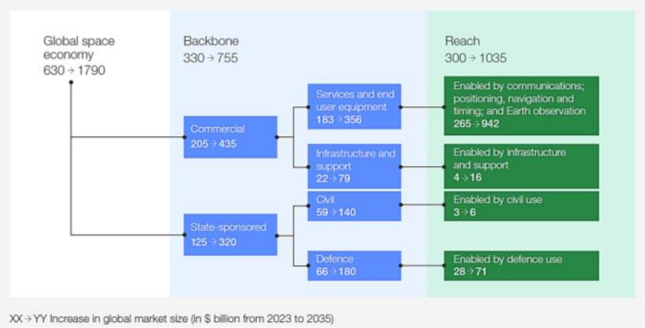
- The aviation market is expected to grow significantly in the coming decades. **By 2038, global air transport is forecast to support 143 million jobs and contribute $6.3 trillion to the global economy.** So, its growth must be sustainable – with affected communities supported and the environment protected

- Key R&I drivers post-COVID include **Advanced Air Mobility** and low-level ATM evolutions (e.g., **UAS Traffic Management**), **high-altitude flight** (i.e., above FL600), and **high-speed/suborbital transportation**

Space Industry Snapshot

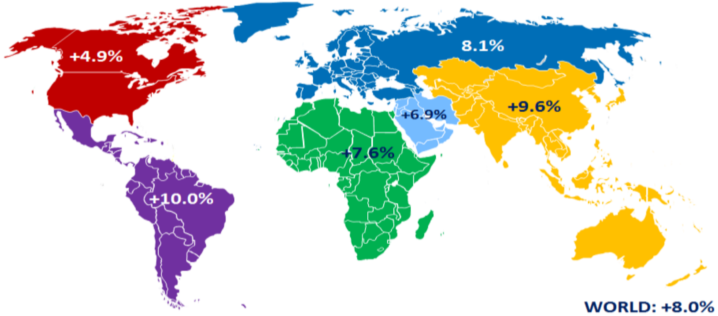
- ❖ The global space economy is worth approximately 500 billion USD and, at the current annual growth rate (9%), is set to reach $1.8 trillion by 2035 (*)
- ❖ Space-based and/or enabled technologies such communications; positioning, navigation and timing; and Earth observation services are expected to be the key drivers of this growth
- ❖ Five sectors – supply chain and transport; food and beverage; state-sponsored defense; retail, consumer and lifestyle; and digital communications – are forecast to generate 60% of the global space economy by 2035, although others will also benefit
- ❖ Space will play an increasingly vital role in mitigating world challenges, ranging from disaster warning and climate monitoring, to improved humanitarian response and more widespread prosperity



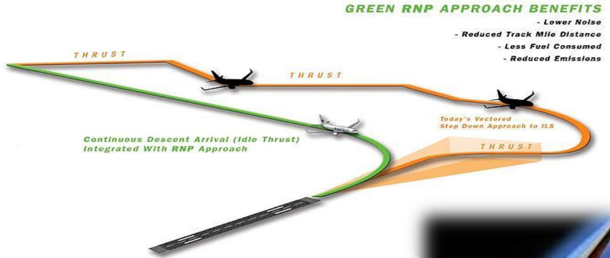


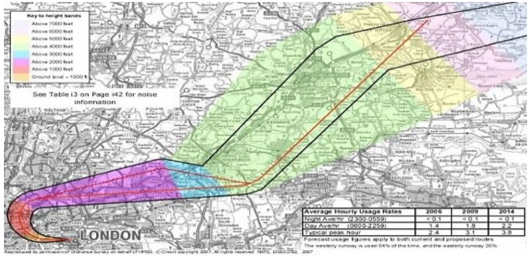
(*) World Economic Forum (2024): https://www.weforum.org/agenda/2024/04/space-economy-technology-invest-rocket-opportunity/

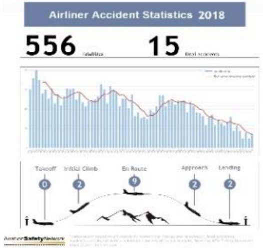
Current Challenges

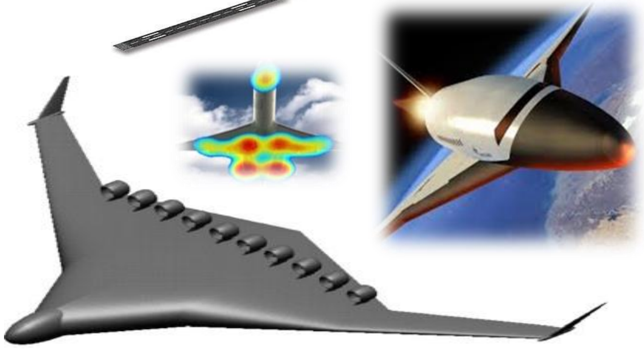


- **Enhancing <u>Safety, Efficiency and Environmental Sustainability</u> of air and space transport to support the anticipated growth of the sector**
- **Research and Innovation Areas**
  - Next Generation ATM Communications, Navigation, Surveillance (CNS) & Avionics (A) Systems (CNS+A)
  - UAS access to all classes of airspace (trusted autonomy)
  - Development and rapid uptake of low-emission technologies (gaseous and noise emissions)
  - Improved efficiency and capacity of airports and spaceports (digitalisation/multimodal)
  - Solutions for enhanced safety and security

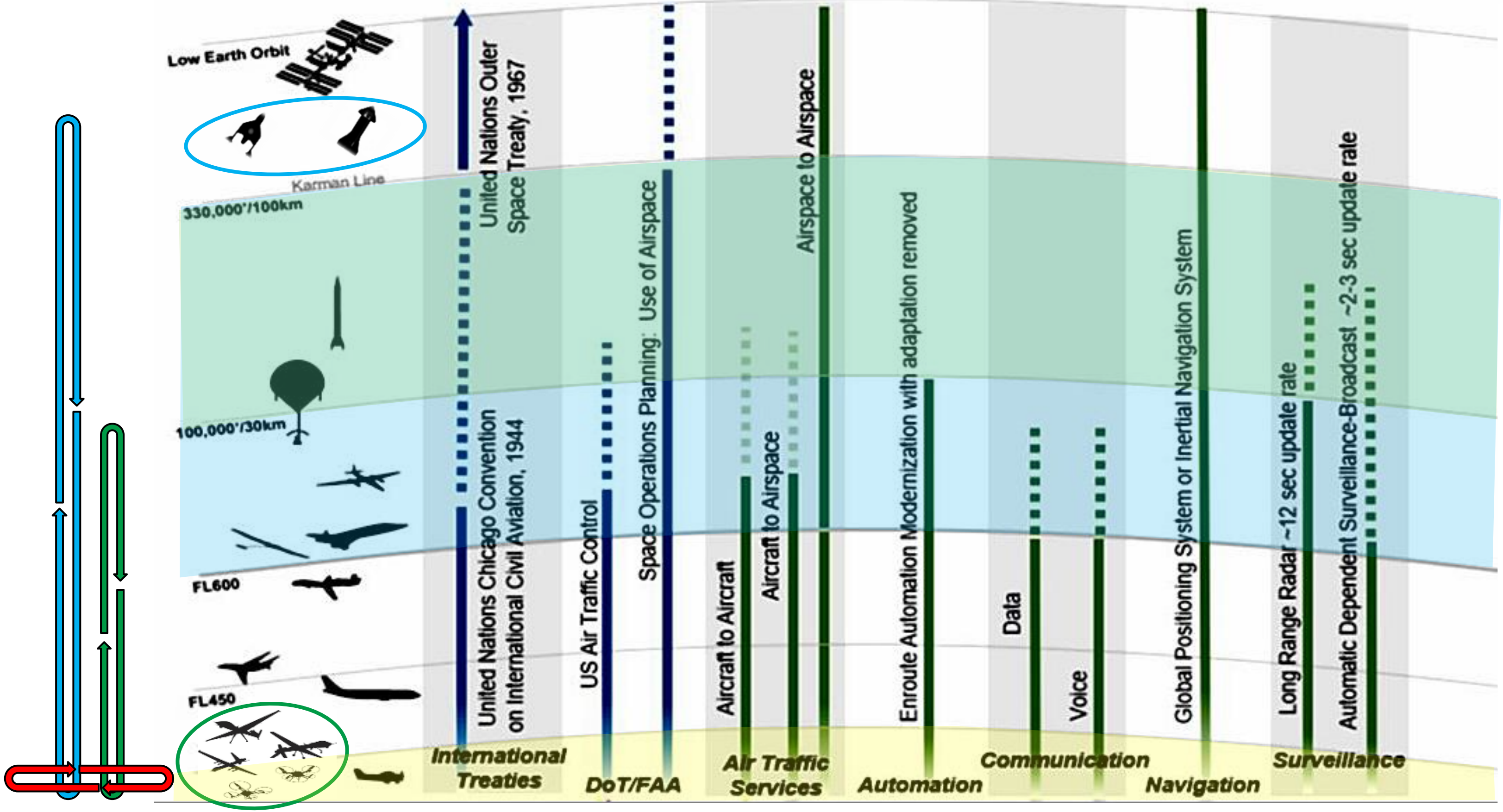






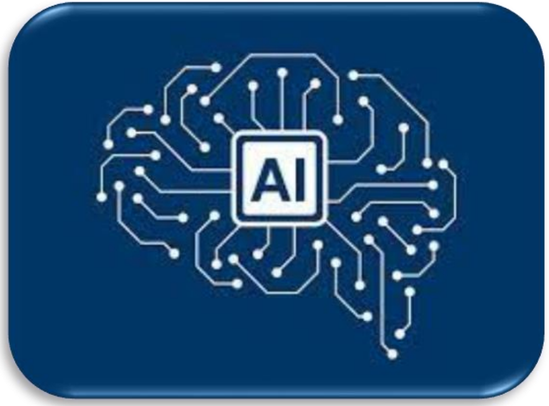


Evolving Airspace and Systems



Credit: FAA

Automation and AI in Aerospace Systems



- **Integrated and Interoperable CNS+A (cyber-physical systems)**
- **UAS access to all classes of airspace (trusted autonomy)**
- **Improved efficiency/capacity of airports and spaceports (digitalisation/multimodal)**
- **New solutions for enhanced safety and security**

Cyber-Physical Aerospace Systems

The aerospace community is focusing on two special categories of Cyber-Physical Systems (CPS):

- **Autonomous Cyber-Physical (ACP) systems**
  - Semi-Autonomous Cyber-Physical (S-ACP) systems
- **Cyber-Physical-Human (CPH) systems**

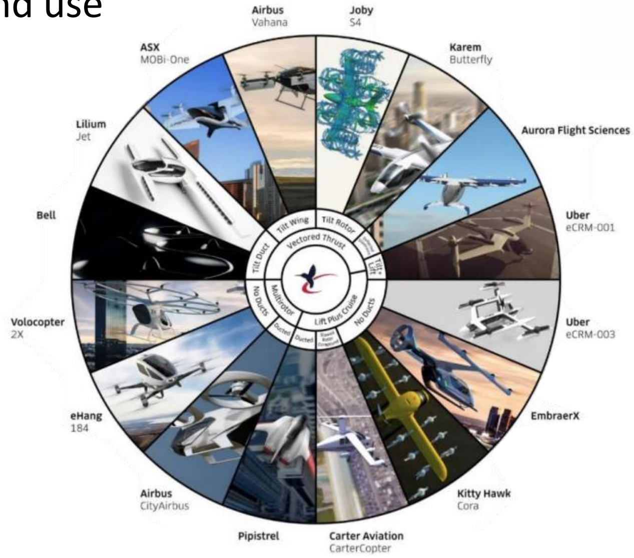
The challenge is to develop robust, fault-tolerant and secure ACP and CPH systems that ensure **trusted autonomous operations** given:

- Specific hardware constraints
- Variability of mission requirements
- Uncertainties in physical processes
- The possibility cyber/physical attacks and human errors

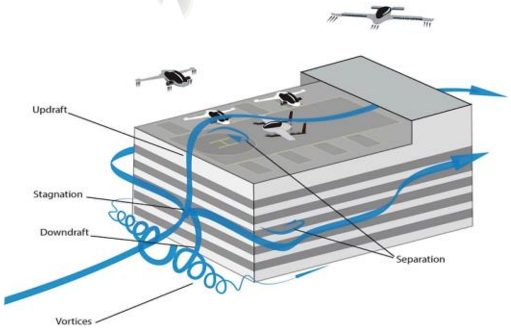
Advanced Air Mobility (AAM)

- AAM integrates innovative aircraft like electric and hybrid-electric VTOLs and UAS technologies into airspace (predominately low-altitude airspace), enhancing transport for people and goods

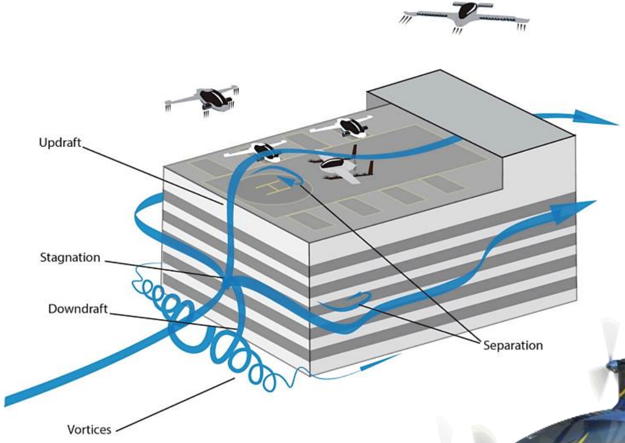
- Set to transform air travel, especially in urban, suburban and rural areas, with diverse applications and use cases (air taxis, regional cargo, transport, aeromedical, etc.)

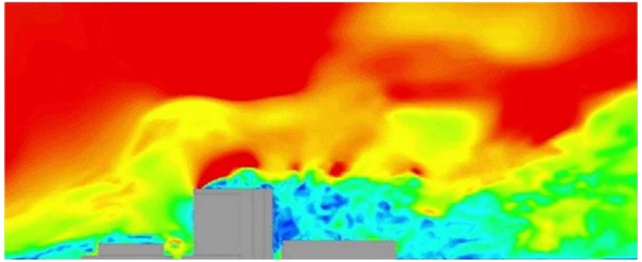


- The system promises to reduce congestion, improve accessibility, and offer sustainable transportation solutions



AAM VTOL Platforms and Environment





Sustainable Flight Platforms

High-Altitude & High-Speed Flight Platforms

Atlas LTA

Kea Atmos

Stratobus

Proteus

NASA Helios

UAVOS

Lockheed – Mach 1.8

Boeing – Mach 5

NASA X-59 – Mach 1.4

Evolving Space Transport Ecosystem

- Introduction of Commercial Space Industry has accelerated development of Reusable Space Vehicles (Reaction Engines, Virgin Galactic, Sierra Nevada, etc.)
- Space Tourism, Research, Point to Point transport have been identified as commercially and economically viable markets
- The need for integration of space and traditional atmospheric traffic is widely accepted (NextGen, SESAR)
- A global, harmonized Air and Space Traffic Management network will require the implementation of advanced CNS+A technology
- Success of industry will fundamentally depend on the ability to demonstrate an acceptable level of safety

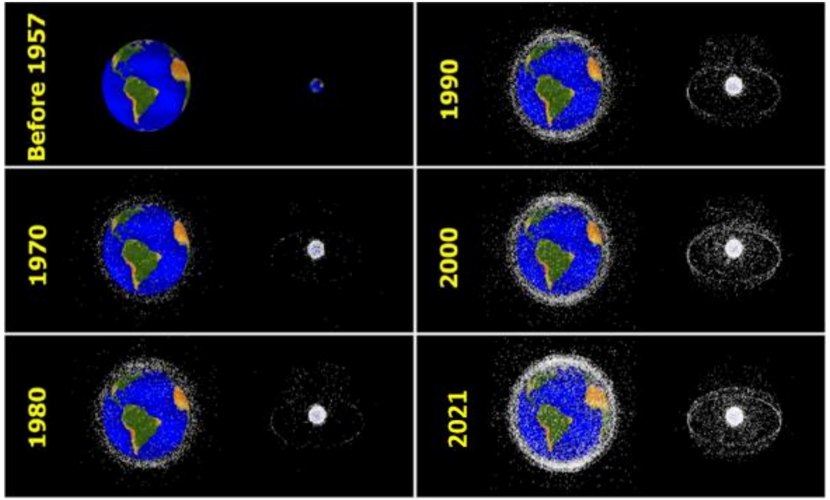
Virgin Galactic Space Ship 2
Credit: Virgin Galactic

Sierra Nevada Dream Chaser
Credit: Sierra Nevada

Reaction Engines Skylon
Credit: Reaction Engines

Orbital Congestion

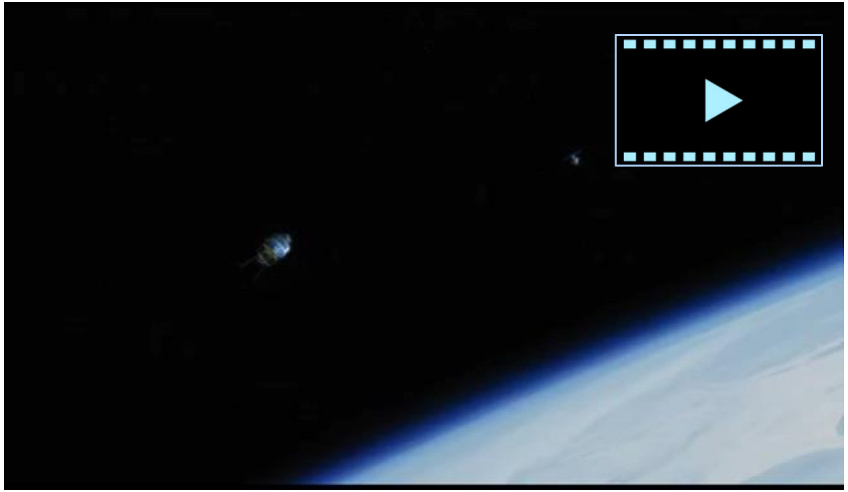
- Resident Space Objects (RSO) > 1mm
- The estimated total number of these RSO is > 170 million
- Any of these RSO can cause harm to an operational spacecraft



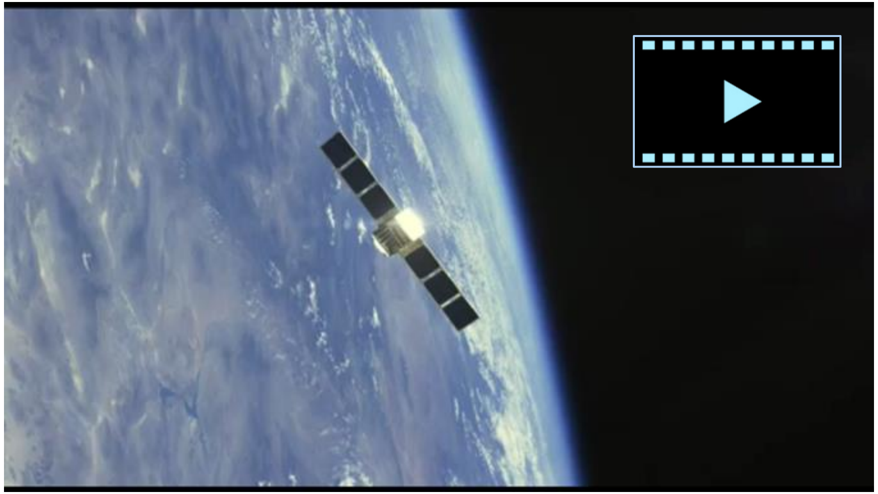
Courtesy: ESA

https://www.esa.int/ESA_Multimedia/Images/2019/10/Distribution_of_space_debris_around_Earth

Collision Events



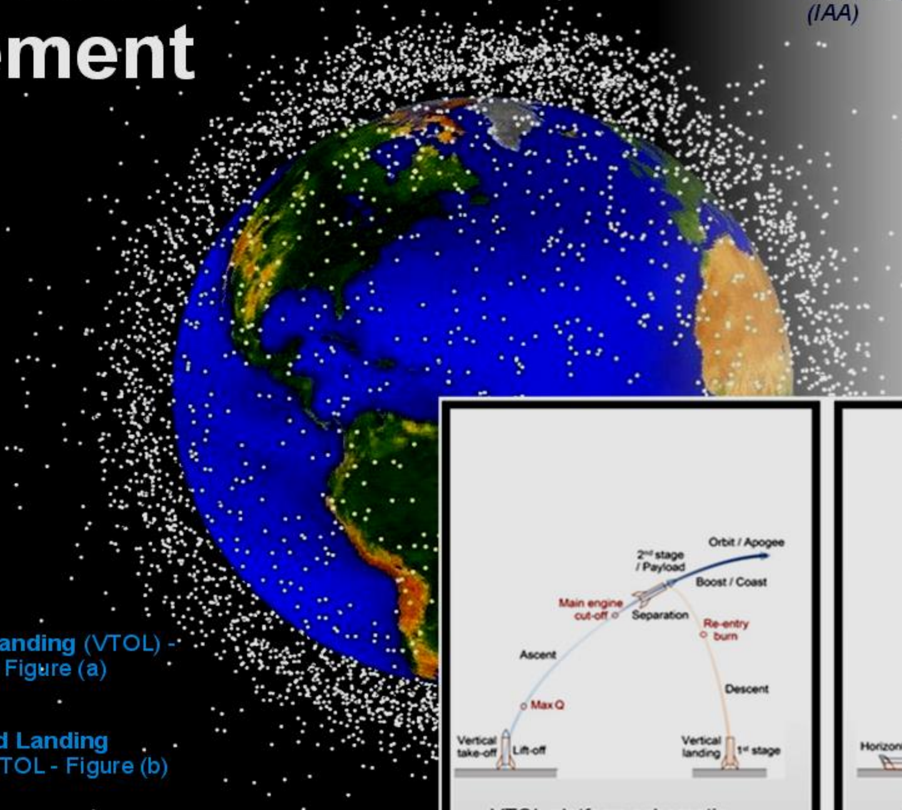
IRIDIUM vs. KOSMOS collision event (2009)



PRC Anti-Satellite Missile Test (2007)

Space Traffic Management

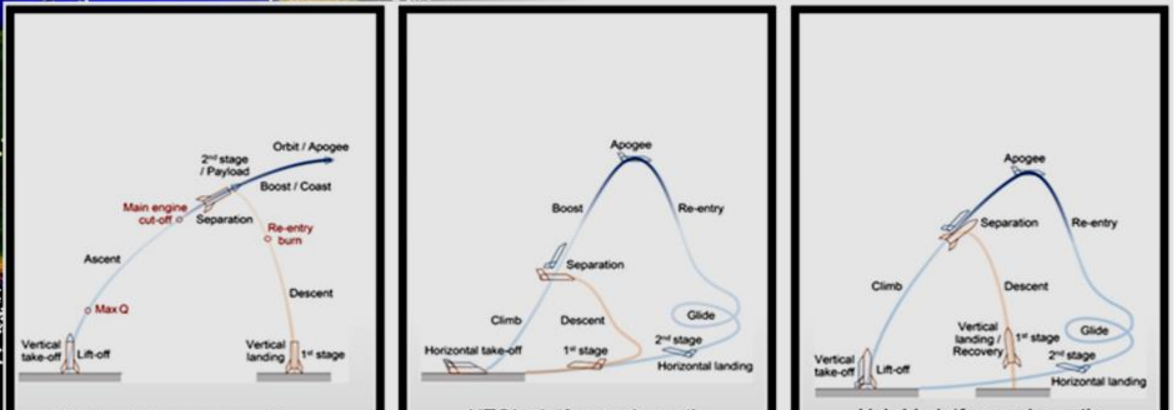
"Space traffic management is the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference." - International Academy of Astronautics (IAA)



Only a few organisations have the global sensor networks and computational capability to perform this task

- Space Surveillance Network (SSN), USA,
- Space Surveillance and Tracking (SST) system, European Space Agency (ESA) ,
- Space Surveillance System (SSS),Russia,
- Network for Space Objects, Tracking, and Analysis (NETRA), ISRO,
- Canadian Space Surveillance System (CSSS), Canada.

- **Vertical Take-off and Landing** (VTOL) - E.g., SpaceX Falcon 9 - Figure (a)
- **Horizontal Take-off and Landing** (HTOL) - NASP and HOTOL - Figure (b)
- **HYBRID**-Space Shuttle Orbiter and Sierra Nevada Corporation's Dream Chaser platforms - Figure (c)



VTOL platform schematic (a)

HTOL platform schematic (b)

Hybrid platform schematic (c)

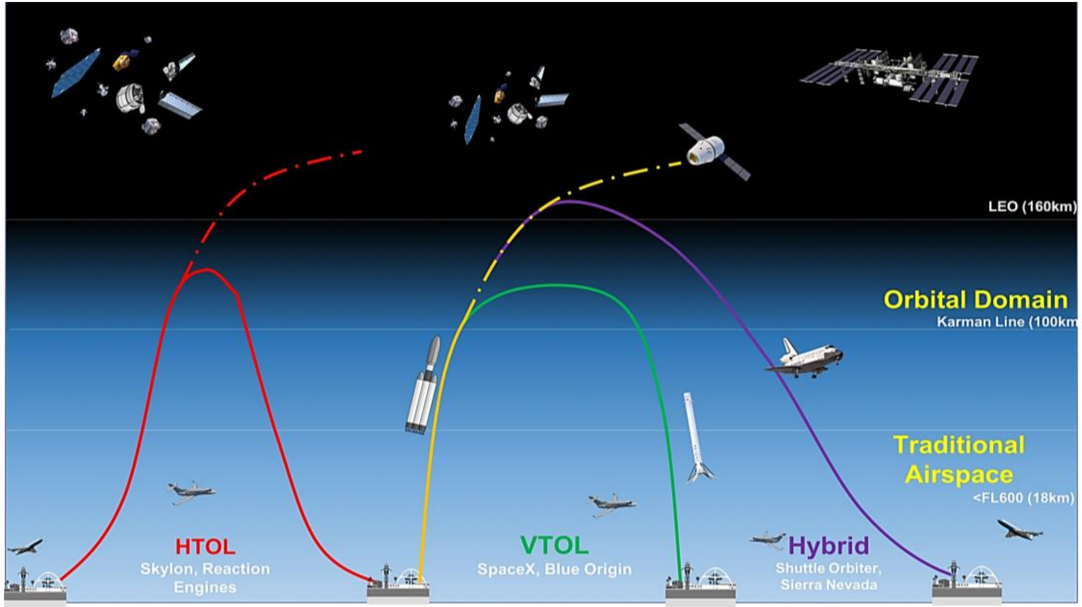
Space Transport Platforms

Vertical Takeoff & Landing

- Traditional approach to access space
- Limited in maneuverability (non-lifting body)
- Vertical landing pioneered by SpaceX reusable vehicle
- Minimized time in atmosphere is primary advantage from ATM perspective

Horizontal Takeoff & Landing

- Ability to perform "tactical" maneuvers like atmospheric aircraft
- More accommodating in their integration with ATM systems (can enact rerouting and tactical deconfliction)
- Promising concept for Suborbital Point-To-Point transportation

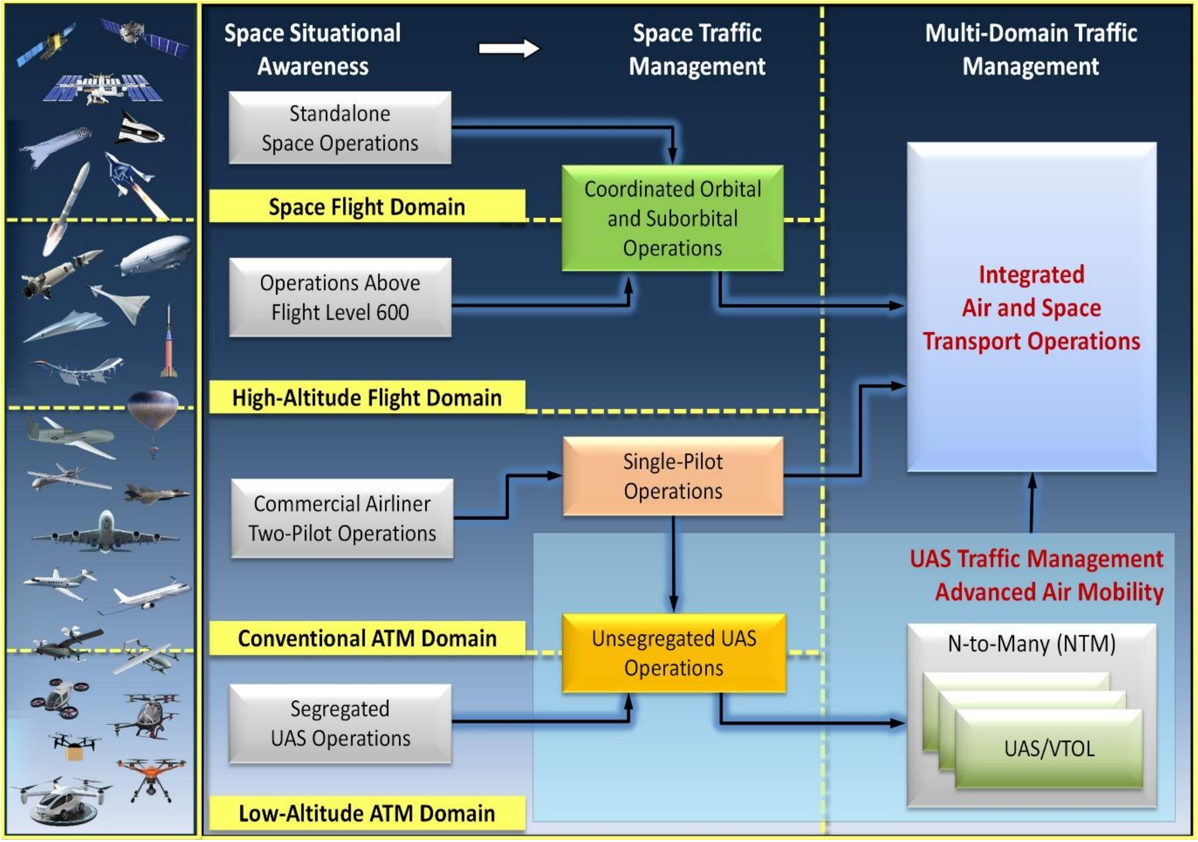


Hybrid

- Typically carrier aircraft taking space vehicle to launch altitude
- Gliding flight most commonly performed after re-entry
- Promising for reduced environmental impact

Emerging Autonomous Vehicle Concepts

Aerospace Systems Evolution



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K. Thangavel, N. E. Safwat, A. Gardi, R. Sabatini, "Multi-Domain Traffic Management: Towards Integrated Air and Space Transport Operations." IEEE Aerospace and Electronic Systems Magazine, Vol. 40, No. 8, August 2025.

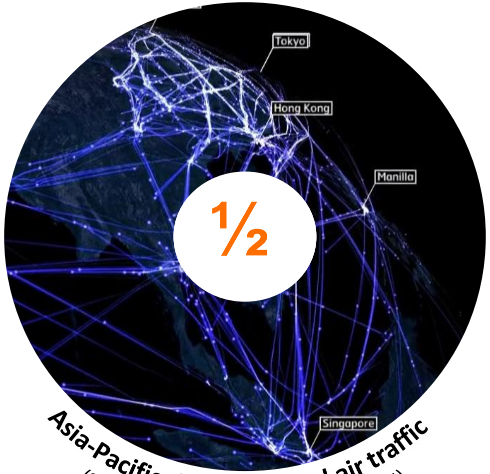
Sustainable Aviation Technology

Global Aviation Challenges

FORECAST
2050

Global Air Traffic

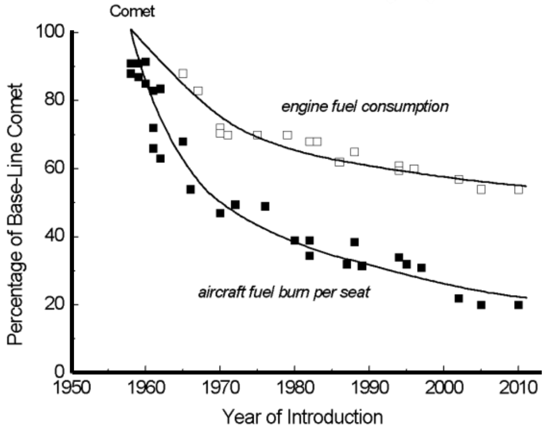
Aviation-induced global warming
(climate change impacts)

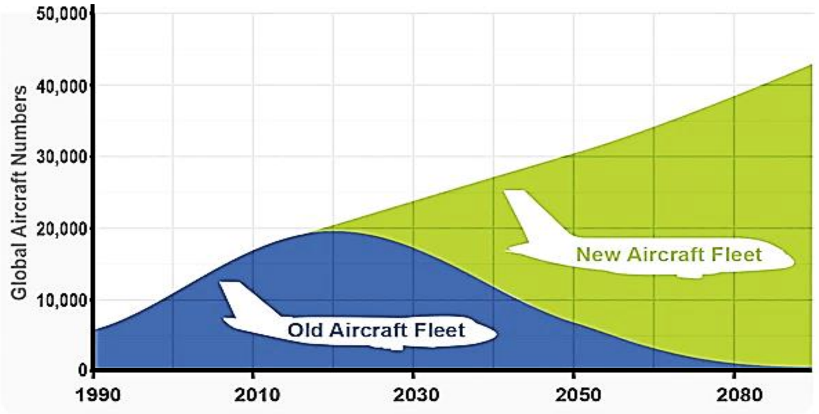


Asia-Pacific share of global air traffic
(215 new airports in China alone by 2035)

Aviation Sustainability Challenges

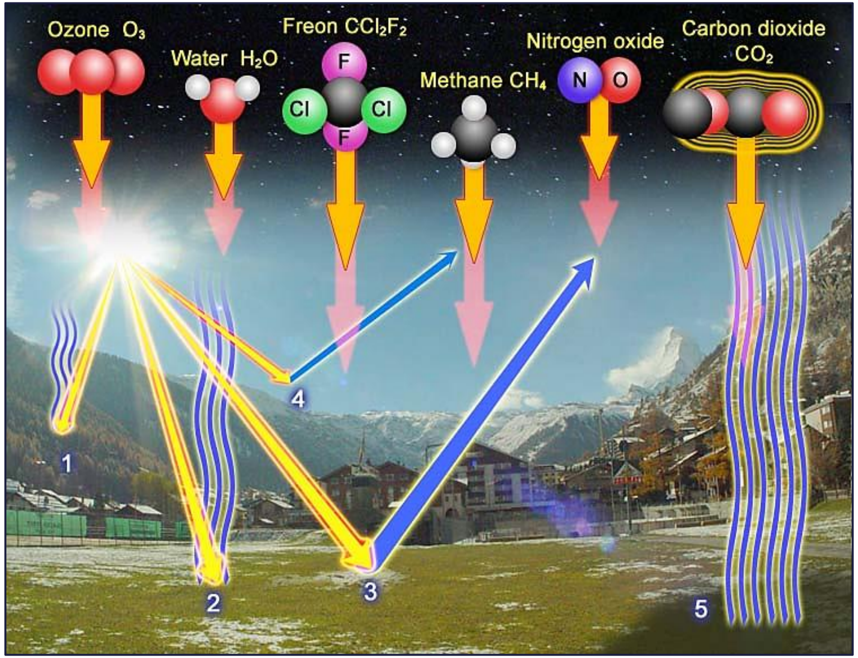
- Aircraft atmospheric pollution includes **carbon dioxide, nitrogen oxide, unburned hydrocarbons** (and more), **all of which contribute to global warming**
- It is estimated that **aviation industry contribution to global warming is currently about 2.5%, although it may increase to 5-10% by 2050** due to the anticipated growth of air traffic
- **Air quality is also degrading significantly due to aviation activities**, especially at and around airports
- **Aviation noise also has short and long-term health impacts** both on humans and other animals
- **Technology advances have been successful in reducing atmospheric pollution and noise emissions from aircraft, but these have not been able to offset the impacts of aviation growth**

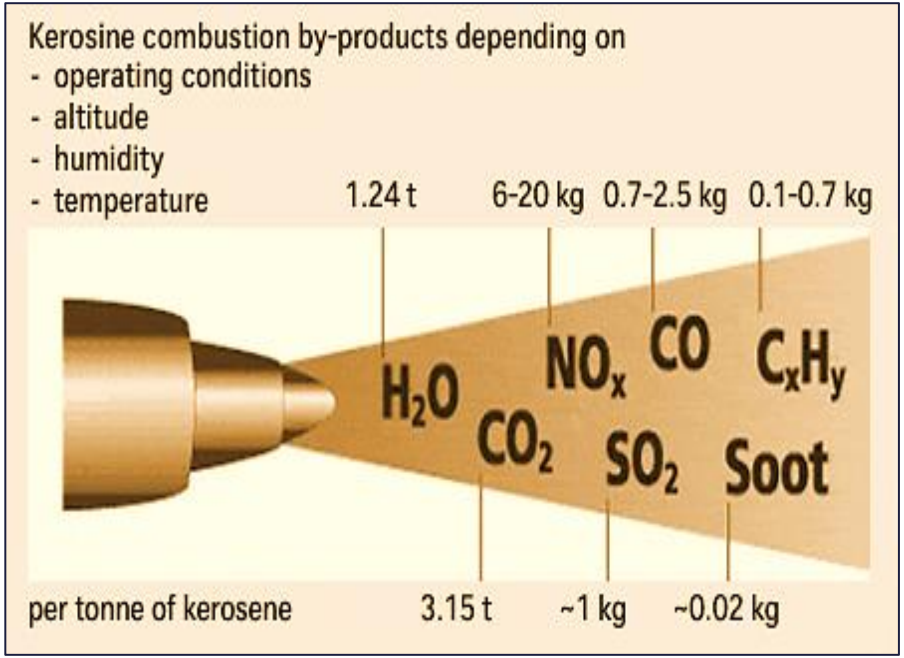




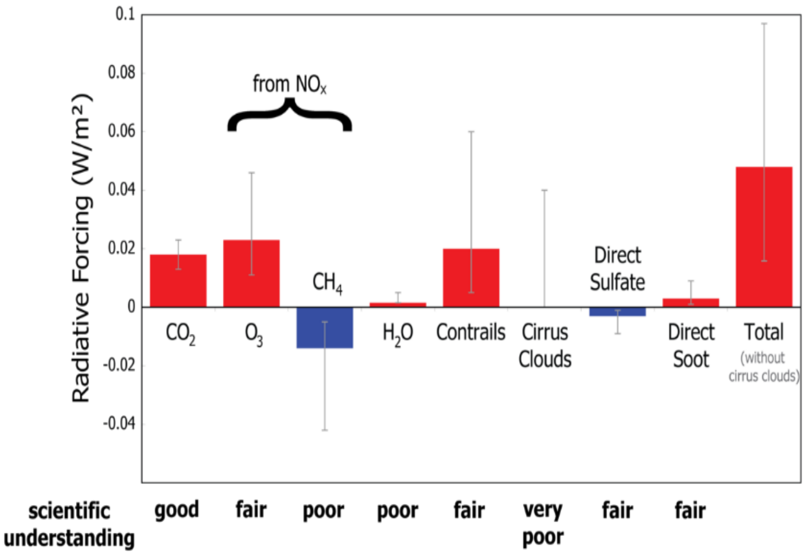
Greenhouse Pollutants and Aircraft Emissions

- Global warming caused by many types of pollutants. Aviation generates most types.

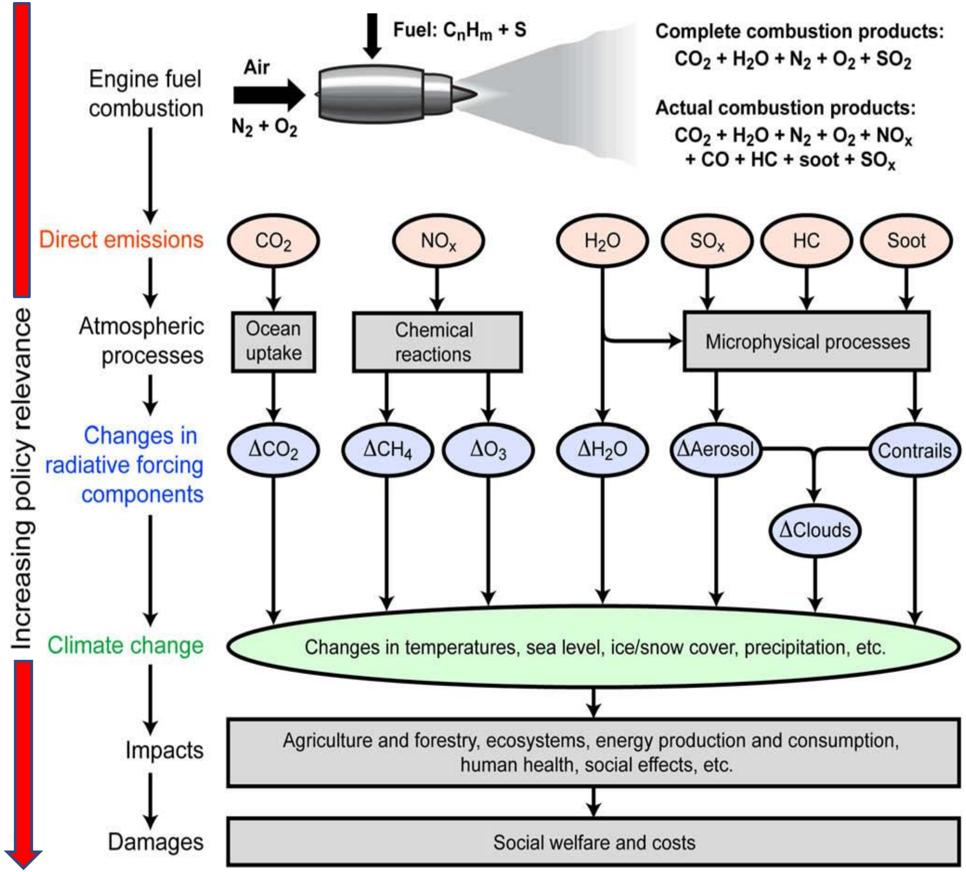




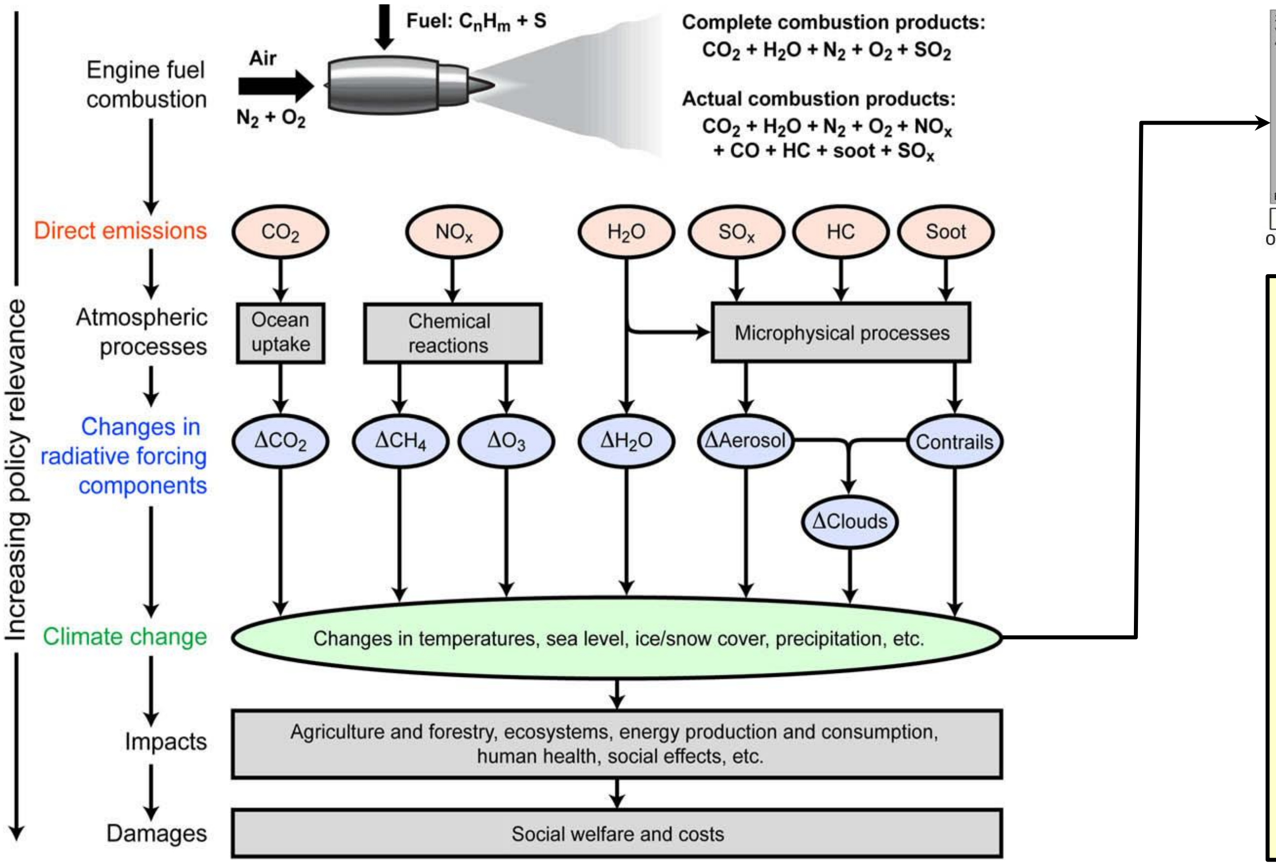
Impacts of Aviation Greenhouse Emissions

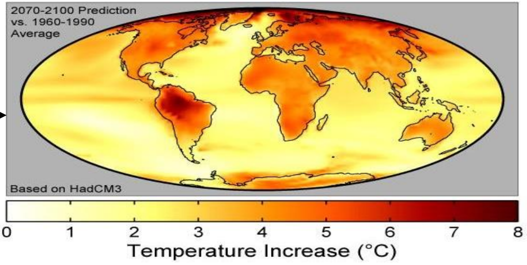


Radiative forcing (RF) is the change in the net vertical irradiance (Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system



Impacts of Greenhouse Emissions



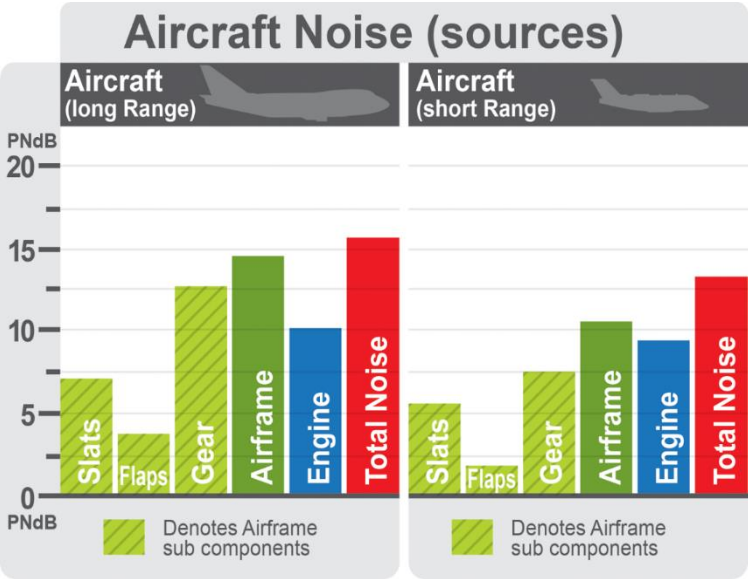


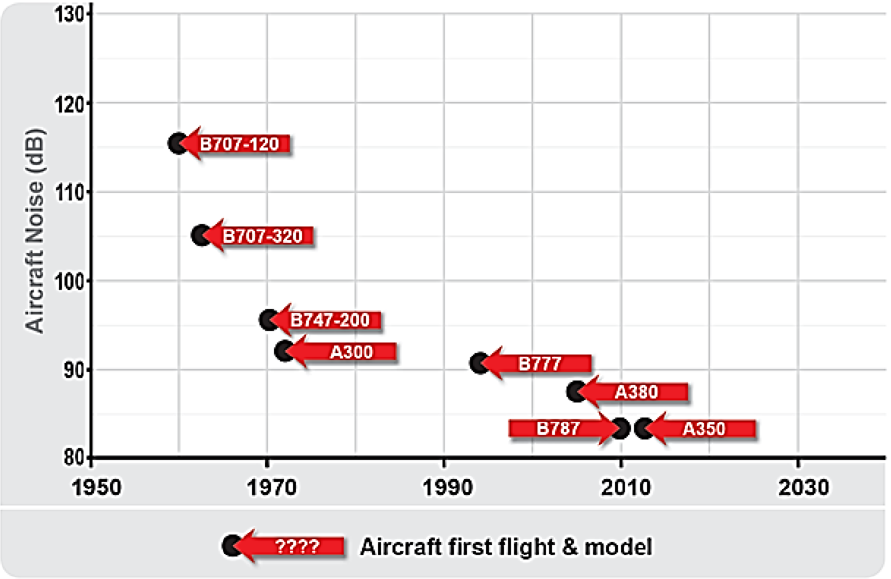
Global Warming Effects on Climate

Phenomenon	Likelihood
Warmer days, less cold days/nights	Virtually certain
More warm spells and heatwaves	Very likely
More heavy rain events	Very likely
More areas hit by drought	Likely
More intense tropical cyclones	Likely
	Likely

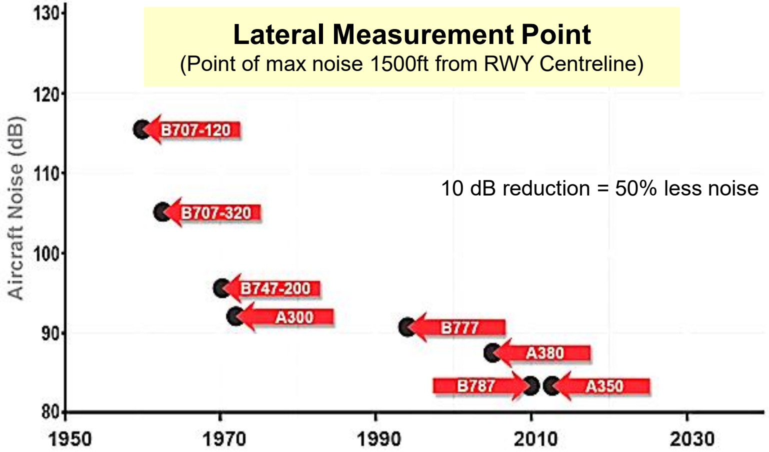
Aircraft Noise Sources and Trends

- Modern aircraft are quieter than their predecessors. However, the steady growth in air traffic increases public exposure to aircraft noise (particularly for people living close to airports)
- Noise can dominate the relationship between airports and local residents, and can lead to restrictions in aircraft operations

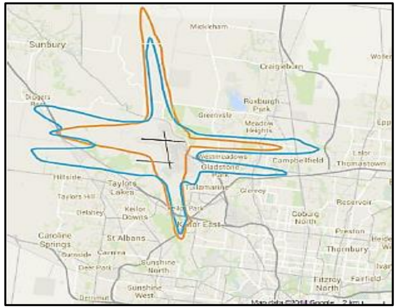


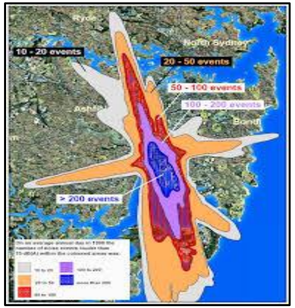


Aircraft Noise Reduction



- Engine noise, aerodynamic noise, complex jet-airframe interactions
- **The noise levels experienced by people on the ground** are influenced by:
  - Aircraft type and size (propulsion and aerodynamics)
  - The distance of the aircraft from the ground (trajectory flown)
  - The way the engine and other aircraft systems are operated
  - The rate at which the aircraft climbs/descends
  - Meteorological conditions
- Noise Exposure Forecast (NEF) used for urban planning





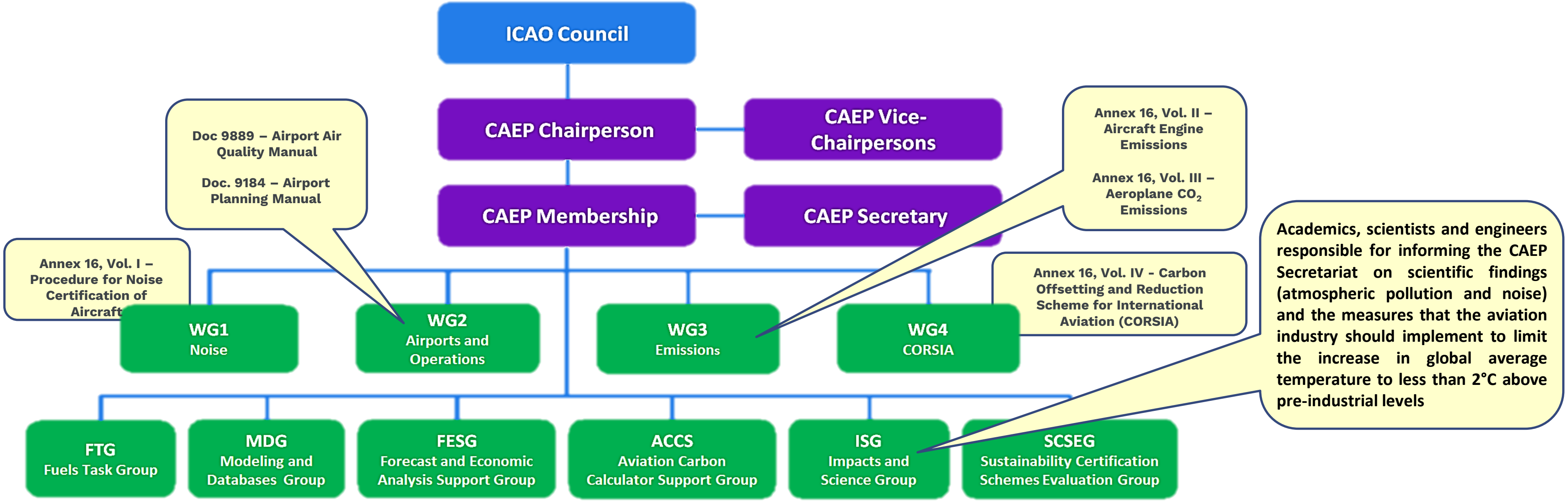
International R&I Priorities

ICAO Environmental Policy

ICAO ENVIRONMENT

Committee on Aviation Environmental Protection - CAEP

- To limit or reduce the number of people affected by significant aircraft noise
- To limit or reduce the impact of aviation greenhouse gas emissions on the global climate
- To limit or reduce the impact of aviation emissions on local air quality and water/land contamination



Fuel, Emissions and Noise Reduction Goals

	ACARE – SRA and SRIA (wrt 2000)		**NASA – ERA** (wrt 1998) **and SIP** (wrt 2005)					
Subsonic A/C Emissions	Vision 2020	**FlightPath 2050**	ERA 2015	ERA 2025	ERA 2035	SIP 2015-25	SIP 2025-35	**SIP >2035**
Fuel/CO_2	50% (38% 2015)	**75%**	50%	50%	60%	40-50%	50-60%	**60-80%**
NO_X	80% (----- 2015)	**90%**	75%	75%	80%	70-75% LTO* 60-70% CRZ	80%	**>80%**
Noise	50% (37% 2015)	**65%**	32dB	42dB	71dB	22-32dB**	32-42dB	**42-52dB**

ACARE - Advisory Council for Aviation R&I in Europe, **SRA** - Strategic Research Agenda, **SRIA** - Strategic Research and Innovation Agenda, **ERA** - Environmentally Responsible Aviation, **SIP** - Strategic Implementation Plan

A/C - Aircraft, **LTO** - Landing and Take/Off, **CRZ** - Cruise, ***Below CAEP6, ****Below Chapter 4. All % reductions are in Passenger-km

Fuel, Emissions and Noise Reduction Goals

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Clean Sky 2 · SESAR Joint Undertaking · NASA · NextGEN

Cooperation Opportunities

ACARE - Advisory Council for Aviation R&I in Europe, **SRA** - Strategic Research Agenda, **SRIA** - Strategic Research and Innovation Agenda, **ERA** - Environmentally Responsible Aviation, **SIP** - Strategic Implementation Plan

A/C - Aircraft, **LTO** - Landing and Take/Off, **CRZ** - Cruise, ***Below CAEP6, ****Below Chapter 4. All % reductions are in Passenger-km

Areas of Focus

❖ Science

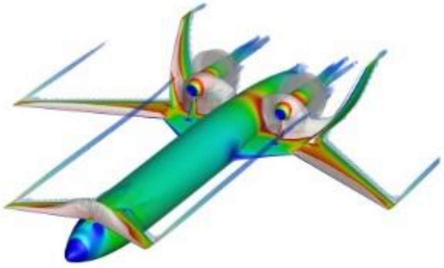
- Assessing aviation environmental impacts
- Forecasting, modelling and analysis

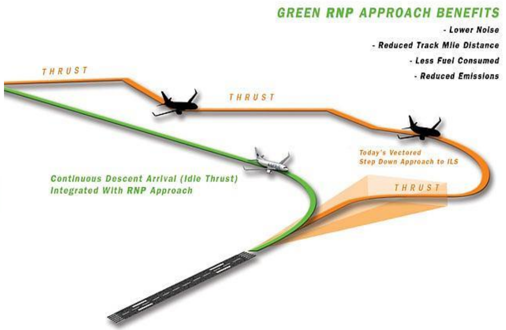
❖ Technology and Operations

- Aircraft and propulsive technologies
- Flight operations, avionics and air traffic management
- Airport design, upgrade and operations
- Advanced manufacturing and logistics

❖ Policy and Regulations

- Sustainability policies for aviation
- Greenhouse/noise limiting standards
- Technology uptake and certification

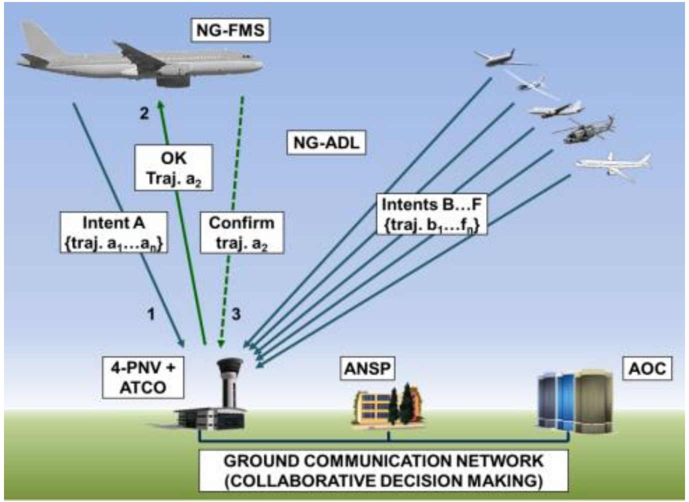


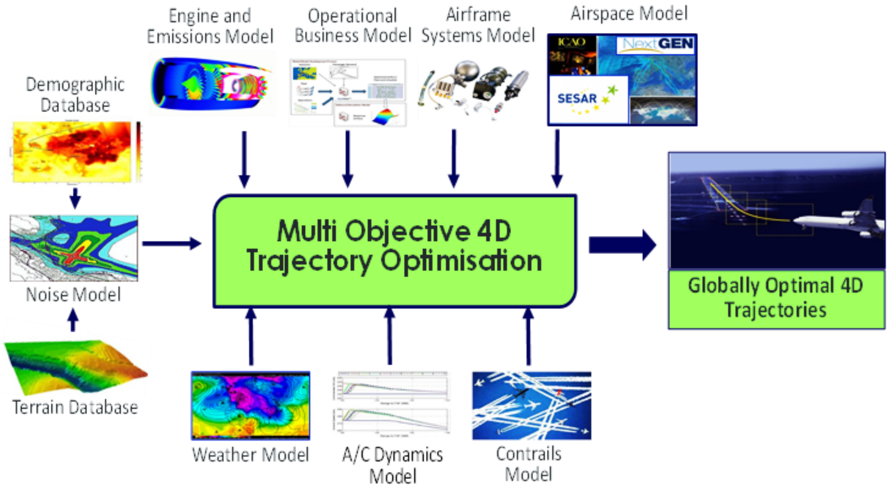


ATM Technologies

4D Trajectories and Intent-Based Operations

- **Development of innovative ATM Decision Support Systems (DSS)** to enable 4D-Trajectory (4DT) optimization, negotiation and validation in the future ATM context
- **4DT Planning, Negotiation and Validation** (4-PNV) in synergy with Next Generation of Flight Management Systems (NG-FMS)



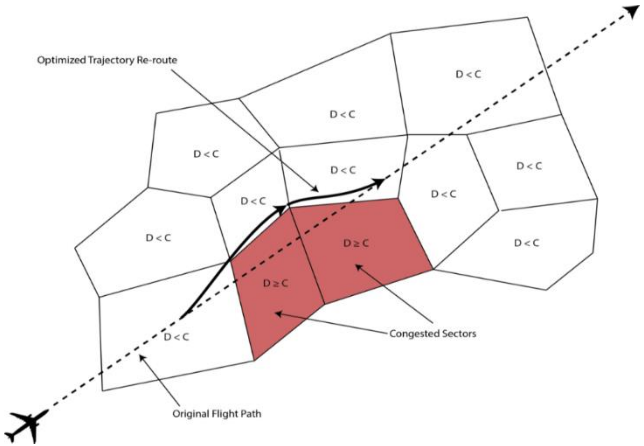


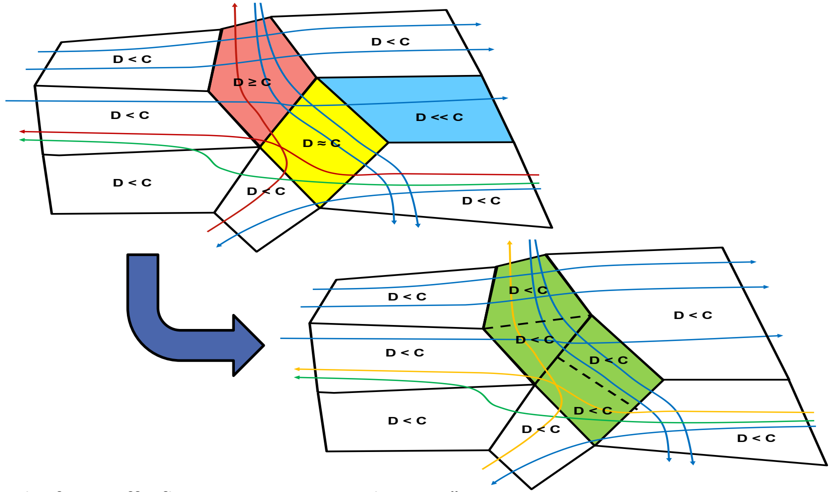
Ref.: A. Gardi, R. Sabatini, and S. Ramasamy, "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", Progress in Aerospace Sciences, vol. 83, pp. 1-36, 2016. DOI: 10.1016/j.paerosci.2015.11.006

Dynamic Airspace Management

- In the near term, ATM systems will automatically validate aircraft intents by implementing **adequate separation assurance and time-based flow optimization methods**

- In the longer term, DSS will evolve to allow **Dynamic Airspace Management** (DAM) with morphing techniques (e.g., dynamic geo-fencing) also supporting UAS Traffic Management (UTM) and Urban Air Mobility (UAM) operations

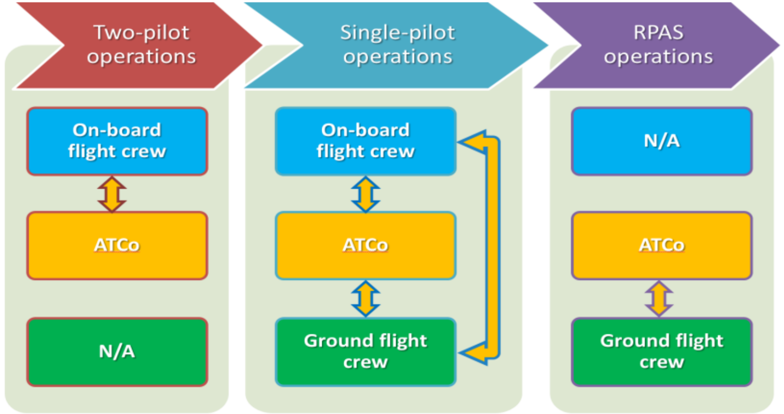


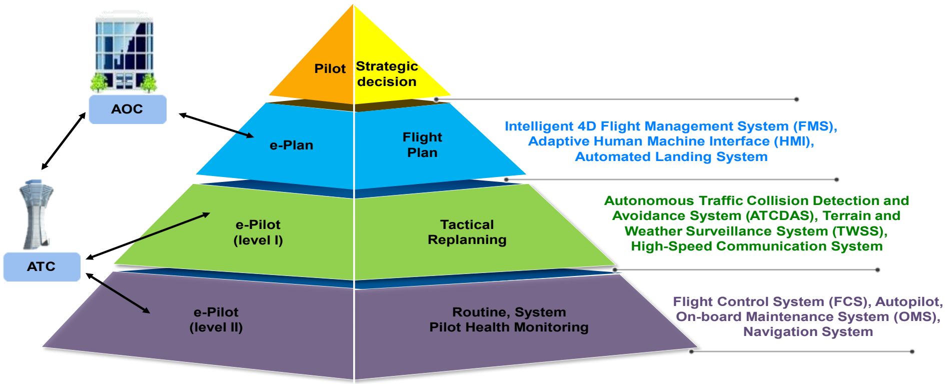


Ref.: T. Kistan, A. Gardi, R. Sabatini, S. Ramasamy, and E. Batuwangala, "An evolutionary outlook of air traffic flow management techniques", Progress in Aerospace Sciences, vol. 88, pp. 15-42, 2017. DOI: 10.1016/j.paerosci.2016.10.001

SiPO to RPAS in Conventional Airspace

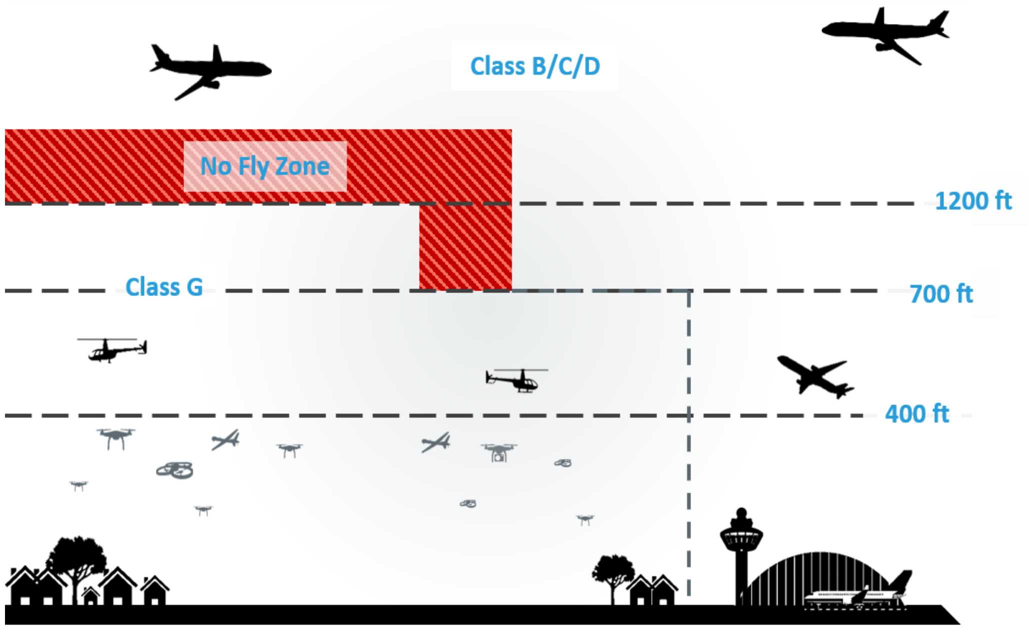
- Improve the total system performance through highly automated CNS+A systems supporting human-machine teaming
- Adaptive Human-Machine Interfaces and Interactions (HMI2) based on:
  - Real-time avionics systems integrity monitoring
  - Sensing of neuro-physiological parameters and AI-based estimation of cognitive states





Ref.: Y. Lim, V. Bassien-Capsa, S. Ramasamy, J. Liu, and R. Sabatini, "Commercial airline single-pilot operations: System design and pathways to certification", IEEE Aerospace and Electronic Systems Magazine, vol. 32, pp. 4-21, 2017. DOI: 10.1109/MAES.2017.160175

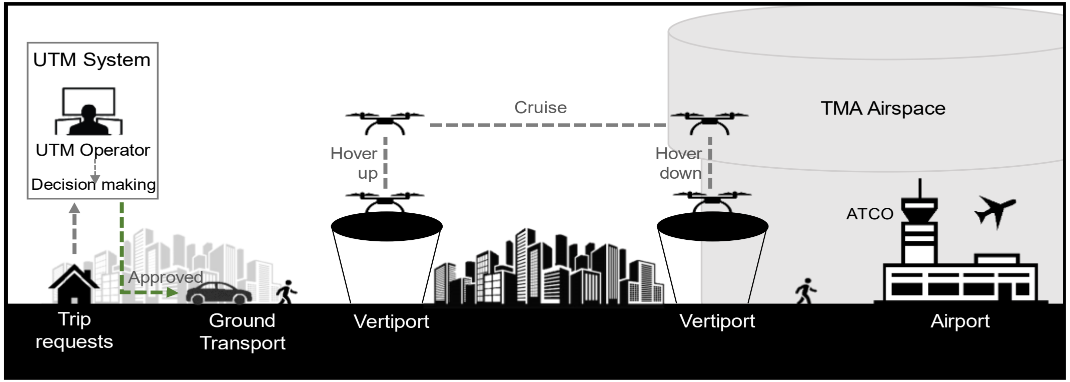
UAS Traffic Management – Key Challenges



- The conventional human-intensive and tactical ATC paradigm cannot fulfil the needs of manned/UAS traffic integration
- A higher degree of automation is necessary in the UTM framework
- The tactical deconfliction approach of traditional ATM cannot be scaled down to apply in UTM
- The tasks and responsibilities of human UTM operators are not fully defined

Ref.: - N. Pongsakornsathien, A. Gardi, R. Sabatini, and T. Kistan, "Evolutionary Human-Machine Interactions for UAS Traffic Management", AIAA Aviation Forum 2021
- N. Pongsakornsathien, A. Gardi, R. Sabatini, T. Kistan, and N. Ezer, "Human-Machine Interactions in Very-Low-Level UAS Operations and Traffic Management", DASC 2020, San Antonio, TX, USA, 2020

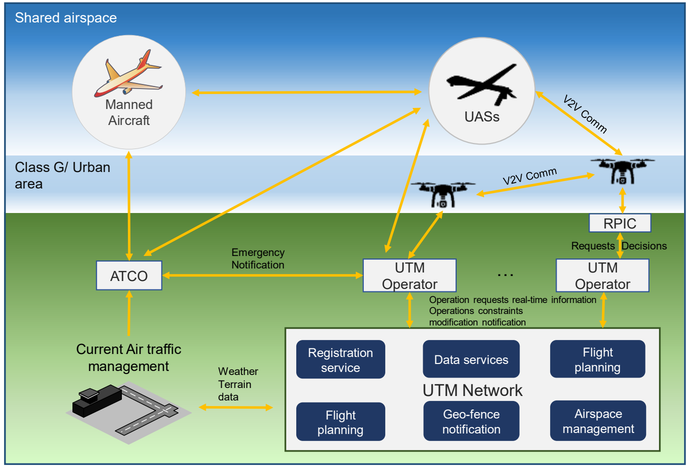
UAS Traffic Management and UAM



Advanced Air Mobility

A safe, automated air transportation system for passengers and cargo in urban and rural locations

- Regional Air Mobility (RAM)
- Urban Air Mobility (UAM)



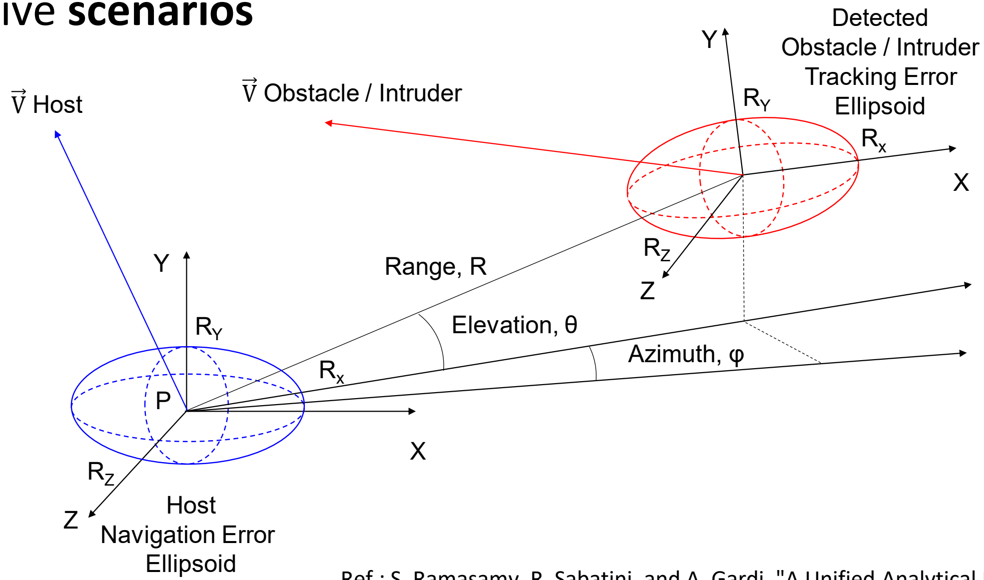
- UTM/AAM are moving towards trusted autonomy
- Highly automated human-in-the-loop operations bring about issues of responsibility allocation and mandates evolutions in the legal and regulatory frameworks (liability concerns)

The tasks and responsibilities of humans and AI agents in UTM/AAM are yet to be defined

Ref.: - N. Pongsakornsathien, A. Gardi, R. Sabatini, and T. Kistan, "Evolutionary Human-Machine Interactions for UAS Traffic Management", AIAA Aviation Forum 2021
- N. Pongsakornsathien, A. Gardi, R. Sabatini, T. Kistan, and N. Ezer, "Human-Machine Interactions in Very-Low-Level UAS Operations and Traffic Management", DASC 2020, San Antonio, TX, USA, 2020

Separation Assurance and Collision Avoidance

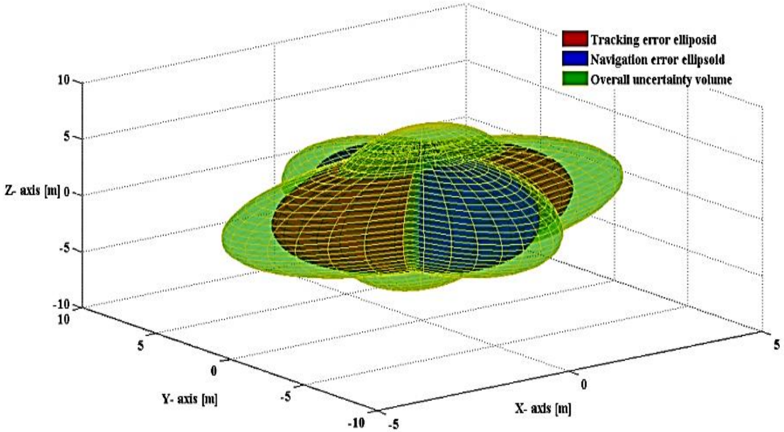
- **Avoidance volume** in the space surrounding each track is determined
- Accomplished by **continuing estimating both navigation and tracking errors** affecting the measurements (plus perturbations) and translating them to **unified range and bearing uncertainty descriptors**, which apply both to cooperative and non-cooperative **scenarios**

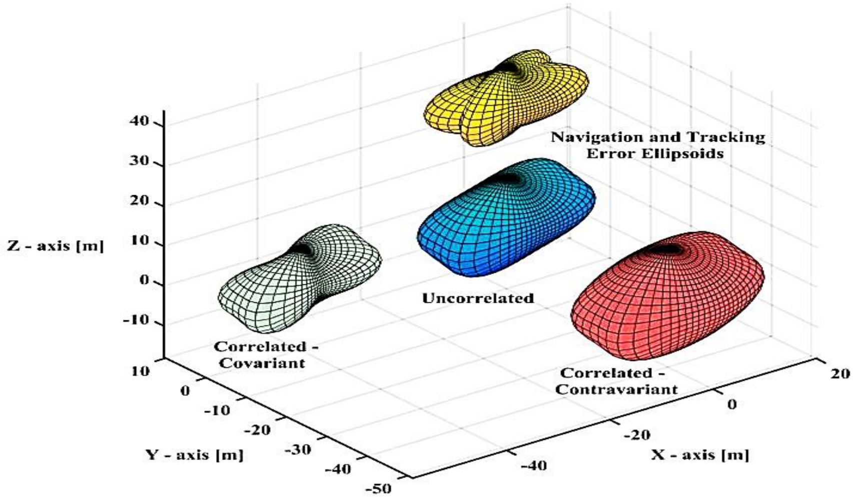


Ref.: S. Ramasamy, R. Sabatini, and A. Gardi, "A Unified Analytical Framework for Aircraft Separation Assurance and UAS Sense-and-Avoid", Journal of Intelligent & Robotic Systems, 91, pp. 735-754, 2018.

SA/CA – Error Analysis

- Errors are statistically correlated (e.g., C-SAA) or uncorrelated (e.g., NC-SAA)
- The avoidance (uncertainty) volume for uncorrelated measurements is obtained by inflating the tracking ellipsoid with the navigation error components
- The uncertainty volume for correlated errors is obtained using vector analysis





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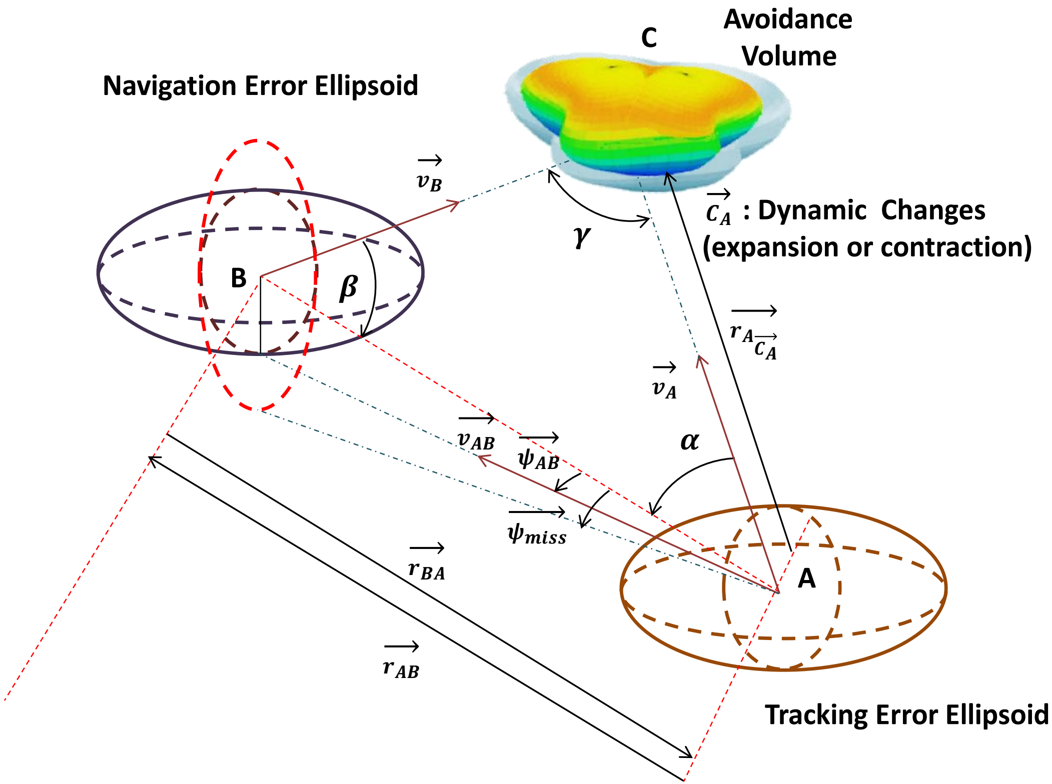
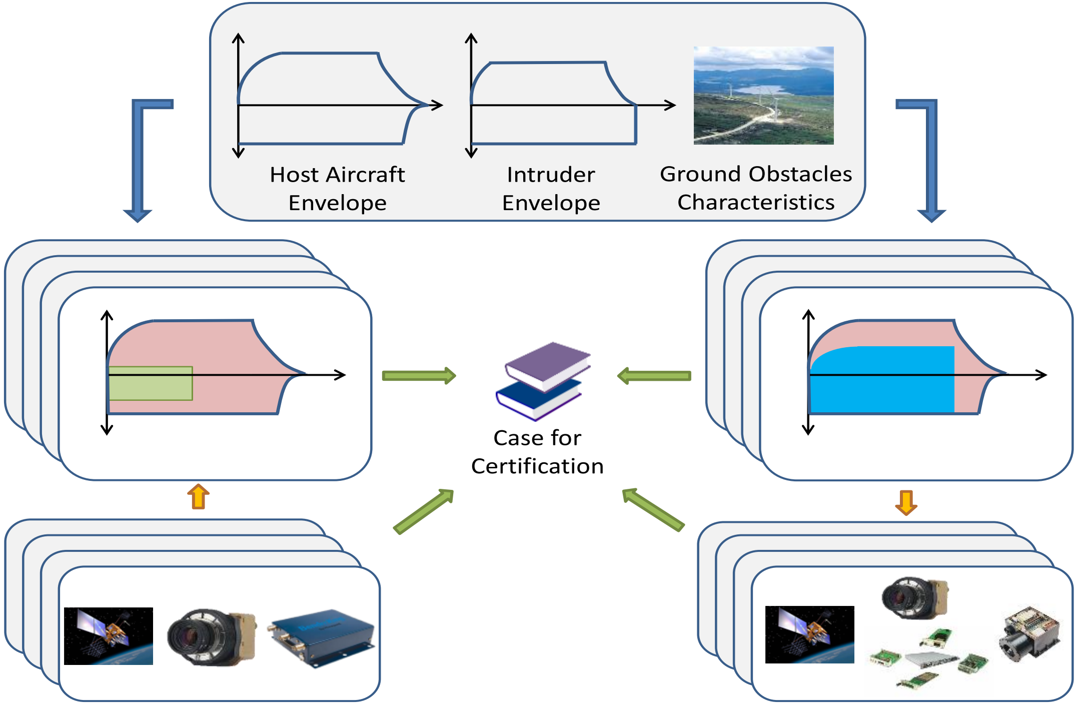
SA/CA – Relative Dynamics and Disturbances



Ref.: S. Ramasamy, R. Sabatini, and A. Gardi, "A Unified Analytical Framework for Aircraft Separation Assurance and UAS Sense-and-Avoid", Journal of Intelligent & Robotic Systems, 91, pp. 735-754, 2018.

SA/CA – Possible Approach to Certification

Distinctive advantage: ability to determine the safe-to-fly UAS envelope based on the on-board sensors/systems and alternatively to identify the required sensors/systems in order to clear a certain predefined safety envelope



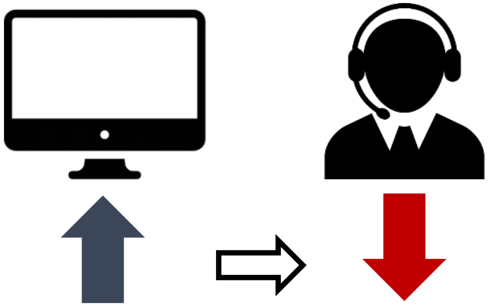
Ref.: S. Ramasamy, R. Sabatini, and A. Gardi, "A Unified Analytical Framework for Aircraft Separation Assurance and UAS Sense-and-Avoid", Journal of Intelligent & Robotic Systems, 91, pp. 735-754, 2018.

HOTL Dynamic Interactions

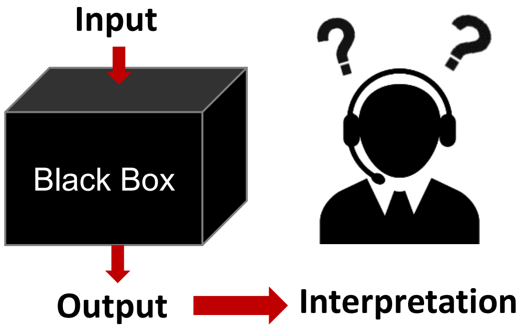
Challenges

Higher level of automation in an out-of-loop paradigm

- Lower cognitive capability
- Progressive deskilling
- Lower situational awareness



Human Factors



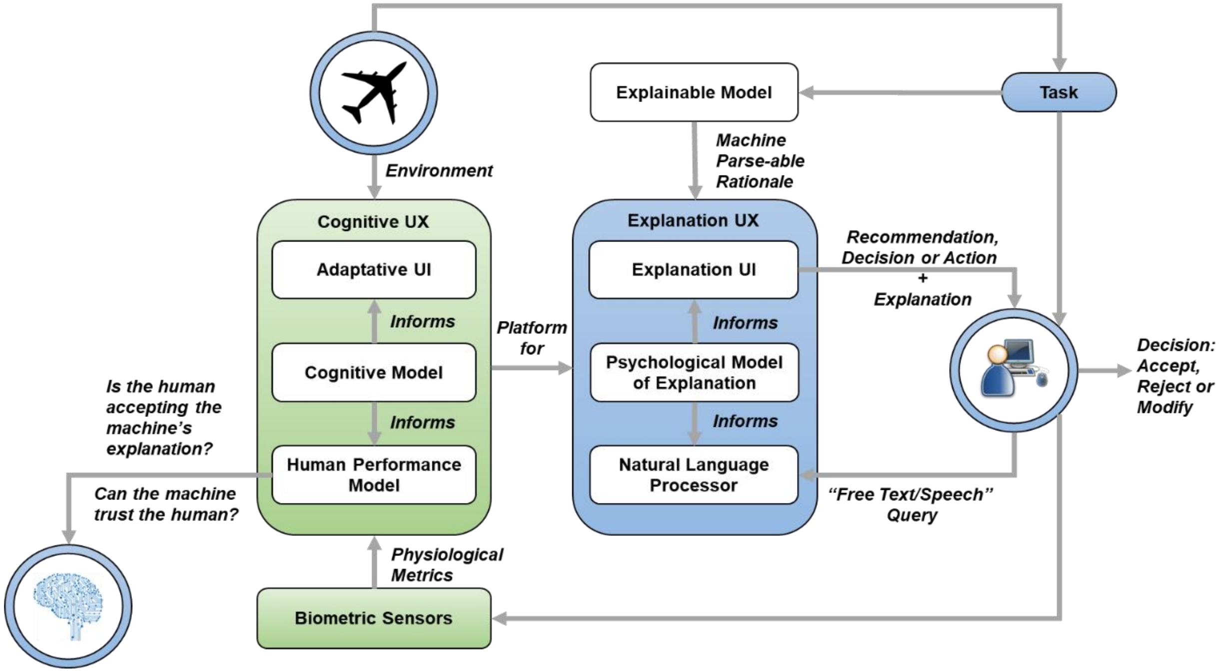
AI Explanation

Solution

Adaptive HMI based on Explainable and Trusted AI

Cognitive Human-Machine Systems (CHMS)

Cognitive HMI and Explanation UX

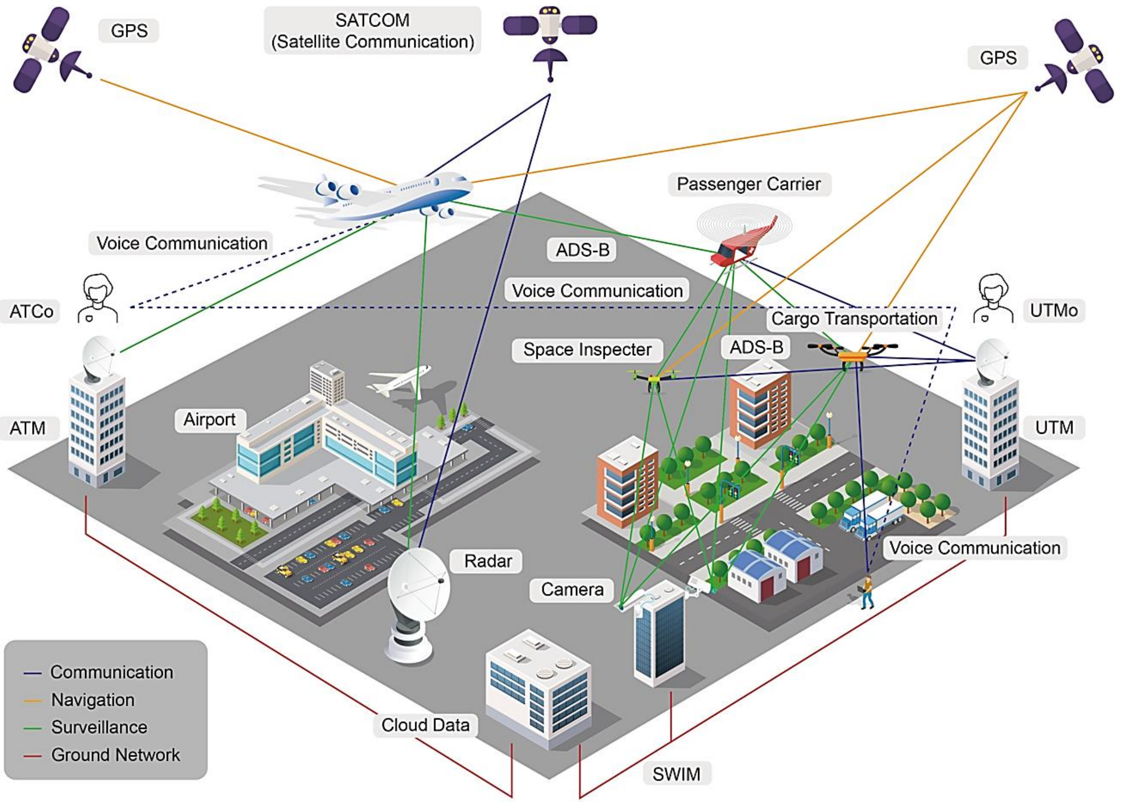


- **Explainable AI**
- **Trusted AI**
- **Certifiable AI**

Ref: T. Kistan, A. Gardi, and R. Sabatini, "Machine Learning and Cognitive Ergonomics in Air Traffic Management: Recent Developments and Considerations for Certification," Aerospace, vol. 5, p. 103, 2018.

Cybersecurity Vulnerabilities in ATM and UTM

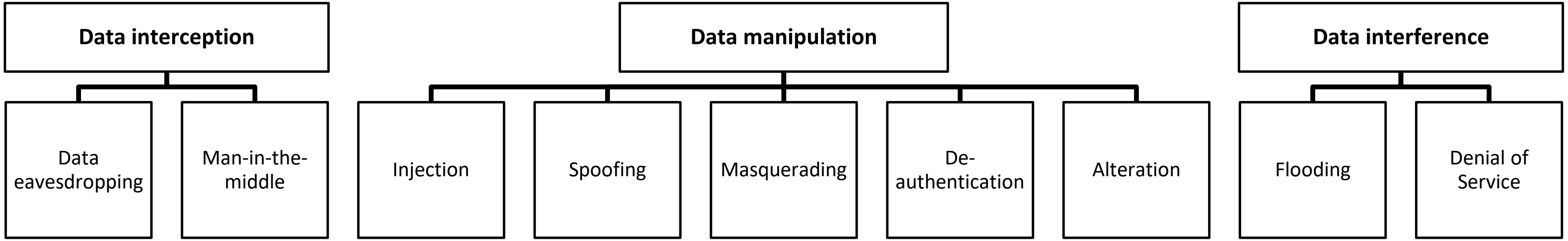
- Communication
  - HF/VHF voice, CPDLC, L-DACS, ACARS, SATCOM, Wireless communication networks
- Navigation
  - TRNAs, GNSS
- Surveillance
  - PSR, SSR, WAM, TACS, ADS-B
- Ground Network
  - SWIM



Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

Cyber Attack Methods

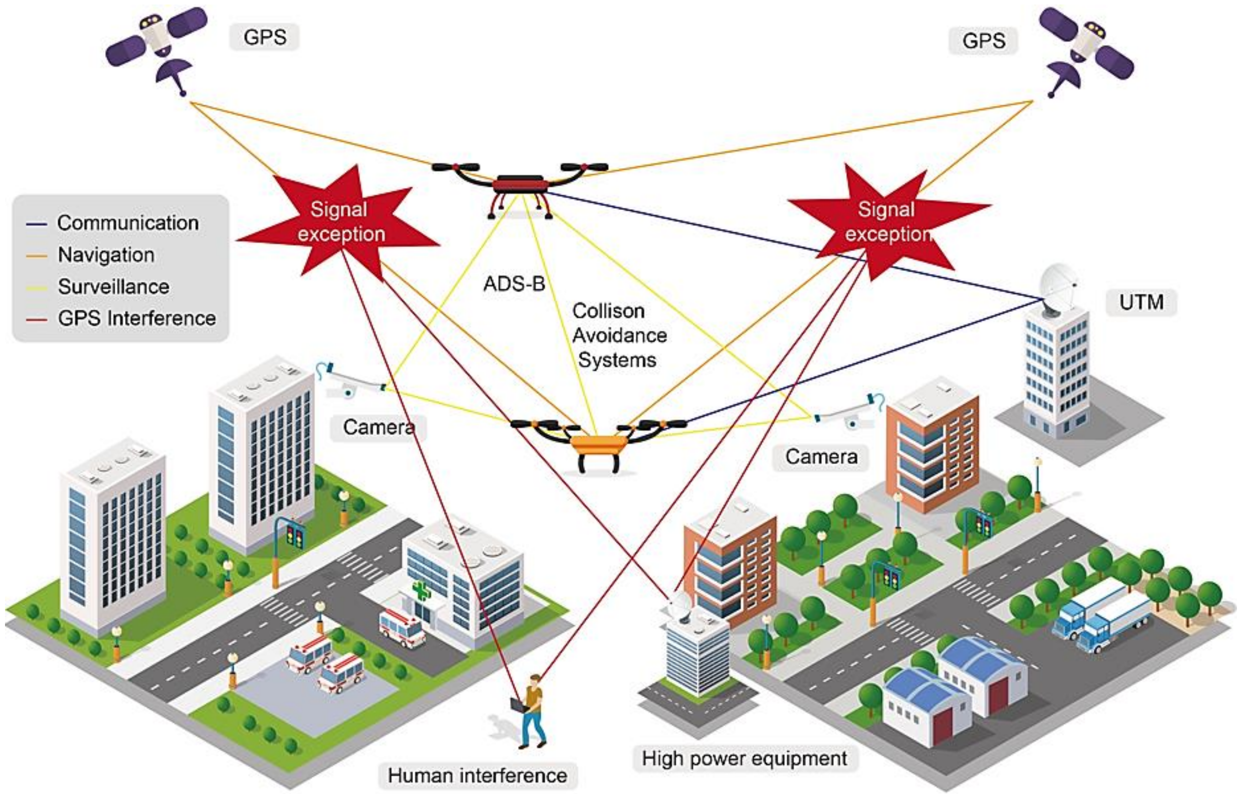
- Cyber-attack can pose threats to both software systems and physical hardware



At present, most UAS cannot be effectively defended against network attacks

Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

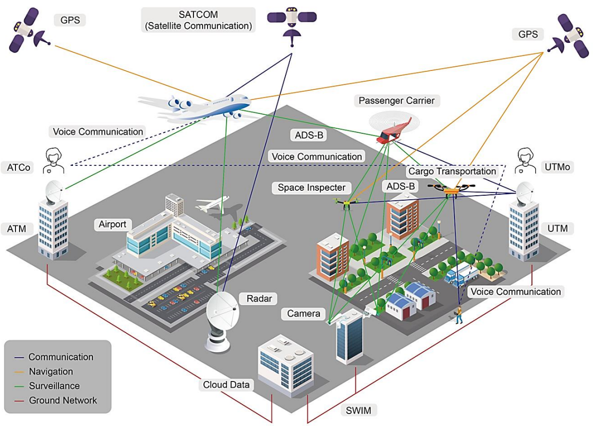
GPS and ADS-B Case Study

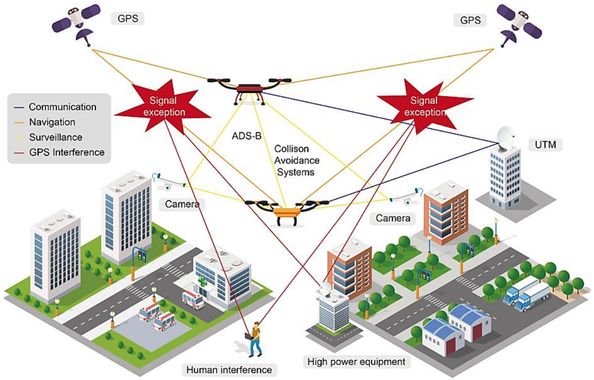


Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

Key Challenges

- Evolving ATM & UTM architectures based on big data and AI plus increased interdependence of CNS/ATM and avionics systems result in an increasing attack surface
- AI-based offensive technologies are bound to become very common, requiring AI-based cyber-defenses
- Need for a new generation of secure management systems and more efficient attack detection techniques



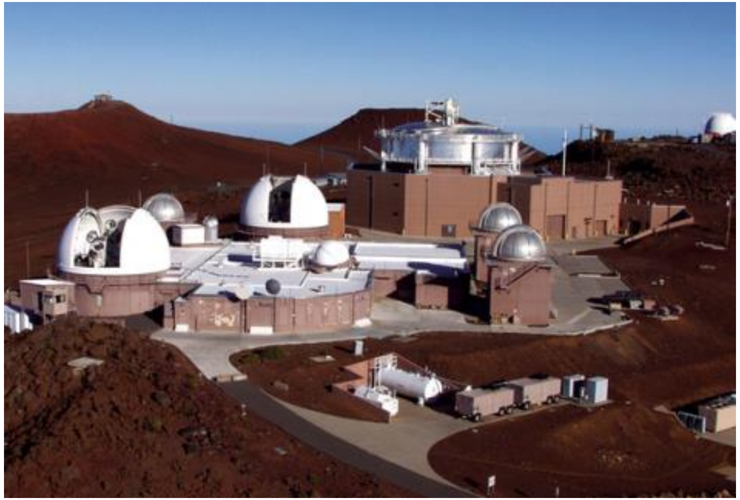


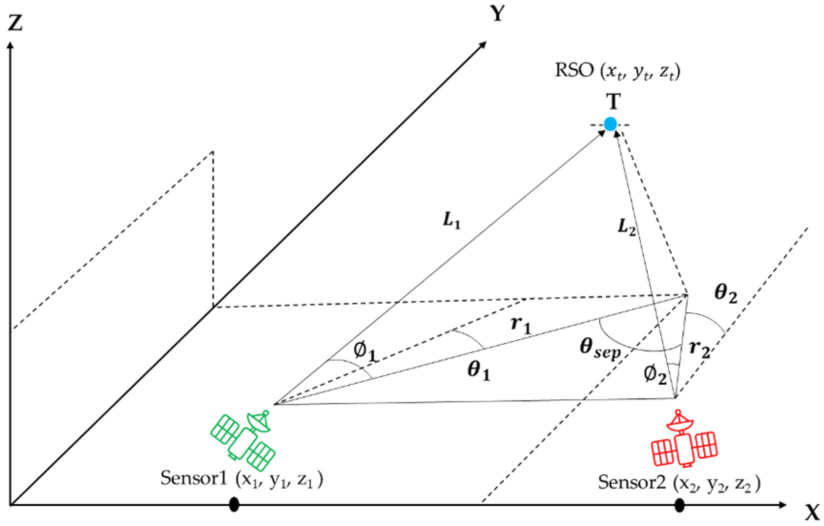
Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

Space Domain Awareness and Space Traffic Management

Multi-Sensor RSO Tracking

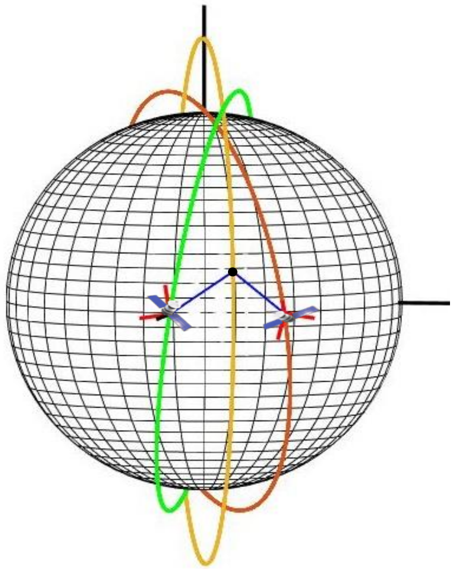
- Cooperative and Non-Cooperative Surveillance for SDA and STM
- Ground-Based Surveillance (GBS) and Space-Based Space Surveillance (SBSS)
- Tracking of <10cm RSO elusive to GBS infrastructure – STM Requires SBSS Integration



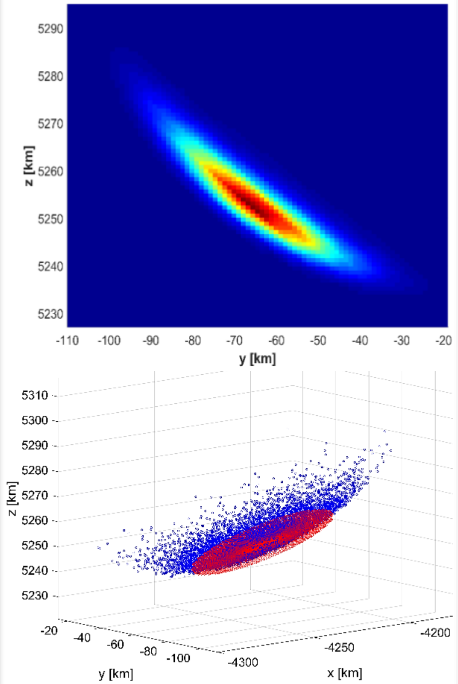


Space Traffic Management

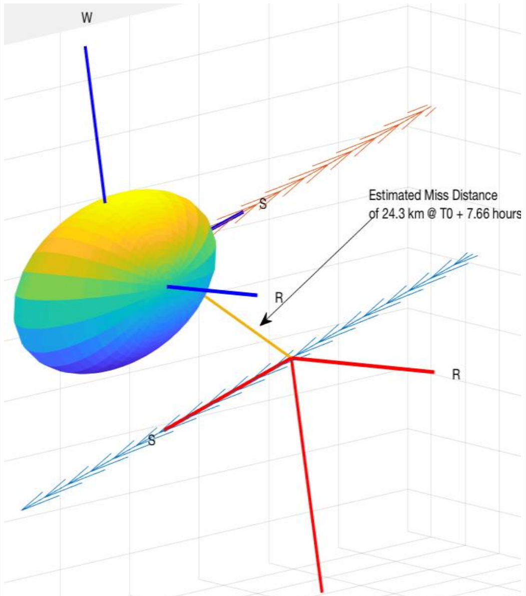
Navigation and Tracking Data Collection and Sharing (Cooperative scenario)



Quantify and Predict Tracked Space Object Uncertainty



Conjunction Analysis and Collision Avoidance

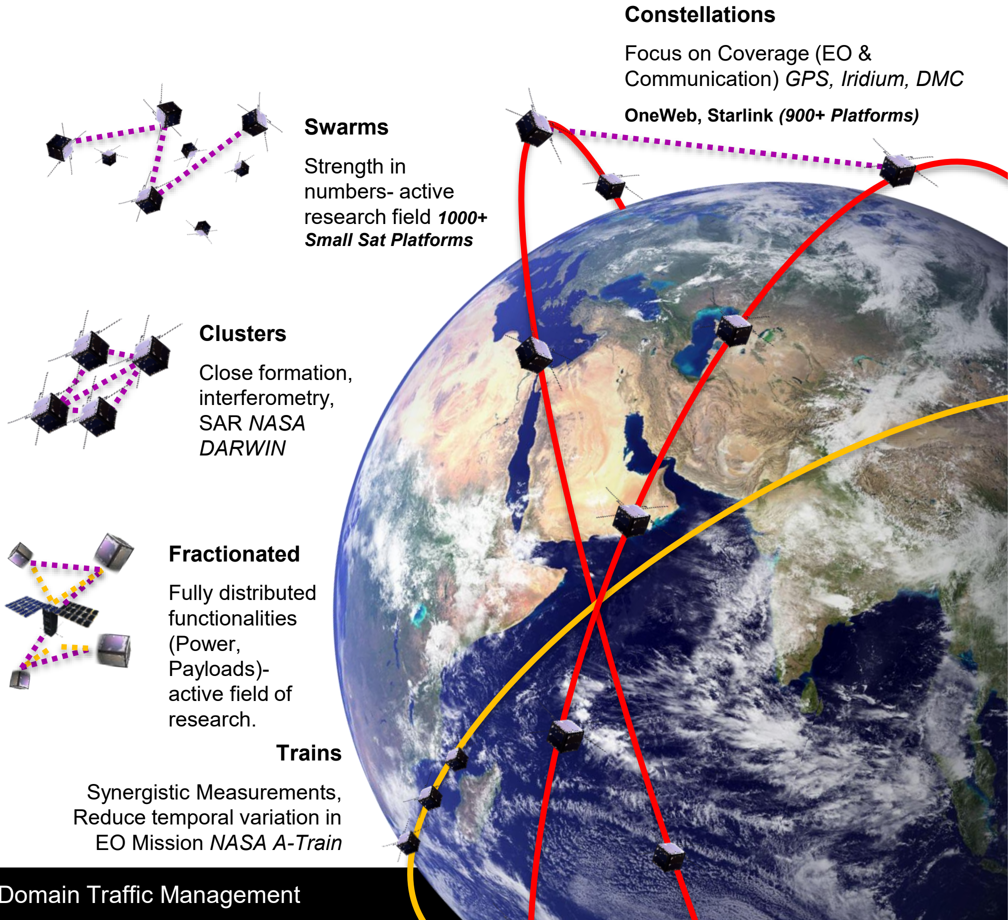


Ref.: - S. Hilton, R. Sabatini, A. Gardi, et al., "Space traffic management: towards safe and unsegregated space transport operations", Progress in Aerospace Sciences, 105, pp. 98-125, 2019.
- S. Hilton, F. Cairola, A. Gardi, R. Sabatini, N. Pongsakornsathien, and N. Ezer, "Uncertainty quantification for space situational awareness and traffic management", Sensors, 19, 2019.

Distributed Space Systems

DSS move away from the **monolithic** space system concept to adopt **multiple** elements that **interact**, **cooperate** and **communicate** with each other, resulting in **new systemic properties** and/or **emerging functions**

Architecture	Mission goals	Cooperation	System makeup	Inter-Sat distance	Operational independence
Constellation	Shared - Focus on coverage	Required	Homogeneous	Regional	Independent to co-dependent
Train	Independent to shared	Optional	Heterogeneous	Local	Independent
Cluster	Shared	Required	Homogeneous	Local	Independent to co-dependent
Swarm	Shared	Required	Homogeneous to heterogenous	Local to regional	Independent to co-dependent
Fractionated	Shared	Optional to required	Heterogeneous	Local	Independent to co-dependent
Federated	Independent	Ad-hoc, optional	Heterogeneous	Local to regional	Independent



AI4SPACE Research Context

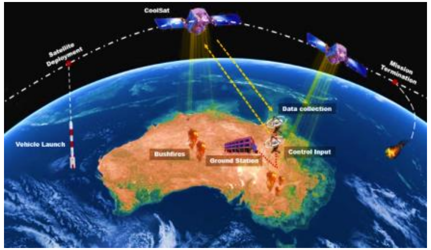
Advanced Satellite Systems, Sensors and Intelligence. Communications, connectivity and IoT technologies. Next Generation Earth Observation Services. Trusted Autonomy and Evolutionary Mission Control Centres

Strengths/Discriminators

- Space-based SDA/STM - Reduction of uncertainty by Tracking of <10cm RSO's elusive to ground infrastructure
- AI-based sensor management and data fusion (autonomous decision making, diagnosis/prognosis and mission management)
- Custom sensors and data analytics products and services for: Mining and Resources, Agriculture/Horticulture/Aquaculture, Transport and Logistics
- Adaptive interfaces and interactions for de-crewing of mission control centres

Research Opportunities

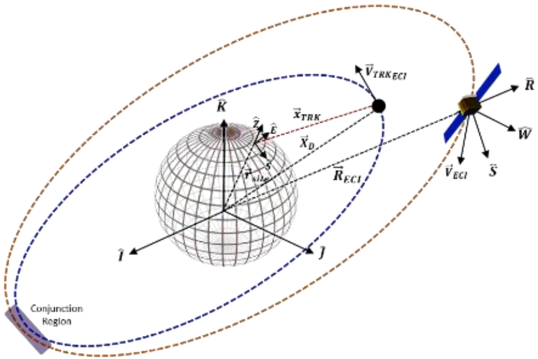
- Artificial Intelligence and Machine Learning (AI/ML) software for trusted autonomous operation
- Fault-tolerant avionics/spaceflight systems research
- Intelligent satellite health management systems
- Passive and active EO/IR sensors and systems

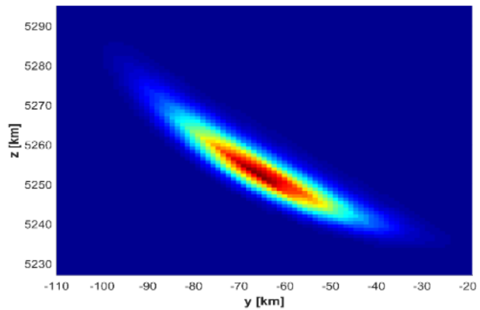


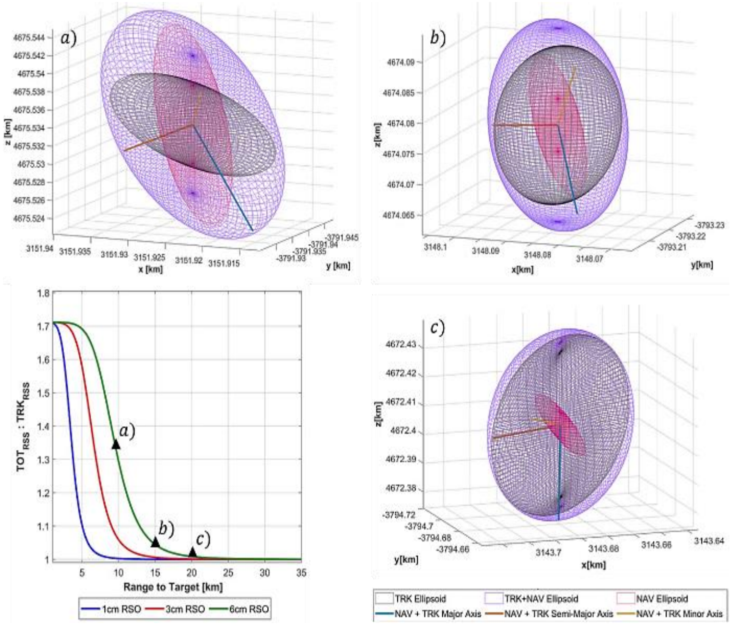
Space Domain Awareness and Traffic Management

Non-cooperative/cooperative tracking, multi-objective trajectory optimisation and goal-based mission planning for time-critical application such as deconfliction of space vehicles

- **Unified mathematical framework** for 4-Dimensional collision uncertainty quantification and mapping
- Considering both space-based and ground-based space surveillance sensors
- Unique software tools employing AI/ML techniques

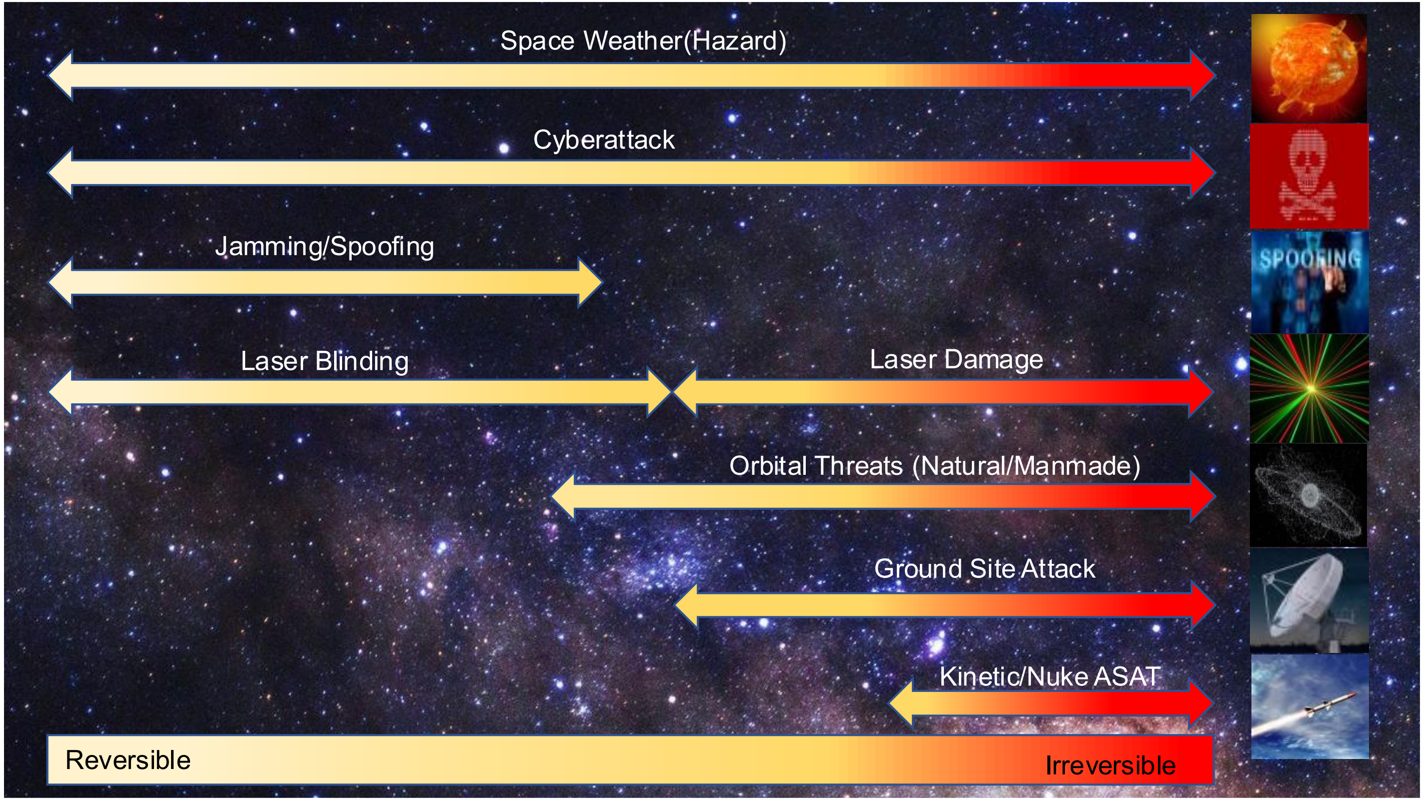






Ref.: - S. Hilton, R. Sabatini, A. Gardi, et al., "Space traffic management: towards safe and unsegregated space transport operations", Progress in Aerospace Sciences, 105, pp. 98-125, 2019.
- S. Hilton, F. Cairola, A. Gardi, R. Sabatini, N. Pongsakornsathien, and N. Ezer, "Uncertainty quantification for space situational awareness and traffic management", Sensors, 19, 2019.

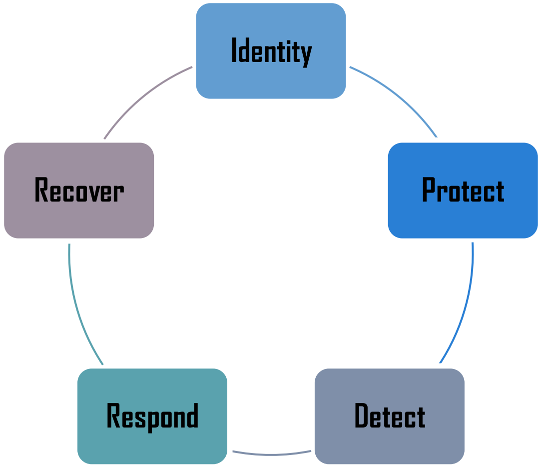
Space Cyber-Physical Threats



K. Thangavel, J.J. Plotnek, A. Gardi, R. Sabatini, "Understanding and Investigating Adversary Threats and Countermeasures in the Context of Space Cybersecurity", IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.

Attack Surfaces and Cybersecurity Framework

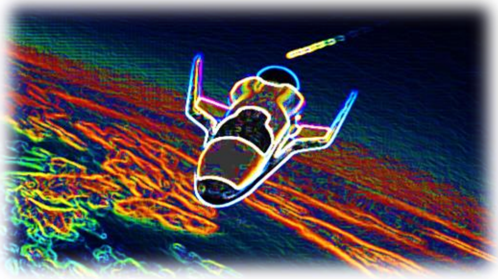
Segment	Vulnerability	Threats
Space Segment	Payload Vulnerabilities	• Denial of Service, • Hardware Backdoor, • Bespoke Malware, • Privilege Escalation, • Hijacking, • Sensor Injection.
Link Segment	Signal Vulnerabilities	• Jamming, • Eavesdropping, • Spoofing, • Metadata-Analysis, • Command Injection, • Replay Attacks, • Signal Injection.
Ground Segment	Ground station Vulnerabilities	• Bespoke Malware, • Generic Malware, • Social Engineering, • Physical Access, • Data Corruption, • Hardware Backdoor.



K. Thangavel, J.J. Plotnek, A. Gardi, R. Sabatini, "Understanding and Investigating Adversary Threats and Countermeasures in the Context of Space Cybersecurity", IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.

Unified Air and Space Traffic Management

- Unified approach to cooperative and non-cooperative SA/CA is necessary
- Accounting navigation/tracking errors, relative dynamics and perturbations
- Both ground-based surveillance and SBSS are needed for a scalable STM
- Data-centric STM and ATM integration (MDTM)
- Cyber and physical security threats
- AI certification challenges



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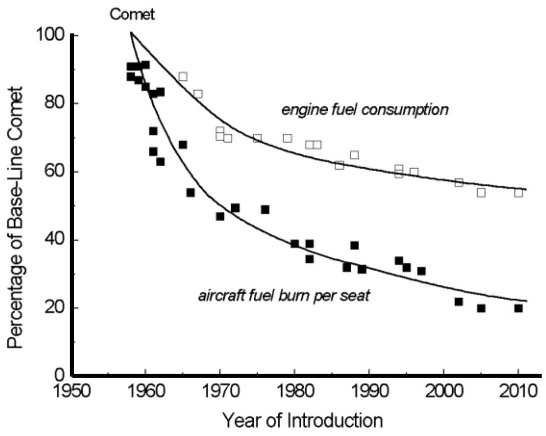
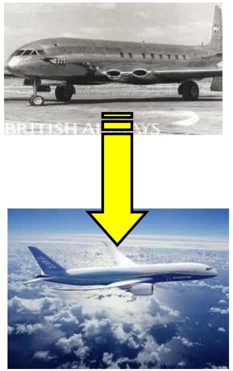
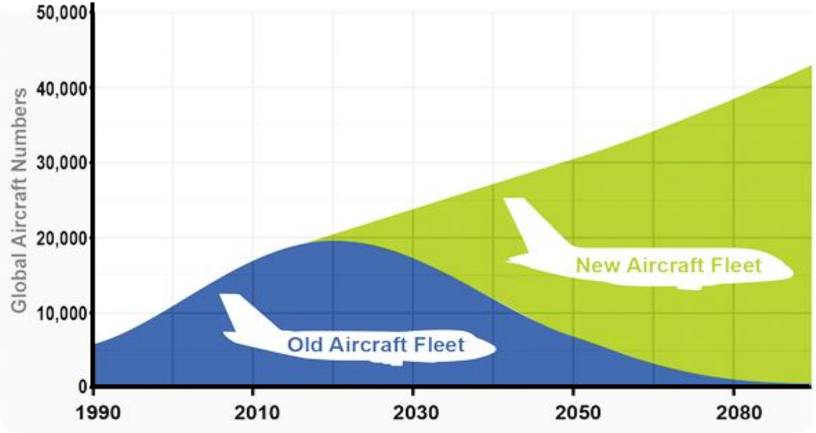
Aviation Noise Impact Assessment and Mitigation

Aviation Sustainability Challenges

- Aircraft atmospheric pollution includes **carbon dioxide, nitrogen oxide, unburned hydrocarbons** (and more), **all of which contribute to global warming**
- It is estimated that **aviation industry contribution to global warming is currently about 3%, although it may increase to 5-10% by 2050** due to the anticipated growth of air traffic
- **Air quality is also degrading significantly due to aviation activities**, especially at and around airports
- **Aviation noise also has short and long-term health impacts** both on humans and other animals
- Technology advances have been successful in reducing atmospheric pollution and noise emissions from aircraft, but these have not been able to offset the impacts of aviation growth

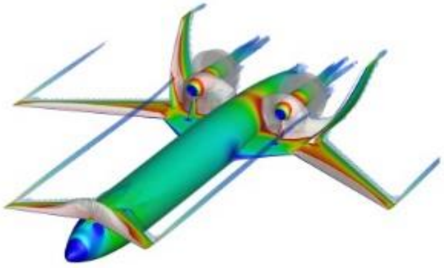


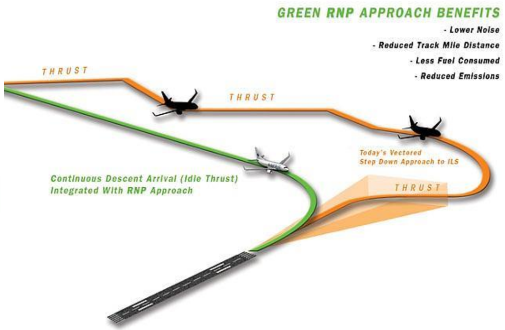




R&I Areas of Focus

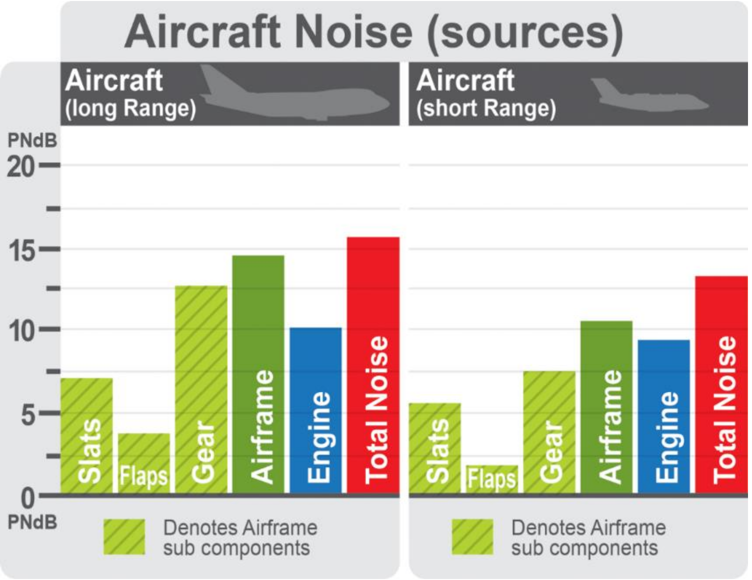
- ❖ **Science**
  - Assessing aviation environmental impacts
  - Forecasting, modelling and analysis
- ❖ **Technology and Operations**
  - Aerodynamics and propulsive technologies
  - Flight operations, avionics and air traffic management
  - Airport design, upgrade and operations
  - Advanced manufacturing and logistics
- ❖ **Policy and Regulations**
  - Sustainability policies for aviation
  - Greenhouse/noise limiting standards
  - Technology uptake and certification

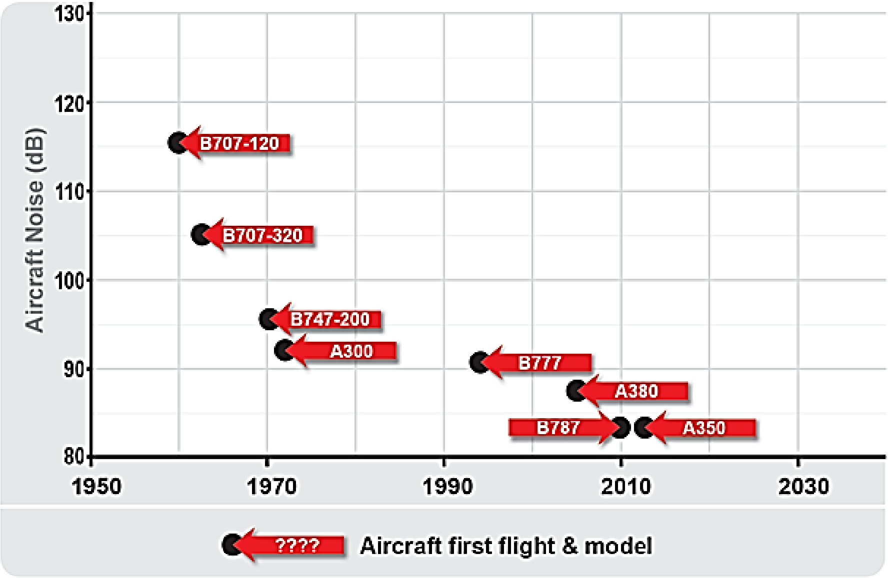




Aircraft Noise Sources and Trends

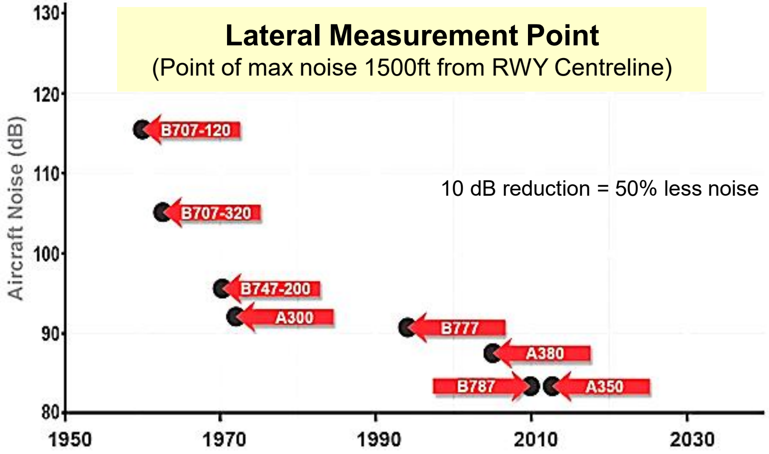
- Modern aircraft are quieter than their predecessors. However, the steady growth in air traffic increases public exposure to aircraft noise (particularly for people living close to airports)
- Noise can dominate the relationship between airports and local residents, and can lead to restrictions in aircraft operations



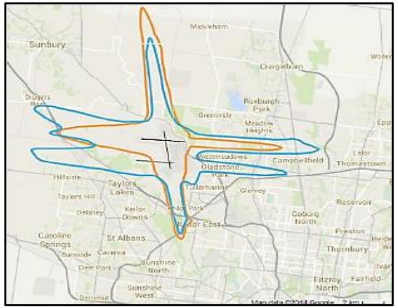


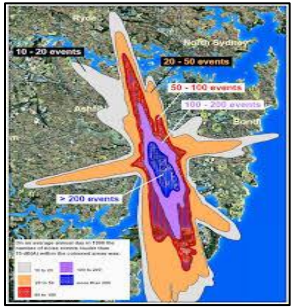
10 dB reduction = 50% less noise

Aircraft Noise Impacts



- Engine noise, aerodynamic noise, complex jet-airframe interactions
- **The noise levels experienced by people on the ground** are influenced by:
  - Aircraft type and size (propulsion and aerodynamics)
  - The distance of the aircraft from the ground (trajectory flown)
  - The way the engine and other aircraft systems are operated
  - The rate at which the aircraft climbs/descends
  - Meteorological conditions
- Noise Exposure Forecast (NEF) used for urban planning





Aircraft Noise – Regulation

- Monitor from society for future solutions
  - New cargo air routes, density, and aircraft types
- Regulation from ICOA, FAA, etc.
  - US Code of Federal Regulations (CFR) Title 14 Part 36
  - UAVs and **electric aircraft** solutions

ICAO Noise Standards[27]

Chapter	Year	Ch. 3 Margin	Types[28]
none	before	none	Boeing 707, Douglas DC-8
2	1972	~+16 dB	Boeing 727, McDonnell Douglas DC-9
3	1978	baseline	Boeing 737 Classic, MD-80
4 (stage 4)	2006	−10 dB	Airbus A320, Boeing 737NG, Boeing 767, Boeing 747-400
14 (stage 5)	2017–2020	−17 dB	Airbus A320, Airbus A320neo, Airbus A330, Airbus A350, A 757, Boeing 777, Boeing 787

Aircraft noise pollution - Wikipedia

Fuel, Emissions and Noise Reduction Goals

	ACARE – SRA and SRIA (wrt 2000)		NASA – ERA (wrt 1998) and SIP (wrt 2005)					
Subsonic A/C Emissions	Vision 2020	**FlightPath 2050**	ERA 2015	ERA 2025	ERA 2035	SIP 2015-25	SIP 2025-35	**SIP >2035**
Fuel/CO_2	50% (38% 2015)	**75%**	50%	50%	60%	40-50%	50-60%	**60-80%**
NO_x	80% (----- 2015)	**90%**	75%	75%	80%	70-75% LTO* 60-70% CRZ	80%	**>80%**
Noise	50% (37% 2015)	**65%**	32dB	42dB	71dB	22-32dB**	32-42dB	**42-52dB**

ACARE - Advisory Council for Aviation R&I in Europe, **SRA** - Strategic Research Agenda, **SRIA** - Strategic Research and Innovation Agenda, **ERA** - Environmentally Responsible Aviation, **SIP** - Strategic Implementation Plan

A/C - Aircraft, **LTO** - Landing and Take/Off, **CRZ** - Cruise, *Below CAEP6, **Below Chapter 4. All % reductions are in Passenger-km

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Clean Sky 2 · SESAR Joint Undertaking · NASA · NextGEN

Cooperation Opportunities

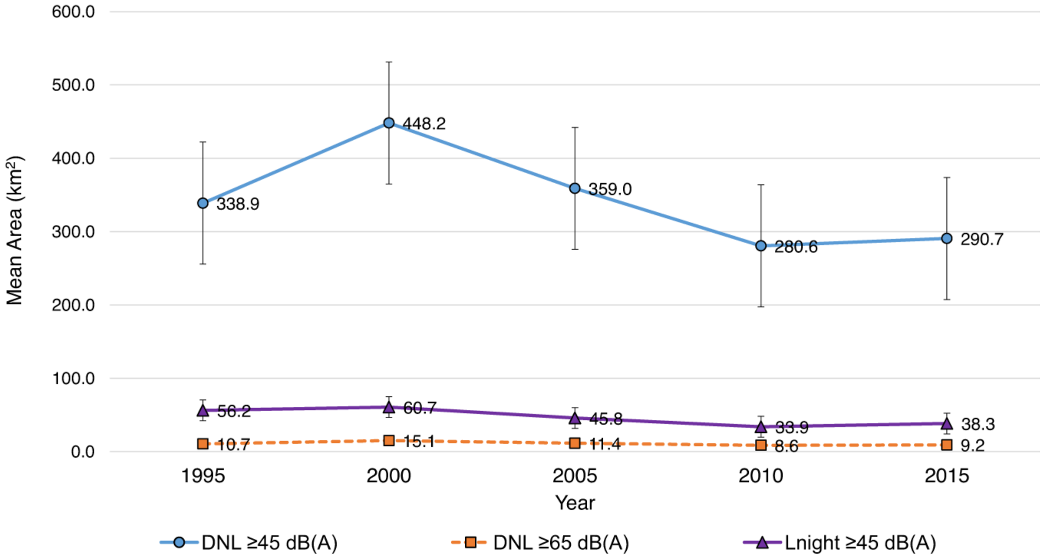
ACARE - Advisory Council for Aviation R&I in Europe, **SRA** - Strategic Research Agenda, **SRIA** - Strategic Research and Innovation Agenda, **ERA** - Environmentally Responsible Aviation, **SIP** - Strategic Implementation Plan

A/C - Aircraft, **LTO** - Landing and Take/Off, **CRZ** - Cruise, ***Below CAEP6, ****Below Chapter 4. All % reductions are in Passenger-km

Aircraft Noise – Trend Analysis

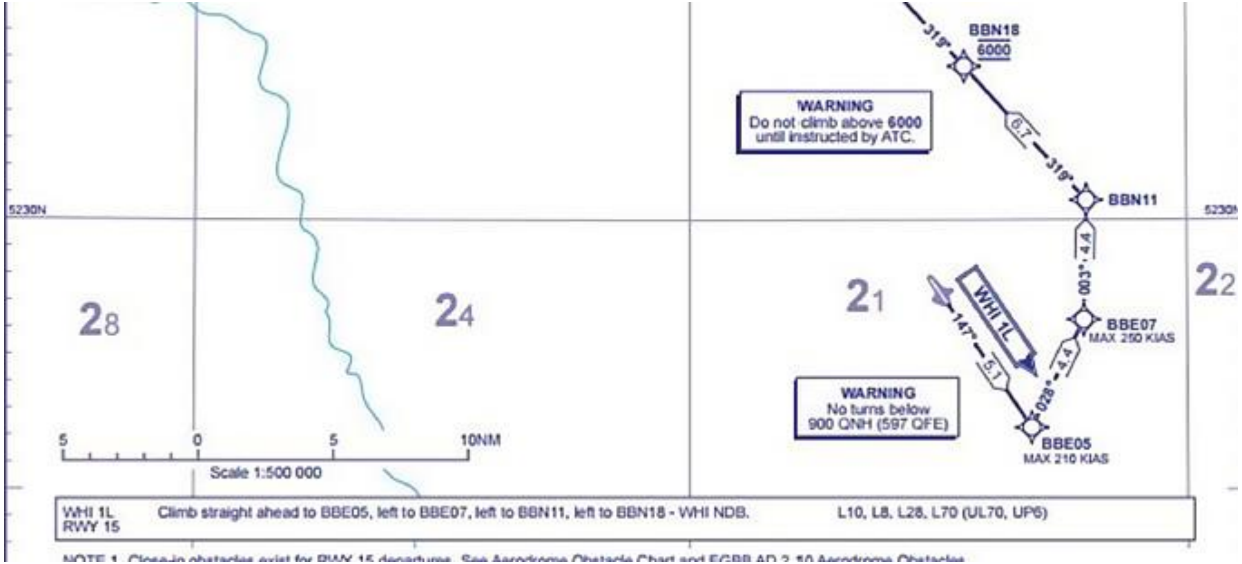
- Analysis of noise levels (Nature study - **Characterizing temporal trends in populations exposed to aircraft noise around U.S. airports: 1995–2015**) influenced by:
  - **Types:** Passenger versus cargo
  - **Regions**– South and North America
  - **Affects:** annoyance, hypertension, child learning
  - 2010 - day-night average sound level (DNL) 55 A-weighted decibels (dB[A])
  - 2015 – levels assessed DNL) 5 dBa and Night 45 dBA
- Assessment and technology helps in the design and analysis for safety

Characterizing **temporal trends in populations exposed to aircraft noise** around U.S. airports: 1995–2015 | Journal of Exposure Science & Environmental Epidemiology (nature.com)



Aircraft Noise – ex Route Planning to Mitigate

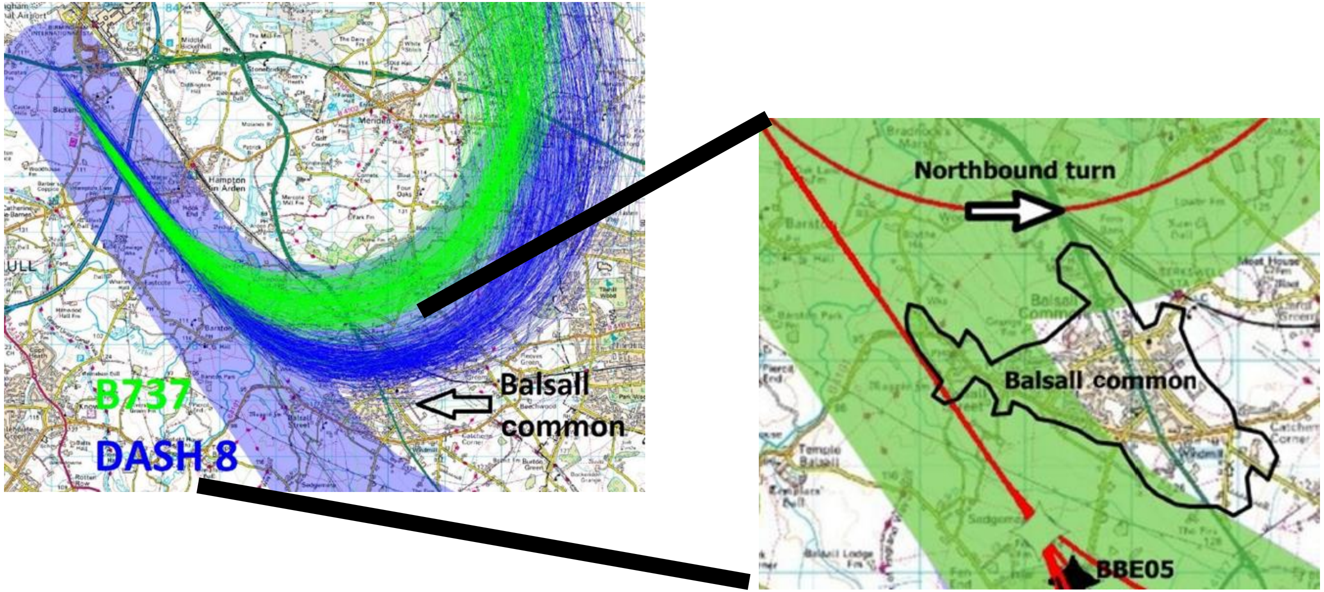
- Parameters for **Aircraft aRea Navigation** (RNAV)
  - **True Airspeed** (TAS)
  - **Turn Radius**
  - **Minimum Stabilization distance** (MSD)
  - -Turning speed
  - - Protective zones
  - - Waypioint Distance



D. Homola, J. Boril, V. Smrz, J. Leuchter, E. Blasch, "Aviation Noise-Pollution Mitigation through Redesign of Aircraft Departures," *Journal of Aircraft*, 56(5):1-13, Sept: 2019. https://doi.org/10.2514/1.C035001

Aircraft Noise – ex Route Planning to Mitigate

- Routes and Balsall City, UK – data collected from ADS-B information
  - Two routes over city (city sprawl after airport built)



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Aircraft Noise – ex Route Planning to Mitigate

- Replanning the departure – RNAV **standard departure route** (SDR) chart
  – accounting for **wind** speeds, direction and spiral

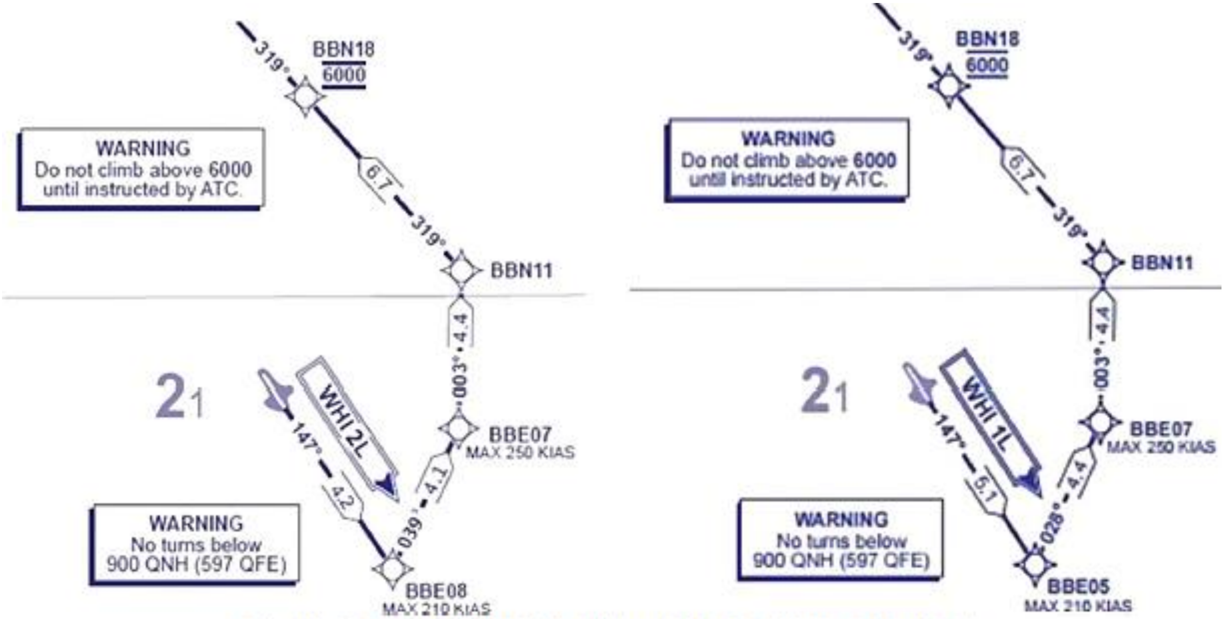
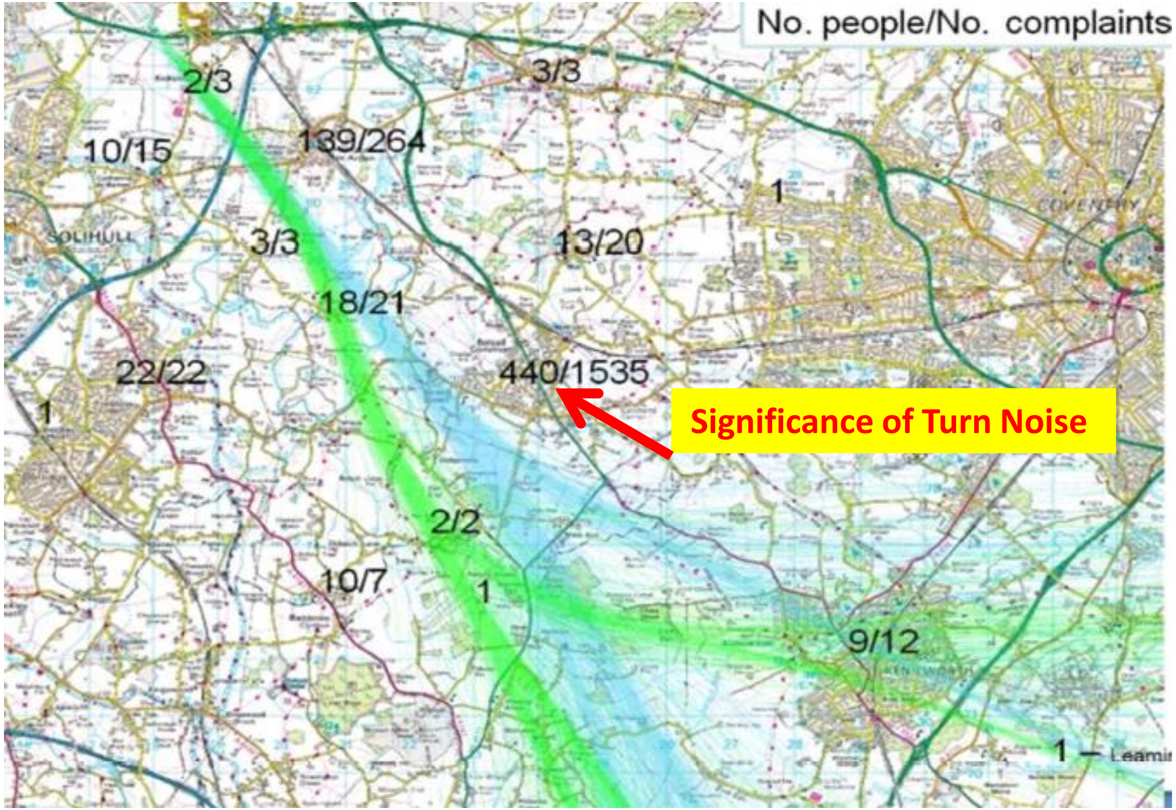


Fig. 13 RNAV 1 SID WHI 2L (left) and RNAV 1 SID WHI 1L (right).

D. Homola, J. Boril, V. Smrz, J. Leuchter, E. Blasch, "Aviation Noise-Pollution Mitigation through Redesign of Aircraft Departures," *Journal of Aircraft*, 56(5):1-13, Sept: 2019. https://doi.org/10.2514/1.C035001

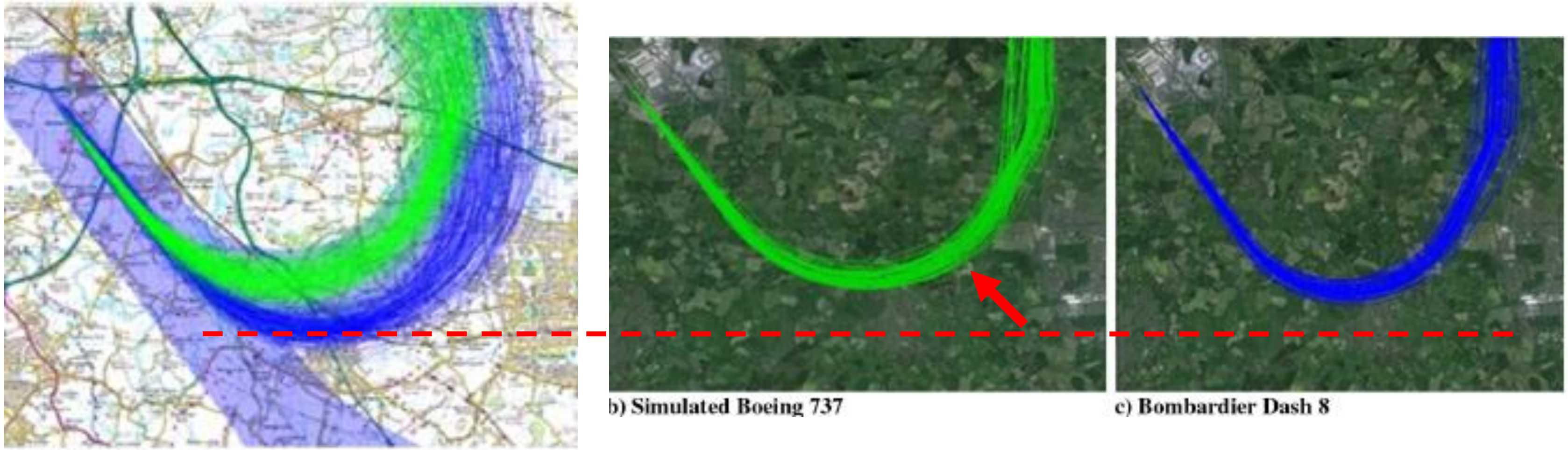
Aircraft Noise – ex Route Planning to Mitigate

- **Noise Complaints**
- More complaints at the turn when the aircraft is flying up and out



Aircraft Noise – ex Route Planning to Mitigate

- Replanning the departure – **direction**
- Move the **turning curvature to the north** (away from the complaints in Balsall)



a) Radar data

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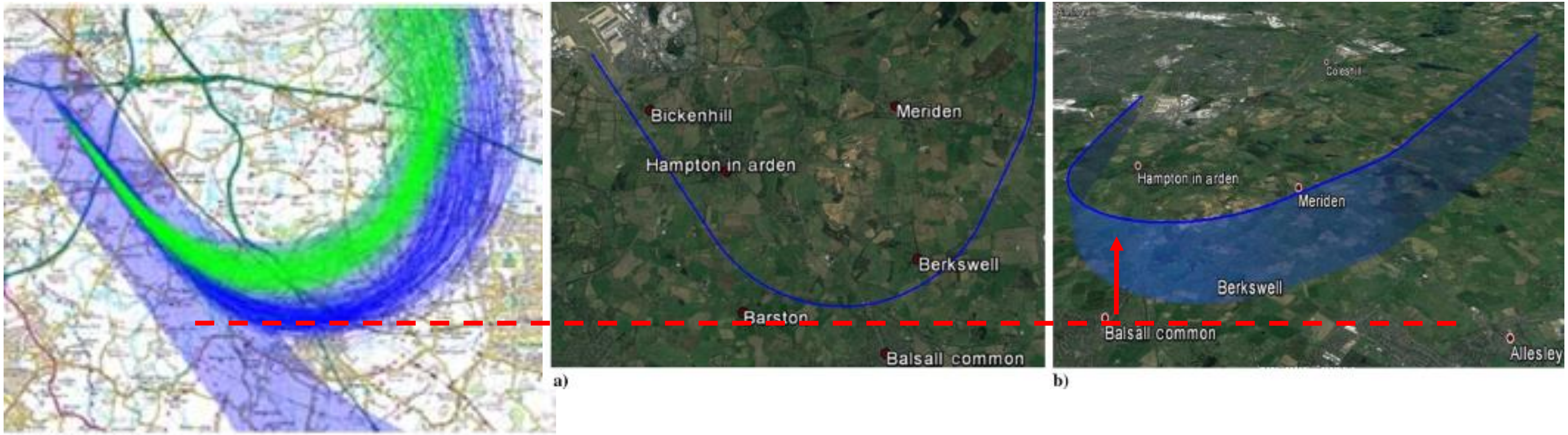
Aircraft Noise – ex Route Planning to Mitigate

- Replanning the departure - **height**
- Move the **turning curvature in altitude** (away from the complaints in Balsall)



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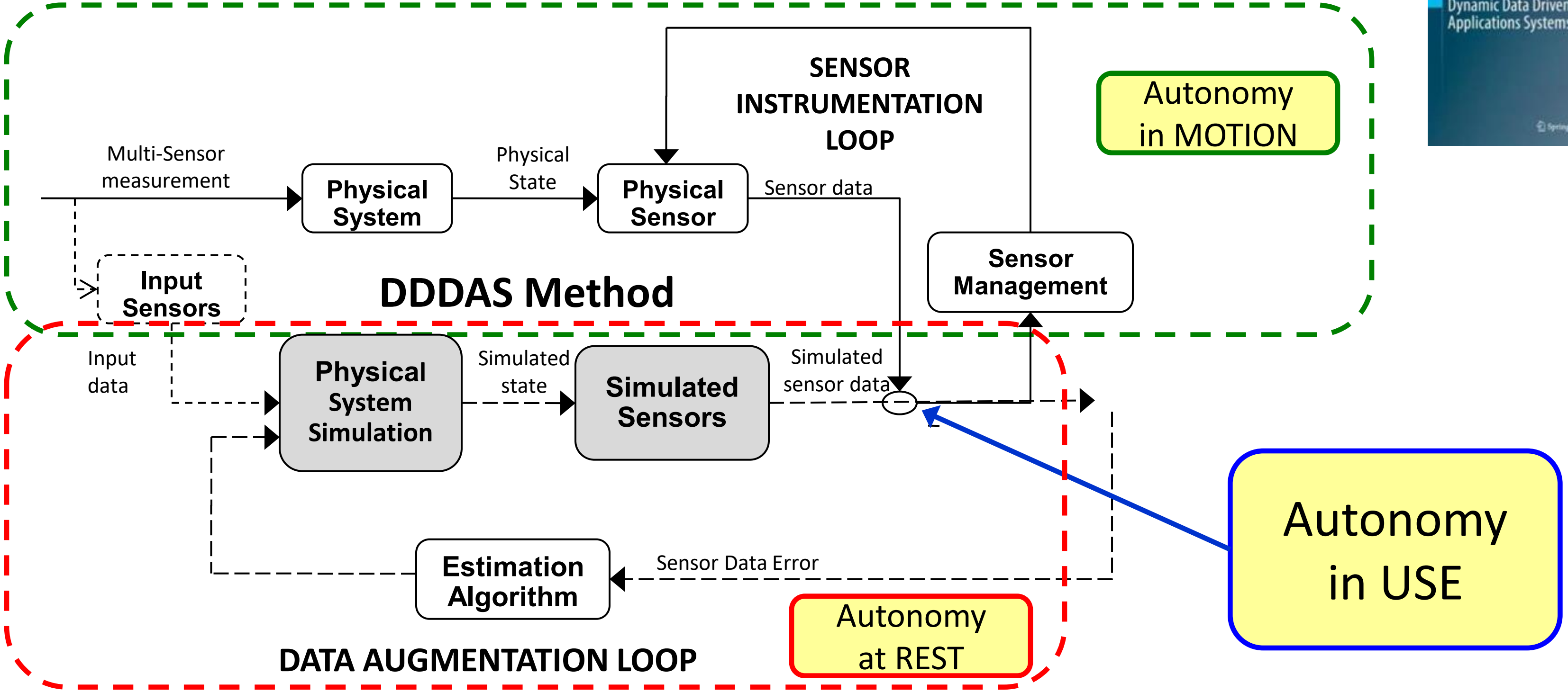
ATM and Flight Management Systems

Emerging Challenges

- Lack of **international cooperation and possible R&D funding reduction**
- Diminishing returns on investment for non-disruptive technology solutions
- Reduced community engagement and influence of non-government organizations (e.g., "green" lobby groups)
- Effects of anti-globalization and separatism initiatives (e.g., trade wars)
- Evolving geopolitical challenges
  - Political instability and terrorism threats
  - Ongoing conflicts in the Middle East and Ukraine
  - South China Sea border disputes (including airspace)

Physics-based and Human-Derived Information Fusion

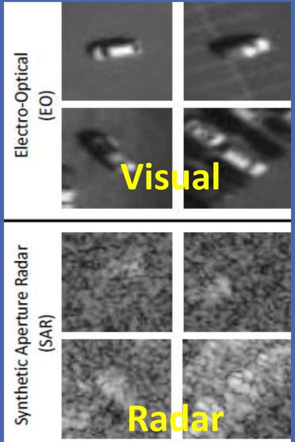
Dynamic Data Driven Application Systems (DDDAS)



E. Blasch, S. Ravela, A. Aved (eds.), *Handbook of Dynamic Data Driven Applications Systems*, Springer, 2019.

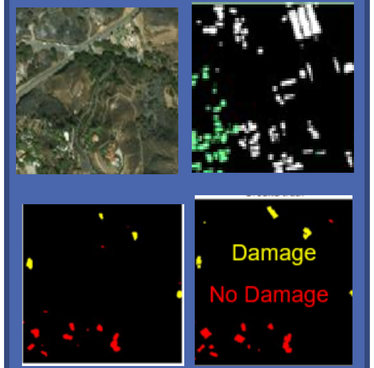
Dynamic Data Driven Application Systems

Multimodal Imagery Awareness



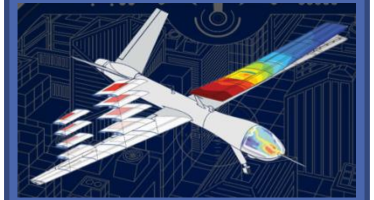
Domain Adaptation / Transfer Learning

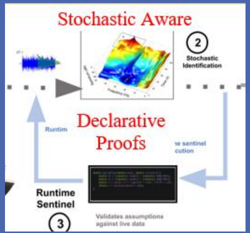
Overhead Imagery from Aerial Systems



Contrastive Method for damage assessment

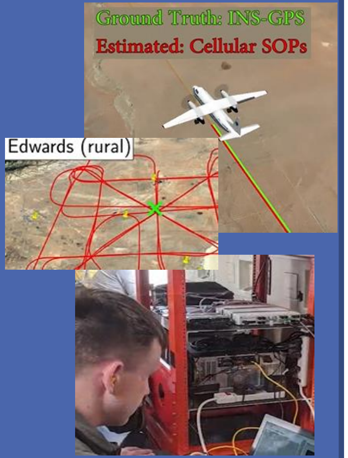
Flight Awareness





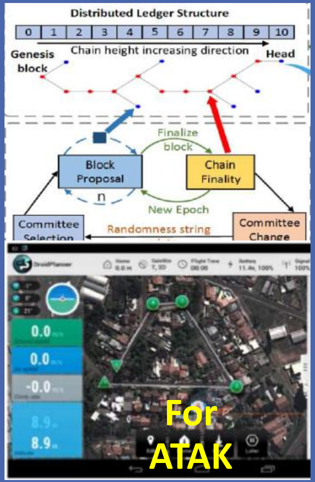
Declarative (Formal) Avionics

Robust Navigation



Nonlinear Filtering of Cellular signals (denied GPS)

Avionics Security



Blockchain – 5G Distributed Ledger

High-Rate Structural Health Monitoring

Space Domain Awareness

Materials (Metal/composite) Inspection

Avionics Teaming

- E. Blasch, S. Ravela, A. Aved (eds.), *Handbook of Dynamic Data Driven Applications Systems*, 1st ed., Springer, 2018

Avionics Education and Training

Avionics System Design

- Design of Safety Critical Aerospace Systems
- Design of CNS/ATM Systems
- Avionics and Payload Integration
- Human Factors Engineering/Mission Systems

CNS/ATM Systems

- Aerospace Navigation and Guidance Systems
- Aircraft Communications & Networking
- Surveillance Systems &Tracking
- Filtering and Estimation Theory

Unmanned Aircraft Systems

- Autonomous Systems Guidance & Control
- UAS Traffic Management
- UAS Airspace Integration Technologies
- Alternative PNT Systems
- UAS Design, Test and Evaluation

Avionics Software & Cyber Security

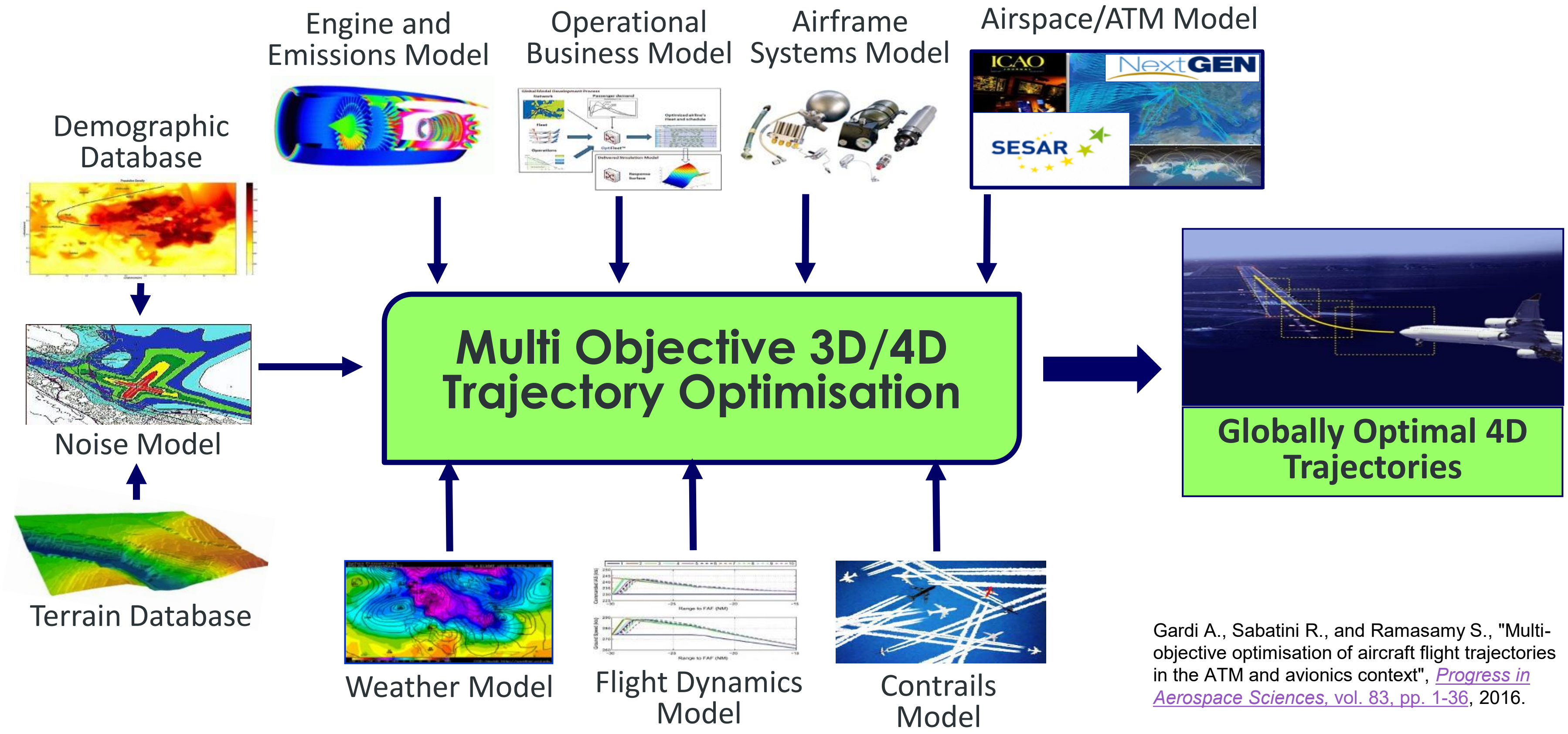
- Software Design and Certification
- Avionics and CNS/ATM Cyber Security
- Embedded Systems Cyber Security
- IMA/Multi-Core Systems Software
- Agile and DevOps for Avionics Systems

AESS IEEE Aerospace & Electronic Systems Society

I. Majid, R. Sabatini, K. A. Kramer, E. Blasch, G. Fasano, G. Andrews, C. Camargo, A. Roy, “Restructuring Avionics Engineering Curricula to Meet Contemporary Requirements and Future Challenges.” IEEE Aerospace and Electronic Systems Magazine, Vol. 36, No. 4, pp. 46-58, April 2021.

R. Sabatini and A. Gardi (Editors), “Sustainable Aviation Technology and Operations: Research and Innovation Perspectives.” Aerospace Series, John Wiley & Sons, Chichester, 2023

Multi-Objective Trajectory Optimization Concept



Gardi A., Sabatini R., and Ramasamy S., "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", *Progress in Aerospace Sciences, vol. 83, pp. 1-36*, 2016.

MOTO-4D – ATM DSS/FMS Design Requirements

- Efficient optimisation and negotiation
  - Shared dynamic models
  - Synchronisation of states, constraints, optimality criteria and 4DT predictions

    } mathematical consistency of the 4D-TOP
  - Standardised 4DT descriptors & transmission protocols/formats
  - Intent prioritisation
  - Fair scheduling principle

    } global optimality
- Robust and efficient validation
  - Reliable conflict identification algorithms, assessing mandatory separation minima (vertical, horizontal and longitudinal) for both traffic and obstacles
  - Continuous assessment of path constraints fulfilment

Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

Optimal Control Formulation – Theoretical Framework

- Purpose: identify the trajectory that minimises a predefined performance index, subject to dynamics and path constraints, while adhering to boundary conditions
- Optimality criteria (cost function in the Bolza form):

t: time

$\boldsymbol{x}$: states

$\boldsymbol{u}$: controls

$$J_i = \underbrace{\int_{t_0}^{t_f} \mathcal{L}_i(\boldsymbol{x}(t), \boldsymbol{u}(t), t)\, dt}_{\text{Lagrange term}} + \underbrace{\Phi_i(\boldsymbol{x}(t_f), \boldsymbol{u}(t_f), t_f)}_{\text{Mayer term}}$$

- Dynamic constraints:

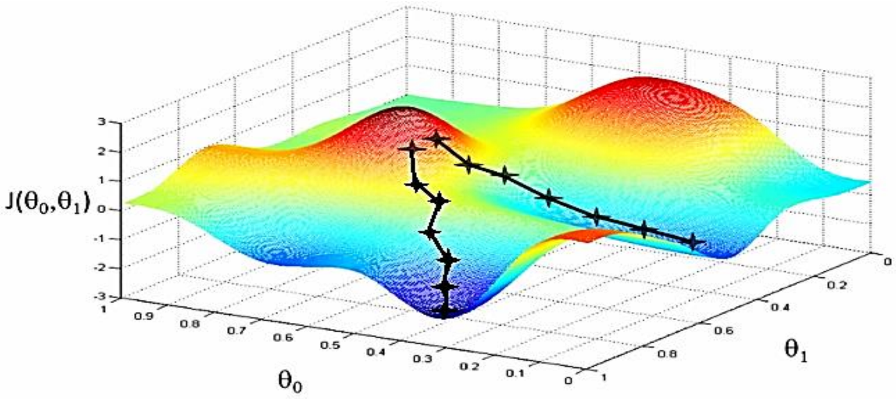
$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, t), t \in [t_0, t_f]$$

- Path constraints:

$$\boldsymbol{C}_{min} \leq \boldsymbol{C}[\boldsymbol{x}(t), \boldsymbol{u}(t), t; \boldsymbol{p}] \leq \boldsymbol{C}_{max}$$

- Boundary conditions:

$$\boldsymbol{\Phi}_{min} \leq \boldsymbol{\Phi}[\boldsymbol{x}(t_0), \boldsymbol{x}(t_f), \boldsymbol{u}(t_0), \boldsymbol{u}(t_f); \boldsymbol{p}] \leq \boldsymbol{\Phi}_{max}$$



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MOTO-4D – Aircraft Dynamics Model

➤ 3 Degrees of Freedom (3DoF) Aircraft Dynamics

$$\boldsymbol{u} = \begin{Bmatrix} \alpha \\ \beta \\ \mu \end{Bmatrix}$$

$$\boldsymbol{x} = \begin{Bmatrix} v \\ \gamma \\ \chi \\ \phi \\ \lambda \\ z \\ m \end{Bmatrix} \quad \begin{cases} \dot{v} = \dfrac{g}{W}\,(T\cos\epsilon - D - W\sin\gamma) \\ \dot{\gamma} = \dfrac{g}{v\,W}\cdot[(T\sin\epsilon + N)\cos\mu - W\cos\gamma] \\ \dot{\chi} = \dfrac{g}{v\,W}\cdot\dfrac{(T\sin\epsilon + N)\sin\mu}{\cos\gamma} \\ \dot{\phi} = \dfrac{v\cos\gamma\sin\chi + v_{w_\phi}}{R_E + z} \\ \dot{\lambda} = \dfrac{v\cos\gamma\cos\chi + v_{w_\lambda}}{(R_E + z)\cos\phi} \\ \dot{z} = v\sin\gamma + v_{w_z} \\ \dot{m} = -FF \end{cases}$$

$$N = \frac{q\cdot S\cdot[(\alpha - \alpha_0)\cdot C_{L\alpha} + \alpha_F\cdot C_{LF}]}{m\cdot g}$$

$$C_{L\alpha} = \frac{2\pi}{1 + 2/AR}$$

$$\boldsymbol{x}(t)$$

t: time

x: states

u: controls

$$\tau = \begin{cases} \beta \;\; if\; \beta > 0 \\ 0 \; otherwise \end{cases}$$

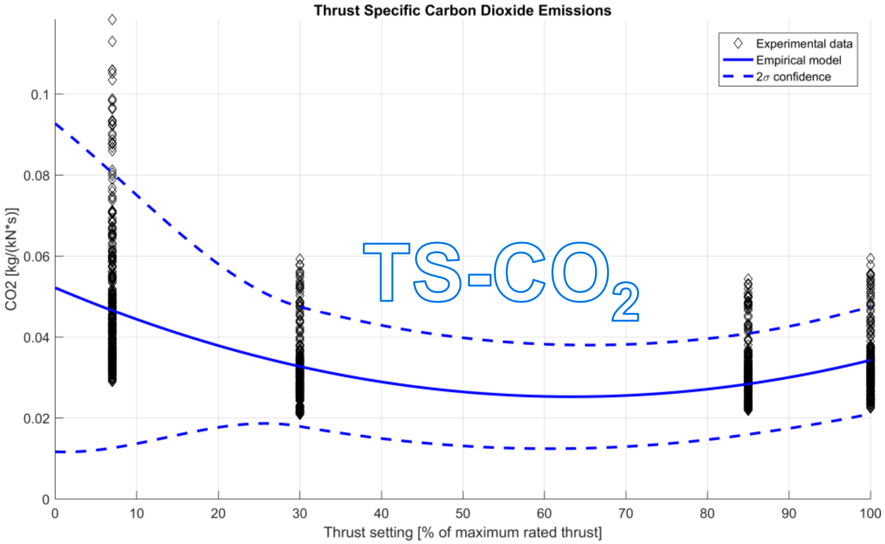
$$\delta = \begin{cases} -\beta \;\; if\; \beta < 0 \\ 0 \; otherwise \end{cases}$$

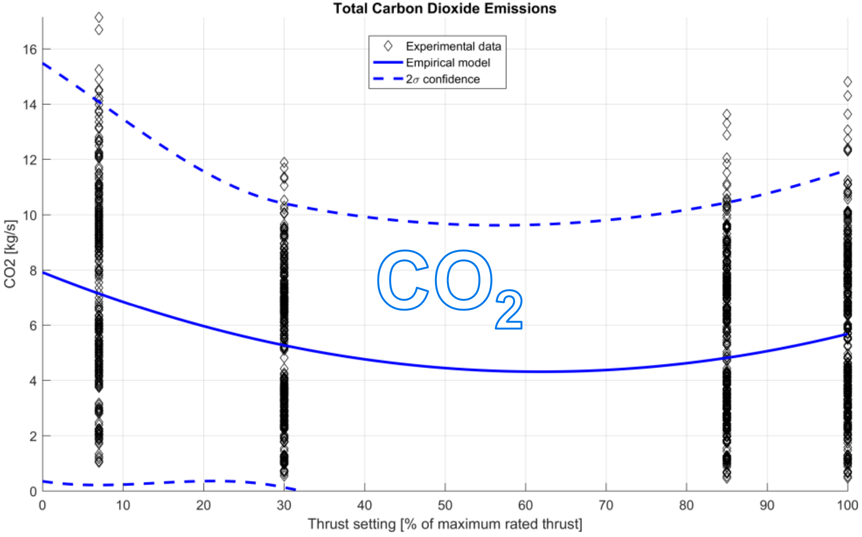
$$T = \tau\cdot\left[C_{T1}\cdot\left(1 - \frac{z_{ft}}{C_{T2}} + C_{T3}\cdot {z_{ft}}^2\right)\cdot\left(1 - C_{T5}\cdot(\Delta T - C_{T4})\right)\right]$$

$$D = q\cdot S\cdot\left[C_{D0} + \left(C_{D2}\cdot {C_L}^2\right) + \delta\cdot\left(\frac{\partial\, C_{D0splr}}{\partial\,\delta}\right)\right]$$

Gardi A., “A Novel Air Traffic Management Decision Support System”, PhD Thesis, RMIT University, Australia, 2017.

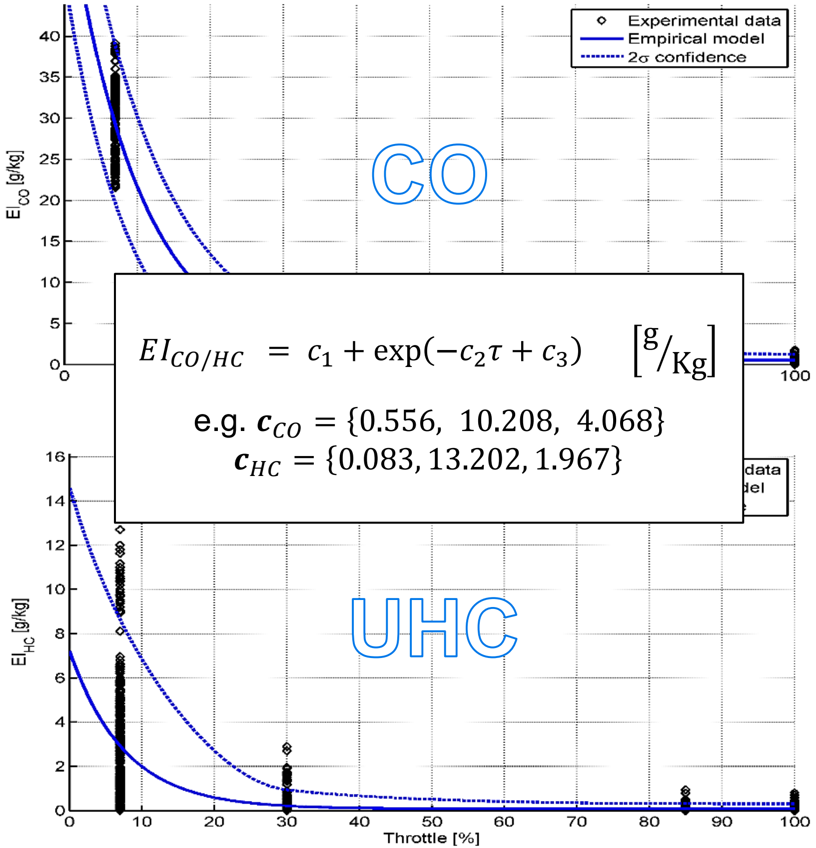
MOTO-4D – Greenhouse Emission Models





Gardi A., “A Novel Air Traffic Management Decision Support System”, PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D – Pollutant Emission Models



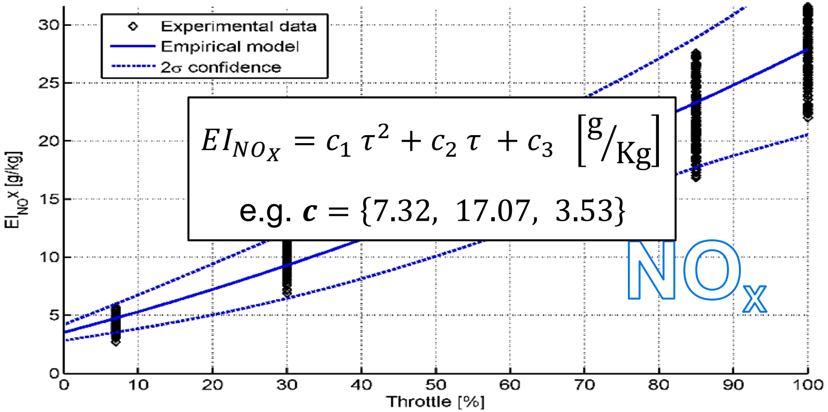
$$EI_{CO/HC} = c_1 + \exp(-c_2\tau + c_3) \quad [{}^{g}/_{Kg}]$$

e.g. $\boldsymbol{c}_{CO} = \{0.556,\ 10.208,\ 4.068\}$

$\boldsymbol{c}_{HC} = \{0.083, 13.202, 1.967\}$

- Emission models capturing dependence on throttle settings
- Aircraft-specific model coefficients
- 3DOF or 6DOF dynamics needed
- BADA models are adequate
- Can be applied as objective function to reduce emissions profile

Gardi A., Sabatini R., and Ramasamy S., "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", *Progress in Aerospace Sciences, vol. 83, pp. 1-36*, 2016.

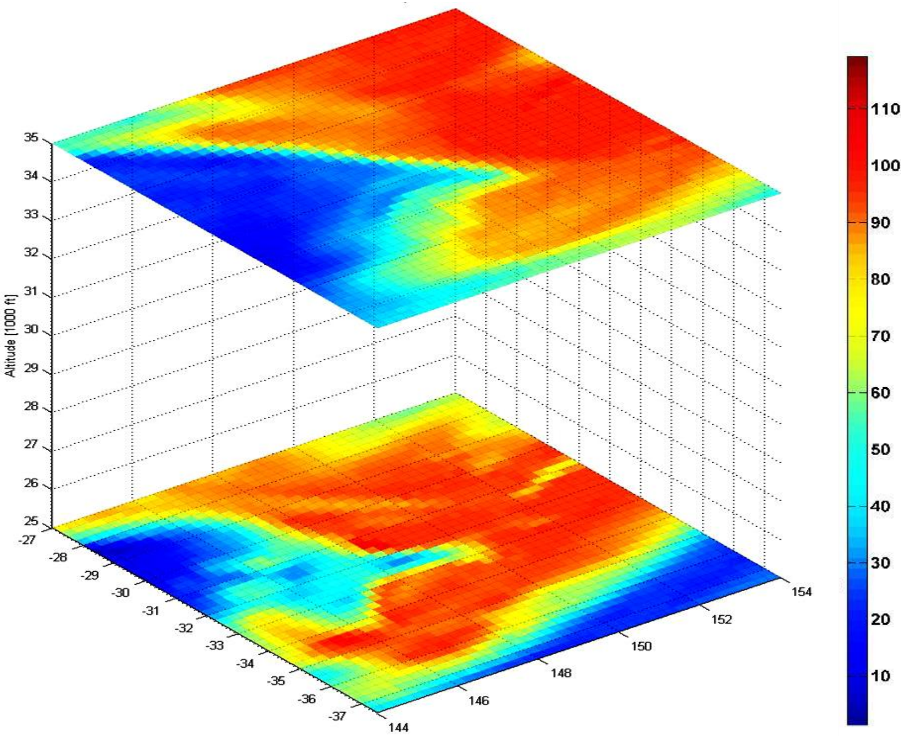


$$EI_{NO_X} = c_1\,\tau^2 + c_2\,\tau + c_3 \quad [{}^{g}/_{Kg}]$$

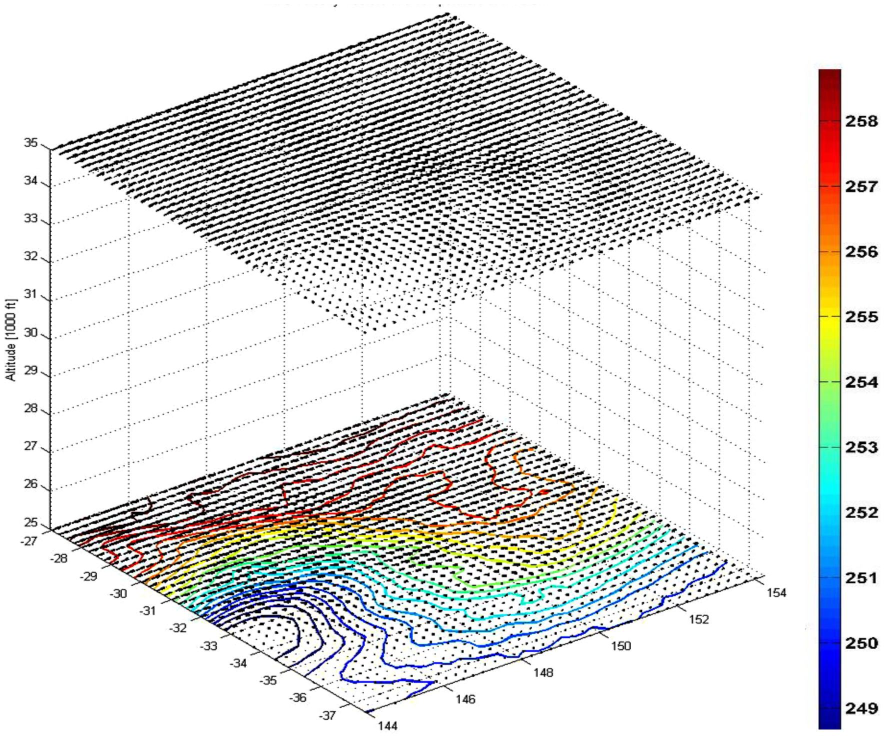
e.g. $\boldsymbol{c} = \{7.32,\ 17.07,\ 3.53\}$

MOTO-4D – Non-Standard Atmosphere and 4D Weather Model

Relative Humidity



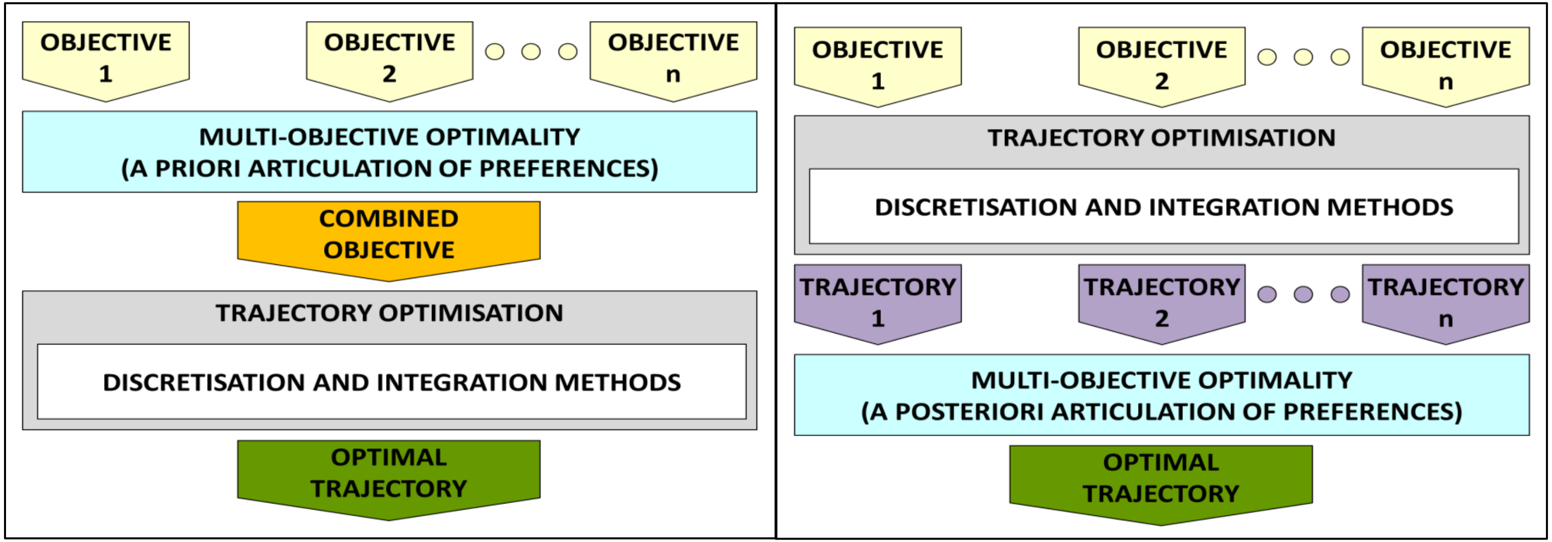
Wind Velocity Vector and Temperature



Gardi A., “A Novel Air Traffic Management Decision Support System”, PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D – Multi-Objective Optimality

- *Articulation of preferences*: "***a priori***" versus "***a posteriori***"



- Other possibilities:
  - ***Progressive articulation of preferences***
  - ***No articulation of preferences***

Gardi A., Sabatini R., and Ramasamy S., "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", *Progress in Aerospace Sciences*, vol. 83, pp. 1-36, 2016.

MOTO-4D – Cost Function (Weighted Product)

$$J = (q_{time} + 1)^{w_{time}} \cdot (q_{fuel})^{w_{fuel}} \cdot (q_{CO})^{w_{CO}} \cdot (q_{NOx})^{w_{NO_X}}$$

Time deviation → $(q_{time} + 1)$; Fuel usage → (q_{fuel}); CO/UHC → (q_{CO}); NO_x → (q_{NOx})

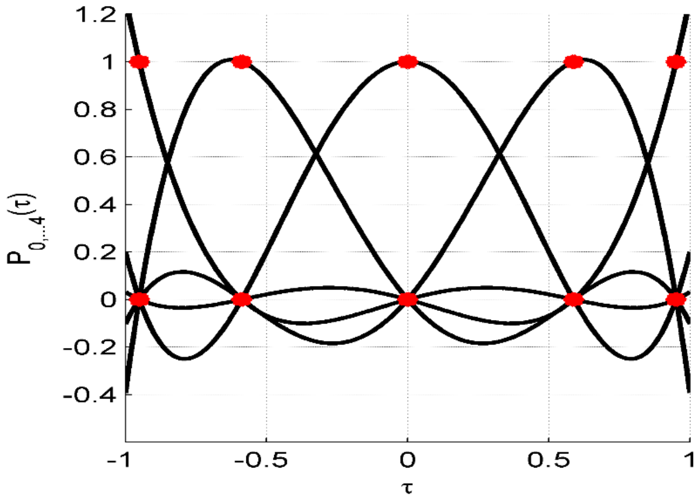
$$w_{time} + w_{fuel} + w_{CO} + w_{NO_X} = 6$$

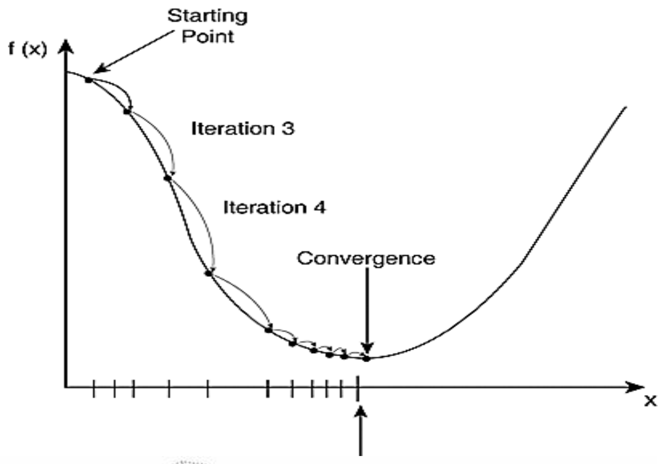
Case	w_{time}	w_{fuel}	w_{CO}	w_{NOX}
1	6	0	0	0
2	5	1	0	0
…	…	…	…	…
73	0	0	0	6

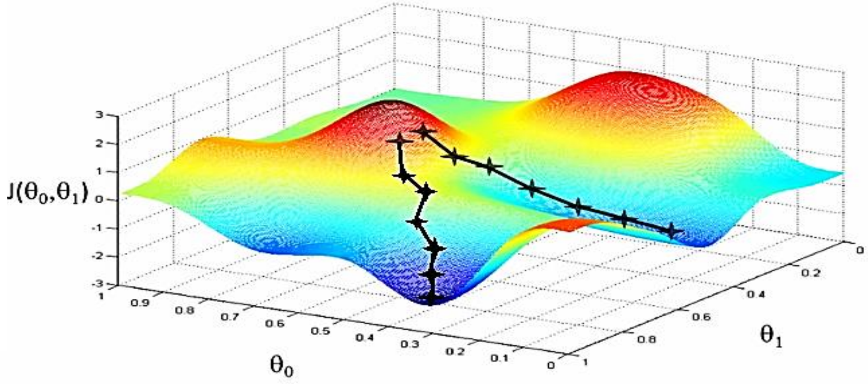
Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D – Iterative Solution for Pseudospectral OCP

- Gradient-based methods:
  $\boldsymbol{x}_{n+1} = \boldsymbol{x}_n - \gamma_n \nabla F(\boldsymbol{x}_n), \forall\, n \geq 0$
- Pseudospectral transcription (global orthogonal collocation)







- Non-global convergence

Gardi A., Sabatini R., and Ramasamy S., "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", *Progress in Aerospace Sciences, vol. 83, pp. 1-36*, 2016.

4-PNV – Distributed MOTO-4D

The traffic flow optimisation problem:

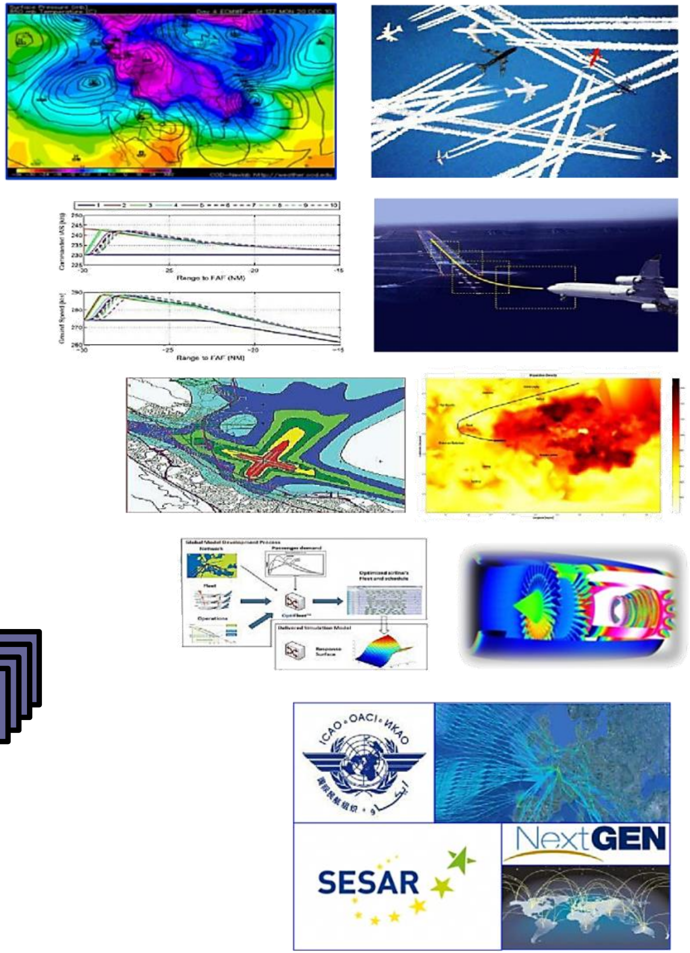
- ❖ Non-deterministic Polynomial Hard (NP-Hard)
- ❖ non-optimal substructure
- ✓ overlapping substructures

Dynamic Programming Approach

Combinatorial Optimisation

4-PNV

NG-FMS

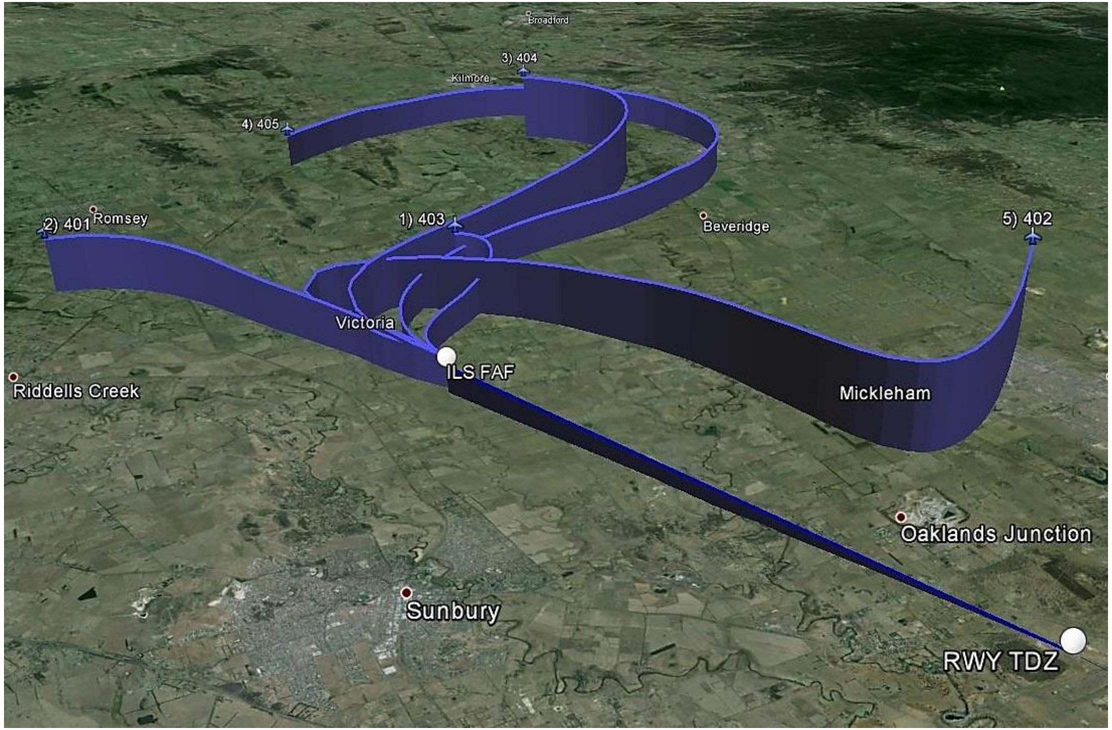


Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D for TMA – Preliminary Verification

Melbourne (RWY 16)

Initial position	Allocated arrival
S 38° 33' 15" E 144° 57' 30" 6851 ft	(1) 152 s
S 38° 33' 53" E 144° 58' 19" 5125 ft	(2) 242 s
S 38° 36' 37" E 144° 36' 58" 8511 ft	(3) 332 s
S 38° 30' 59" E 144° 33' 22" 8328 ft	(4) 422 s
S 38° 43' 8" E 144° 51' 2" 8916 ft	(5) 512 s

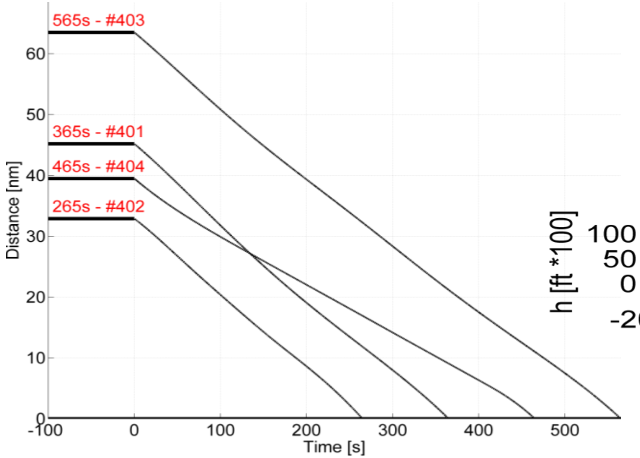


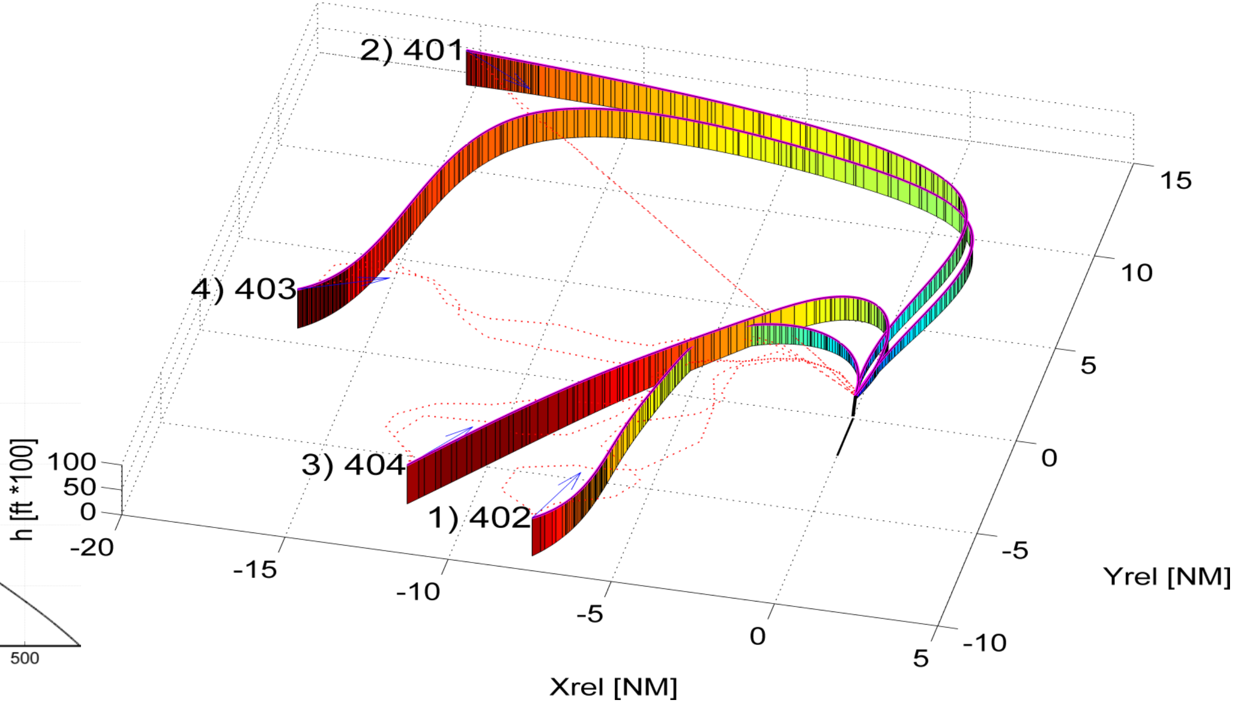
- Negotiation/Validation of all intents in less than 180 sec (167 sec)

Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D for TMA – Verification (Without 4DT Smoothing)

❖ Optimal Sequencing of 4 arrivals using GNSS





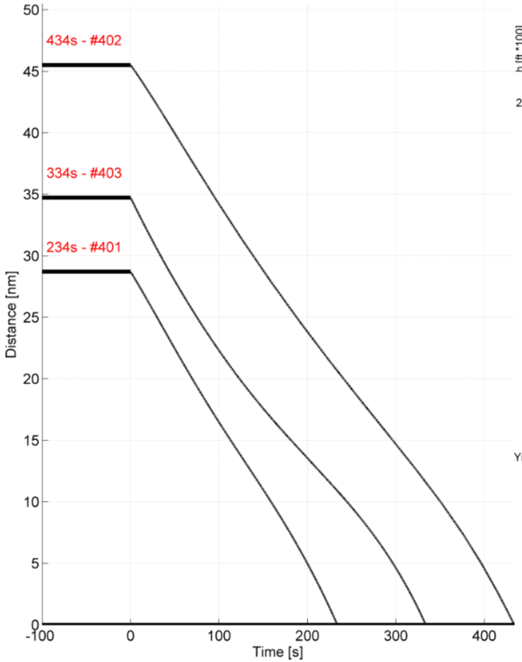
❖ 4 A/C TMA Negotiation/Validation Loops (<100 sec)

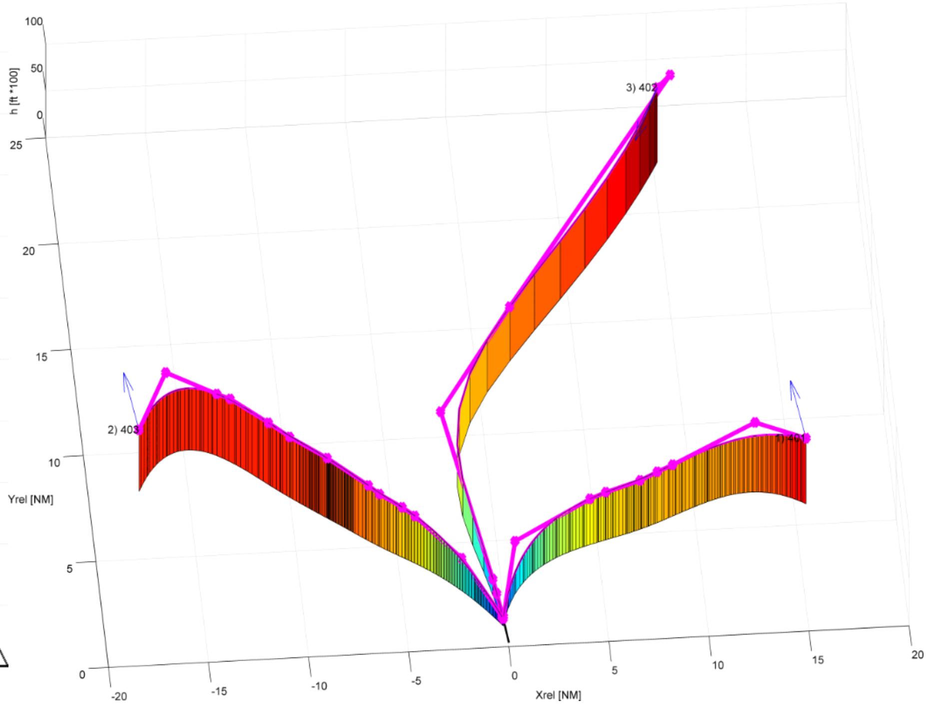
Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D for TMA – Verification (with 4DT Smoothing)

- Intents generated and assessed in 41 s (on average)
- Smoothing:

401: 145 → 10
402: 21 → 8
403: 208 → 14



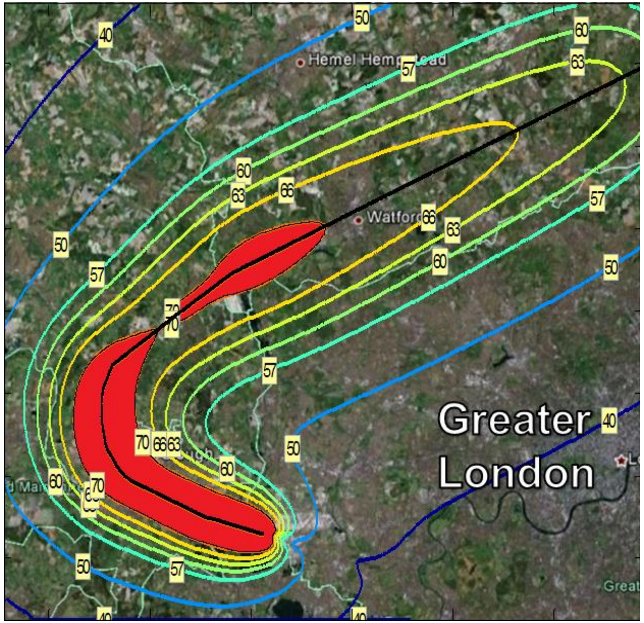


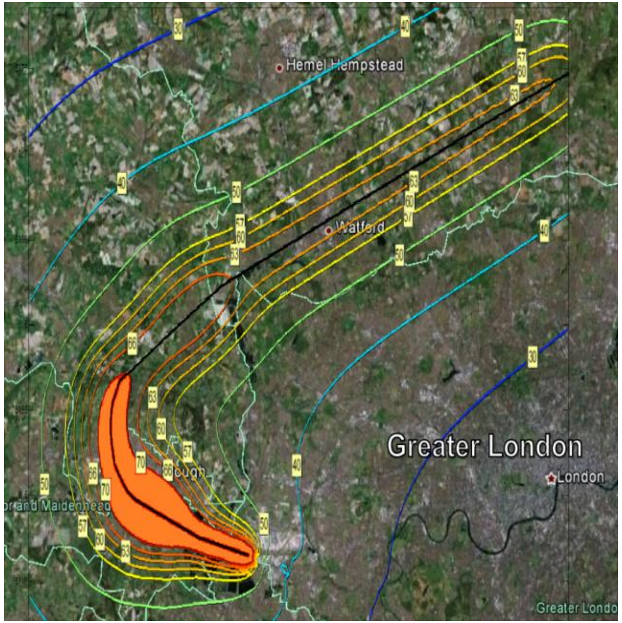
Gardi A., "A Novel Air Traffic Management Decision Support System", PhD Thesis, RMIT University, Australia, 2017.

MOTO-4D for TMA – Departure Case Study

Real commercial flight profile used as benchmark

- Departed at 19:27 GMT (night flight)
- Optimisation: Min Fuel and Noise (SEL 70dBA)



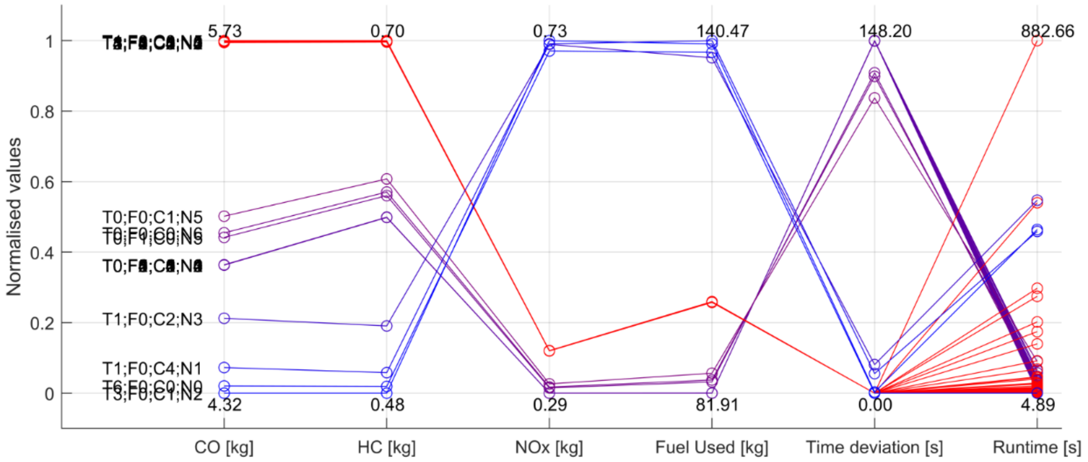


Optimised route for minimum noise indicates approx. **47%** smaller area of SEL 70 dBA (52.3 vs 100.5 km^2)

- ➢ Real Flight: 635 kg fuel
- ➢ MOTO: 469 kg fuel

TEMO in CDA – Results

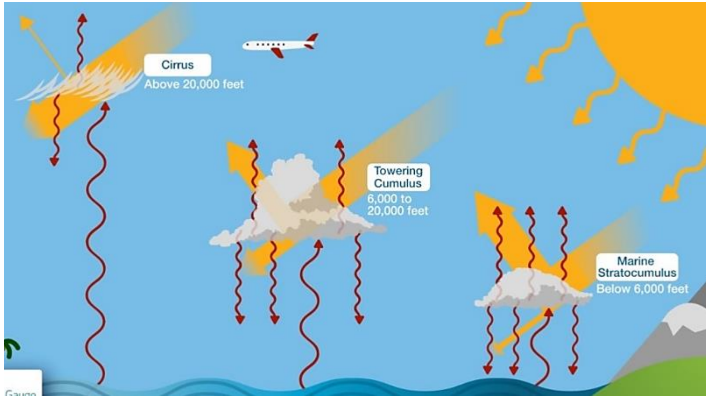
- CO: [4.32 kg – 5.73 kg]; HC: [483 g – 702 g]; NO_X: [289 g – 734 g]
- Fuel: [81.2 kg – 140.47 kg]; Time deviation: [0 s – 148 s]
- Runtime: [4.90 s to 882.66s]
- CO and HC are inversely correlated with fuel use, while NO_X directly correlated
- Most cases converged to two solutions – “Min Fuel” and “Min Time Deviation”
- “Min Fuel” cases tend to reach the FAF in minimum time – idling the throttle appears to consume more fuel

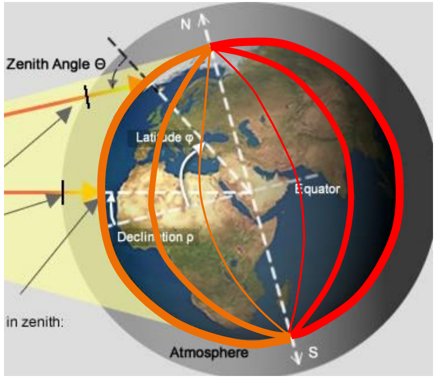


MOTO for Contrail Mitigation – Environmental Impact

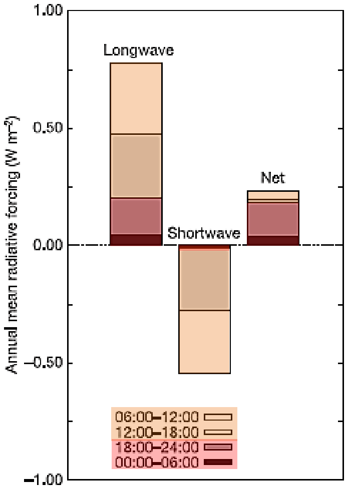
❖ Radiative Forcing (RF)

- **Greenhouse effect**: trapped longwave emissions
- **Albedo effect**: incident shortwave radiation
- Reflected shortwave radiation dependent on solar zenith angle
- Optical depth dependent on particle micro-properties





(Stuber et al 2006)

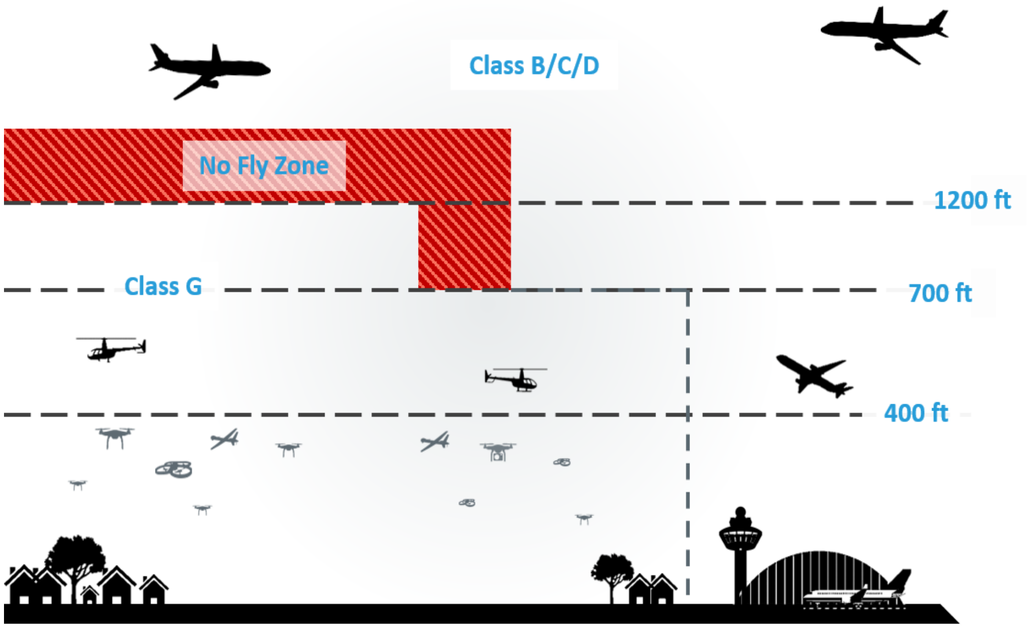


Lim Y., Gardi A., Marino M., and Sabatini R., "Modelling and evaluation of persistent contrail formation regions for offline and online strategic flight trajectory planning", in Sustainable Aviation, ch. 21, pp. 243-277, T. H. Karakoc and et al., Eds., Springer, Geneve, Switzerland, 2016.

UTM, AAM and Trusted Automation

1. Introduction to the IEEE AESS Avionics Systems Panel	Giancarmine
2. Air and Space Transport Integration: Towards Multidomain Traffic Management	Rob
3. Aviation Noise Impact Assessment and Mitigation	Erik
4. ATM and Flight Management Systems	Erik / Alex
5. UTM, AAM, and Trusted Automation	**Erik / Alex**
6. Regulatory Considerations in the Era of AAM: Approaches to Technology Maturity and Standardization	Craig
7. Challenges and Advances in Space Domain Awareness and Space Traffic Management	Giancarmine

UAS Traffic Management (UTM) – Key Challenges

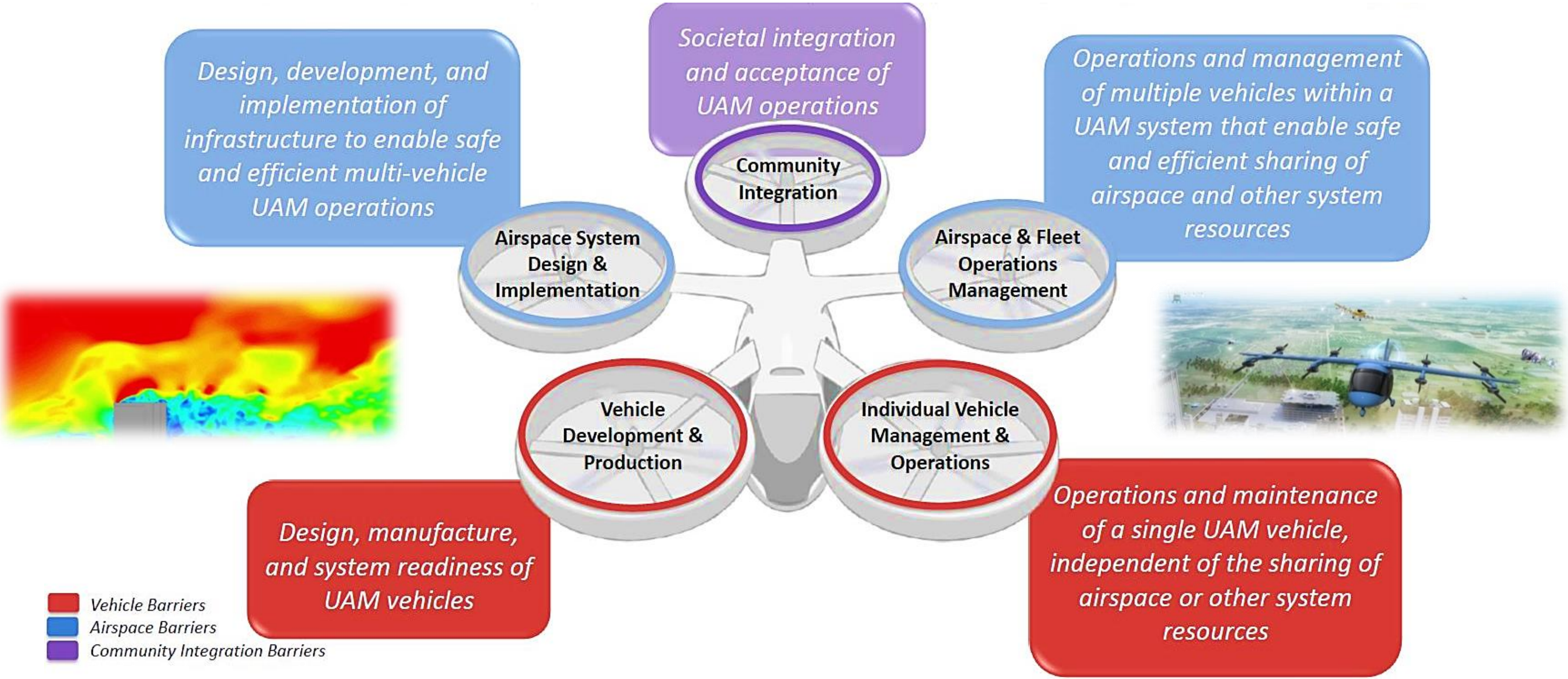


- The conventional human-intensive and tactical ATC paradigm cannot fulfil the needs of manned/UAS traffic integration
- A higher degree of automation is necessary in the UTM framework
- The tactical deconfliction approach of traditional ATM cannot be scaled down to apply in UTM

Pongsakornsathien N., et al., "A Performance-Based Airspace Model for Unmanned Aircraft Systems Traffic Management", *Aerospace, 7(11), 154*, 2020.
Bijjahalli S., et al., "A Unified Airspace Risk Management Framework for UAS Operations", *Drones, 6(7), p. 184*, 2022.

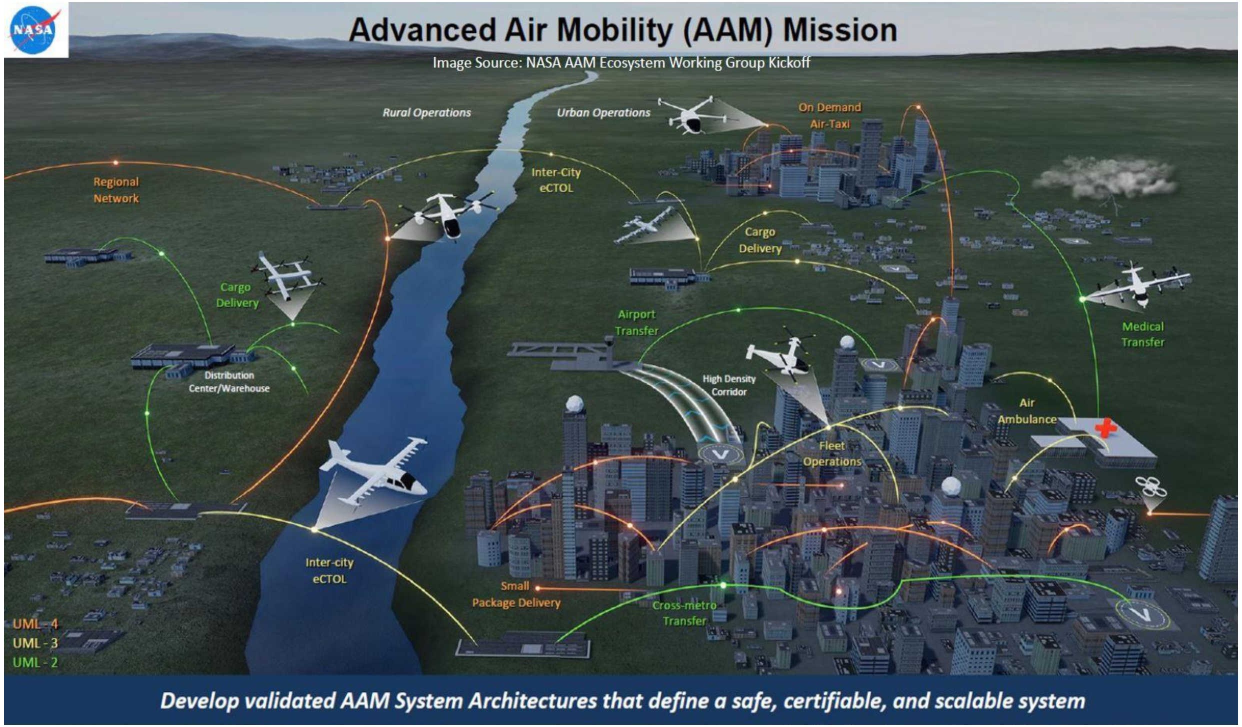
AAM Research Framework

Vision: Revolutionise mobility of metropolitan and regional areas by enabling a safe, efficient, convenient, affordable, and accessible air transportation system

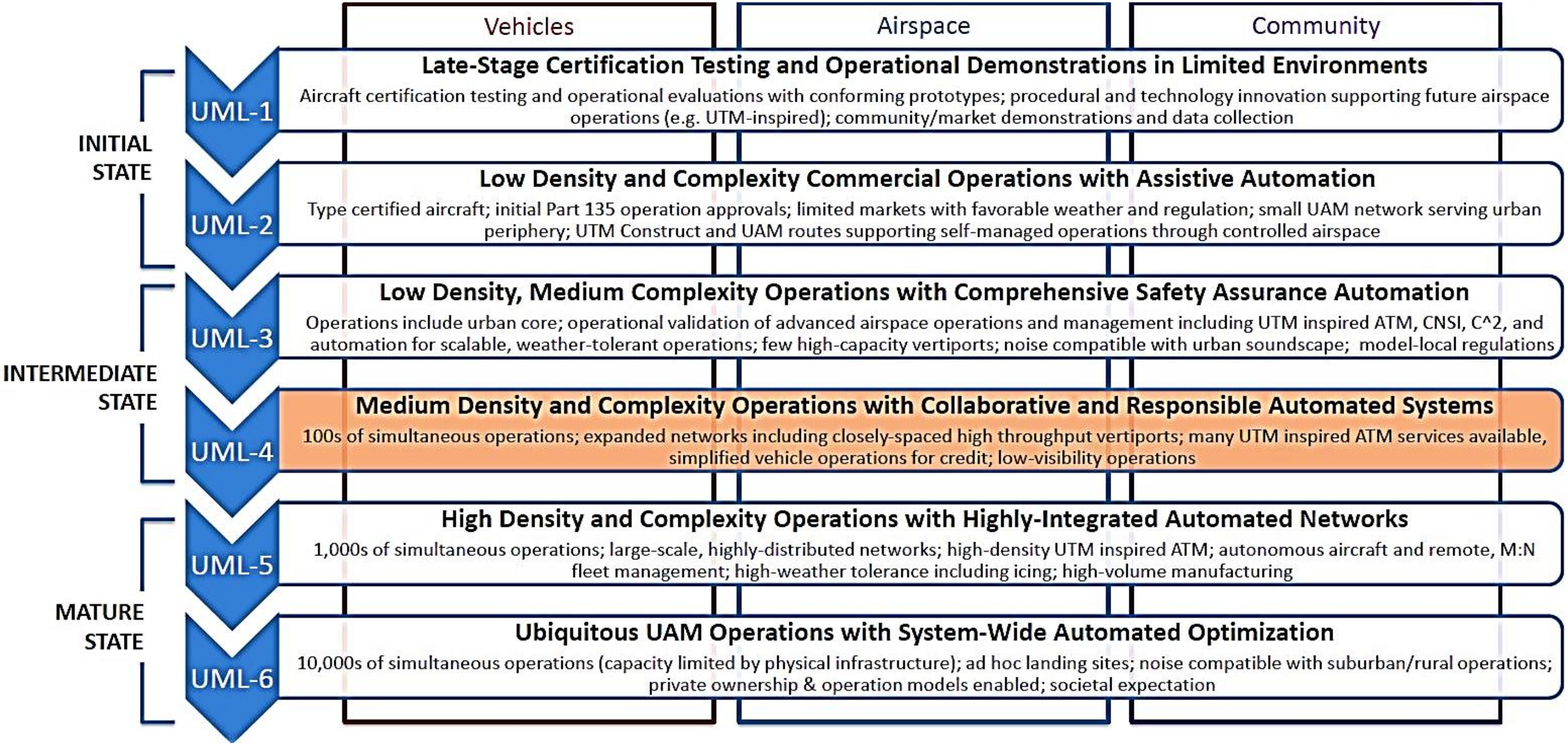


AAM/UAM Missions

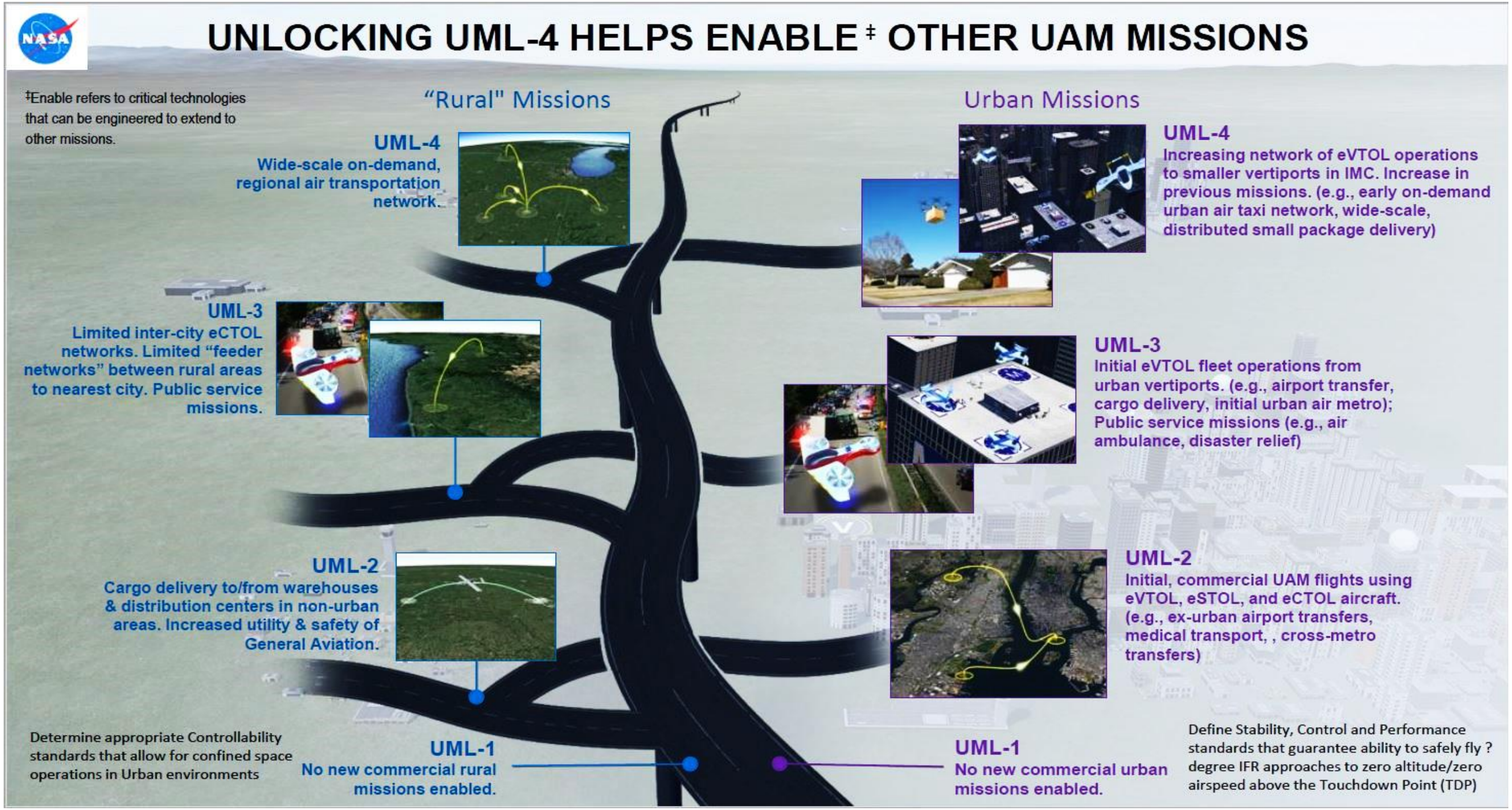
- ❖ Includes rural and urban applications
  - Cargo transport, aerial work, etc.
  - eVTOL, sUAS, hybrid-electric etc.
  - UAM as a challenging use-case
- ❖ Enabled by electrification and scaled through automation
- ❖ Does not include:
  - Supersonic or hypersonic
  - Existing hub-and-spoke



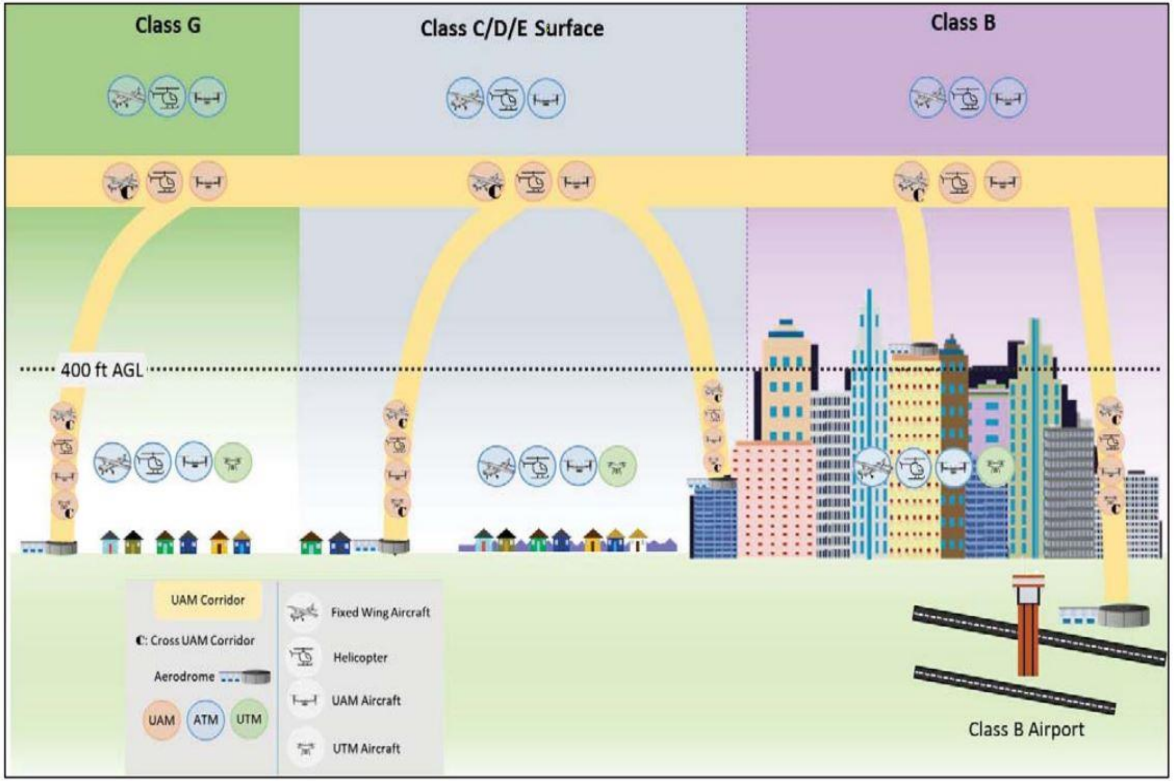
NASA UAM Maturity Levels (UML)



AAM/UAM Missions



Evolutionary systems for UTM and AAM



- ❖ Integrated CNS (ICNS) for the large amount of data/information that needs to be exchanged
- ❖ On-board vehicle situational awareness and sensors required
- ❖ Vertiport infrastructure
- ❖ Time-Based Flow Management
  - PBN and TBO
  - Sequencing and Spacing
  - Congestion Management
- ❖ Moving towards **PBO**
- ❖ Health/performance monitory systems (safety-critical)
- ❖ Microclimate sensor requirements
- ❖ Cyber-physical security

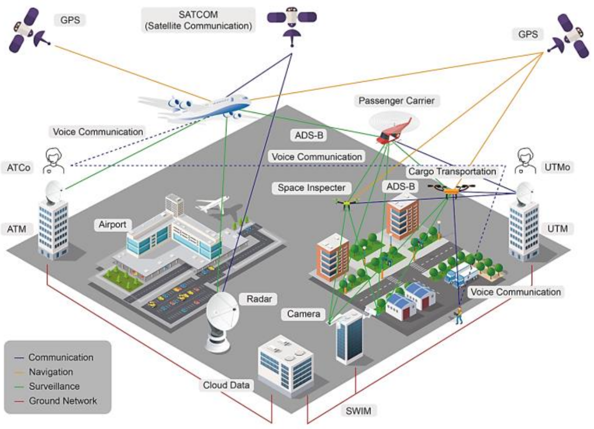
Evolving ATM Cyber-Landscape

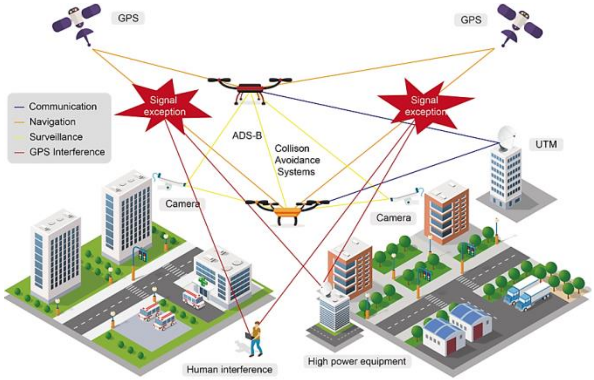
- Over the last three decades, the "cyber-landscape" in ATM has evolved significantly, particularly in conjunction with:
  - a continuing migration from dedicated to **general-purpose hardware**, including PCs, rack servers, tablets, laptops and even personal mobile devices, to which a growing number of COTS wireless devices are connected (incl. headsets, input devices, printers etc.)
  - a continuing migration from a dedicated and largely domestic-only Aeronautical Fixed Telecommunication Networks (AFTN) towards **global IP-based connectivity**
  - the ongoing implementation of new **SESAR and NextGen technologies**, most of which are data-link-based or terrestrial IP-based technologies (incl. SWIM, VDL, 4D-TRAD, AeroMACS, A-CDM etc.)
- The future of ATM (and especially UTM and STM) involves substantially greater amounts of data exchanged in real-time across an increasing number of stakeholders

Xie Y., Gardi A., Sabatini R., "Cybersecurity Risks and Threats in Avionics and Autonomous Systems", *IEEE CyberSciTech Congress 2023, CSC 2023*, Abu Dhabi, UAE, 2023.
Xie Y., Gardi A., and Sabatini R., "Cybersecurity Trends in Low-Altitude Air Traffic Management," *AIAA/IEEE Digital Avionics Systems Conference, DASC 2022*, Portsmouth, VA, USA, 2022.

Key Challenges

- Evolving ATM & UTM architectures based on big data and AI plus increased interdependence of CNS/ATM and avionics systems result in an increasing attack surface
- AI-based offensive technologies are bound to become very common, requiring AI-based cyber-defenses
- Need for a new generation of security management systems and more efficient attack detection techniques

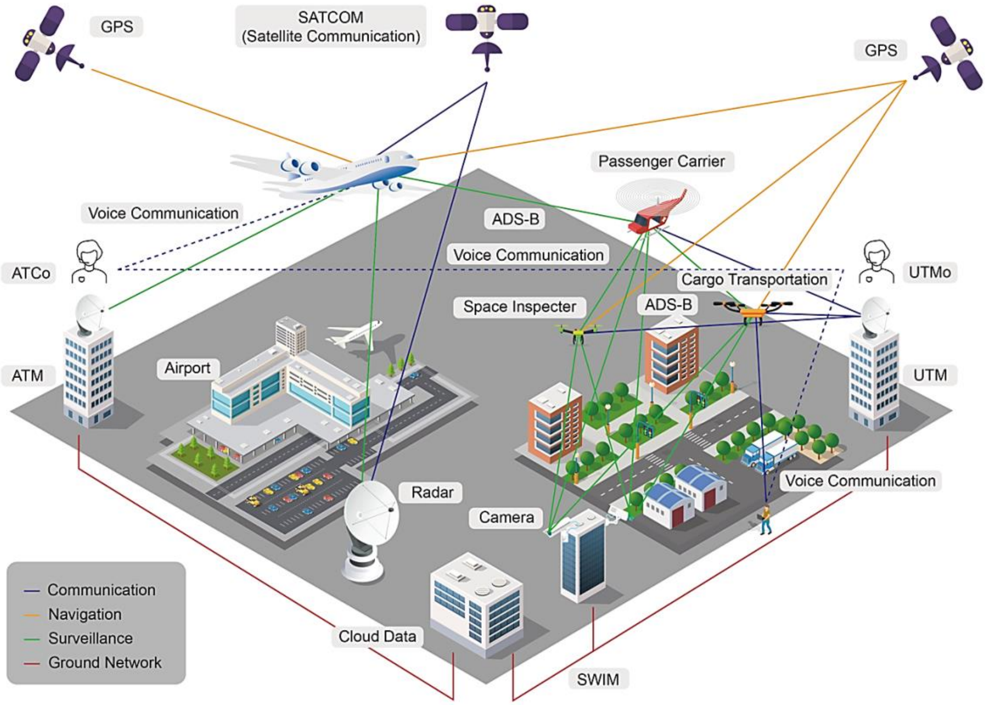




Xie Y., Gardi A., and Sabatini R., "Cybersecurity Trends in Low-Altitude Air Traffic Management," *AIAA/IEEE Digital Avionics Systems Conference, DASC 2022*, Portsmouth, VA, USA, 2022.
Carlos C. Insaurralde, Erik P. Blasch, Paulo C. G. Costa, and Krishna Sampigethaya, "Uncertainty-Driven Ontology for Decision Support System in Air Transport" *Electronics* 11(3):362, Jan 2022.

Cybersecurity Vulnerabilities in ATM and UTM

- Communication
  - HF/VHF voice, CPDLC, L-DACS, ACARS, SATCOM, Wireless communication networks
- Navigation
  - TRNAs, GNSS
- Surveillance
  - PSR, SSR, WAM, TACS, ADS-B
- Ground Network
  - SWIM

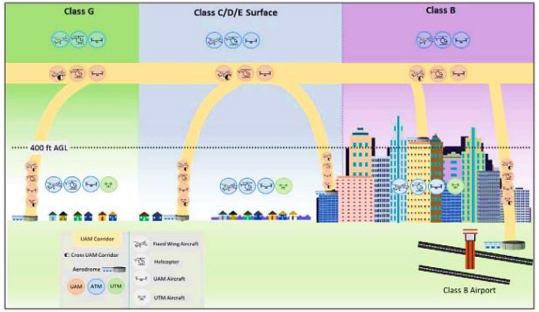


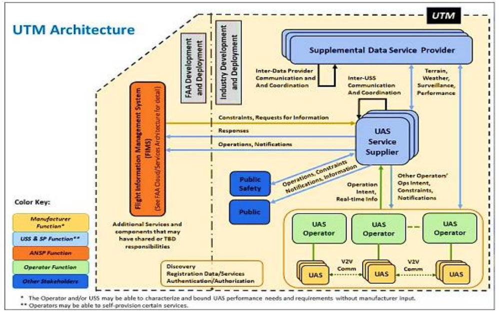
Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

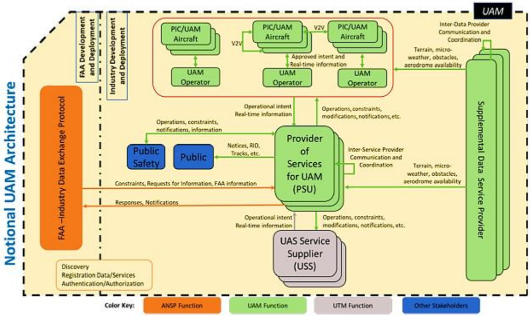
Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Risks and Threats in Avionics and Autonomous Systems." 8th IEEE Cyber Science and Technology Congress (CyberSciTech 2023), Abu Dhabi, UAE, November 2023.

Future Challenges

- ❖ Develop a CONOPS for Low-Altitude Airspace Management (LAAM) encapsulating UTM and emerging AAM requirements, which clearly specifies the human role for various levels of automation
- ❖ Develop new DSS functionalities to enhance human-machine teaming. Current focus is on performance-based airspace modeling and dynamic airspace management
- ❖ Develop an integrated approach to Multi-Domain Traffic Management (long-term)

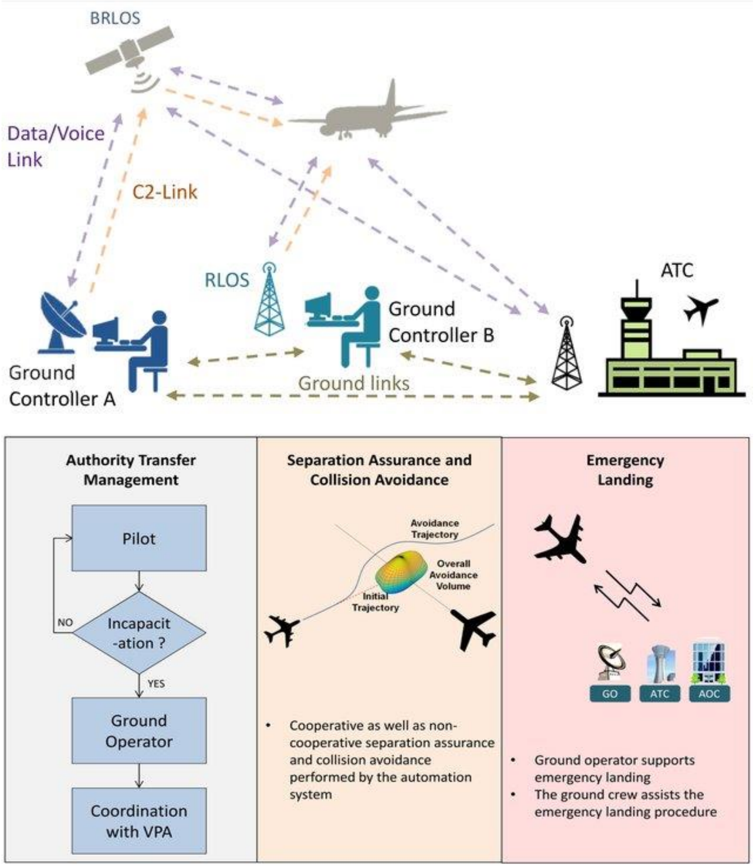


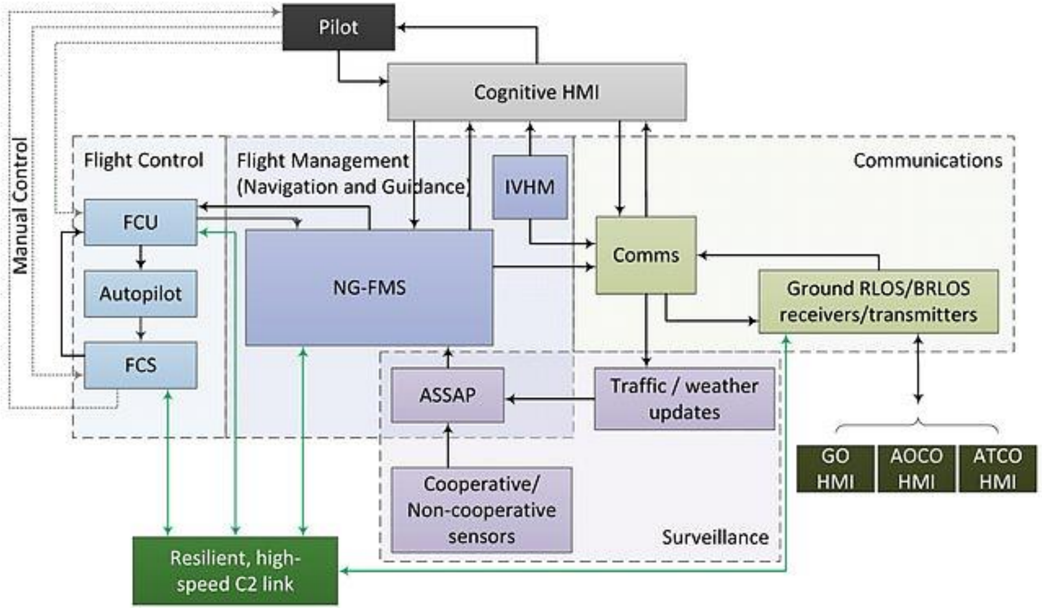




Trusted Automation Research: Focus on SiPO and RPAS

SiPO Avionics Architecture (single-pilot operations)

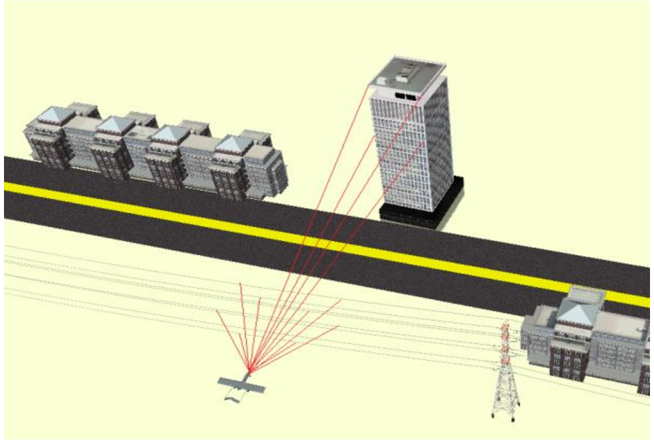


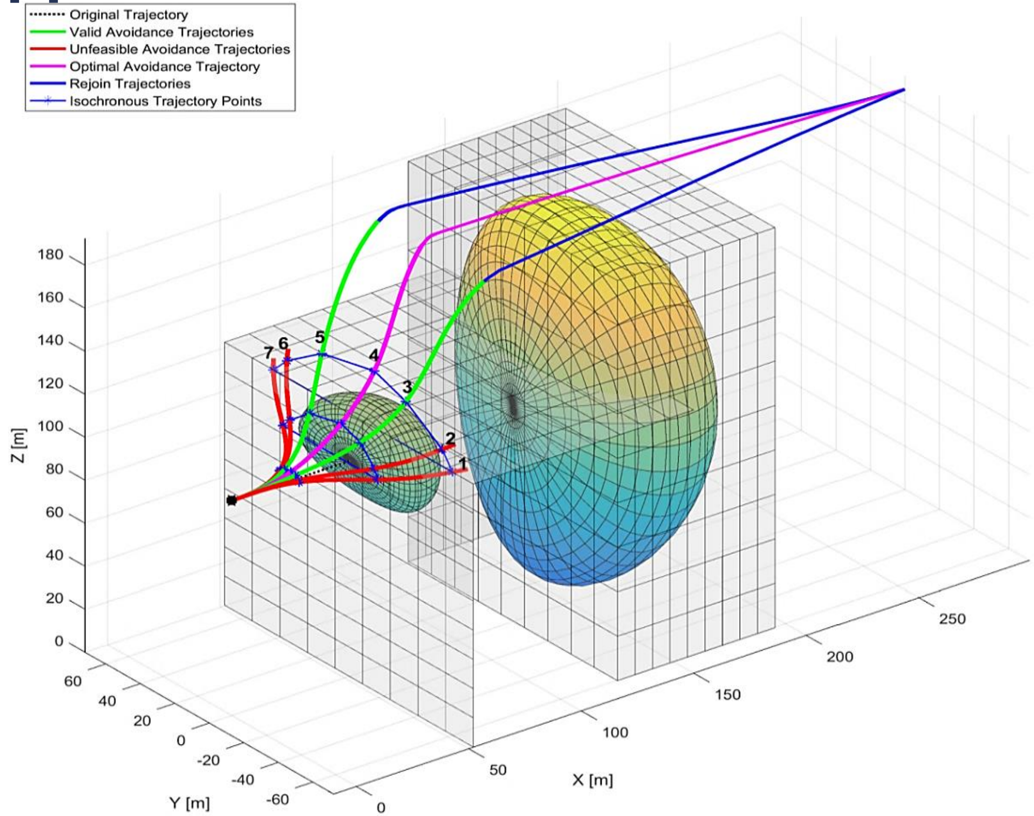


Ref.: Y. Lim, V. Bassien-Capsa, S. Ramasamy, J. Liu, and R. Sabatini, "Commercial airline single-pilot operations: System design and pathways to certification", IEEE Aerospace and Electronic Systems Magazine, vol. 32, pp. 4-21, 2017. DOI: 10.1109/MAES.2017.160175

SA/CA – Safety-critical Applications

- Uncertainty volumes for avoidance of ground obstacles
  - A set of feasible avoidance trajectories is generated in real-time



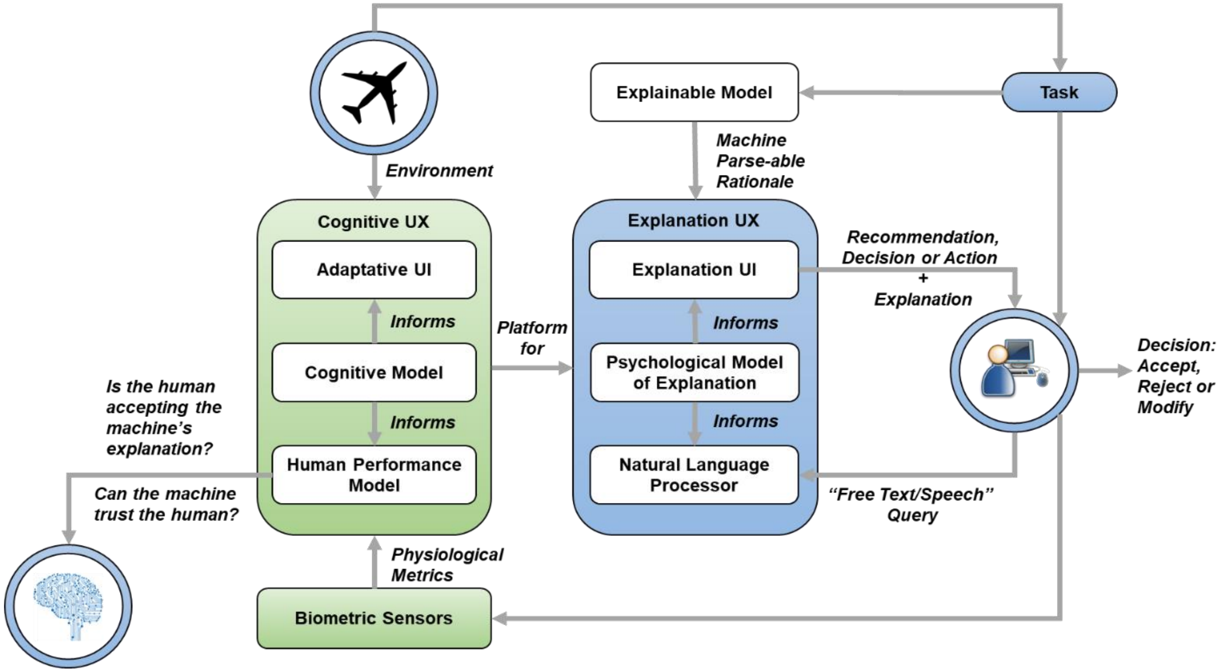


Ramasamy S., et al., "A Unified Analytical Framework for Aircraft Separation Assurance and UAS Sense-and-Avoid", *J. of Intelligent & Robotic Systems, 91, 735–754*, 2018.
Ramasamy S., et al., "LIDAR obstacle warning and avoidance system for unmanned aerial vehicle sense-and-avoid", *Aerospace Science and Technology, 55, pp. 344-358*, 2016.

Challenges for AI Certification in Aviation

- A core premise of AI is learning, where the system learns and adapts its behavior to achieve the optimum, desired outcome
  - The AI system response for a given set of excitations in a given environment are not necessarily the same (i.e., deterministic, unique and predictive)
    - In AI System response, there is always a delta error from the target response
    - An AI System learns from every encounter to reduce & optimize the error delta
- For aviation systems, the regulator expectation is that for every scenario, i.e., a set of excitations in a given environment, the expected system response MUST be the same
  - The safety of life risks and liabilities associated with an uncertain outcome is too large for aviation
- An approach for AI standards and certification could be to provide an acceptable error tolerance for each expected system response
  - Need to have high confidence (10^{-6} to 10^{-9}) or lower probability that response will be outside the tolerance)
  - Standards MUST also define a fail-safe option, to mitigate unexpected AI system behavior

Current Research: Cognitive HMI and Explanation UX



- **Explainable AI**
- **Trusted AI**
- **Certifiable AI**

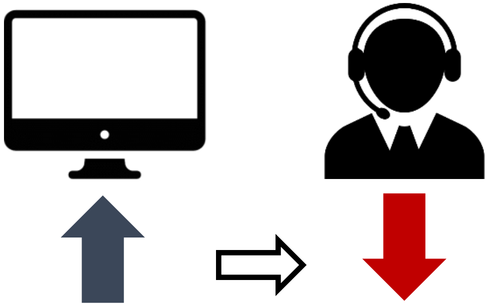
Kistan T., et al., "Machine Learning and Cognitive Ergonomics in Air Traffic Management: Recent Developments and Considerations for Certification", Aerospace, 5(4), p. 103, 2018.
Xie Y., Pongsakornsathien N., Gardi A., Sabatini R., "Explanation of Machine-Learning Solutions in Air-Traffic Management", Aerospace, 8(8), no. 224, 2022.

Current Research: HOTL Dynamic Interactions

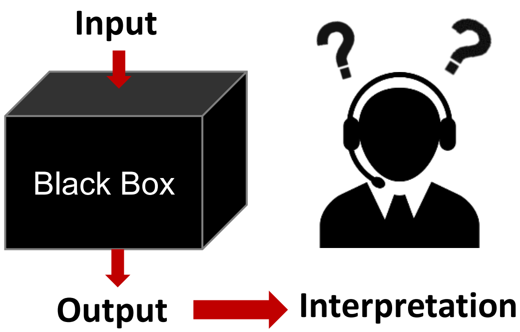
Challenges

Higher level of automation in an out-of-loop paradigm

- Lower cognitive capability
- Progressive deskilling
- Lower situational awareness



Human Factors



AI Explanation

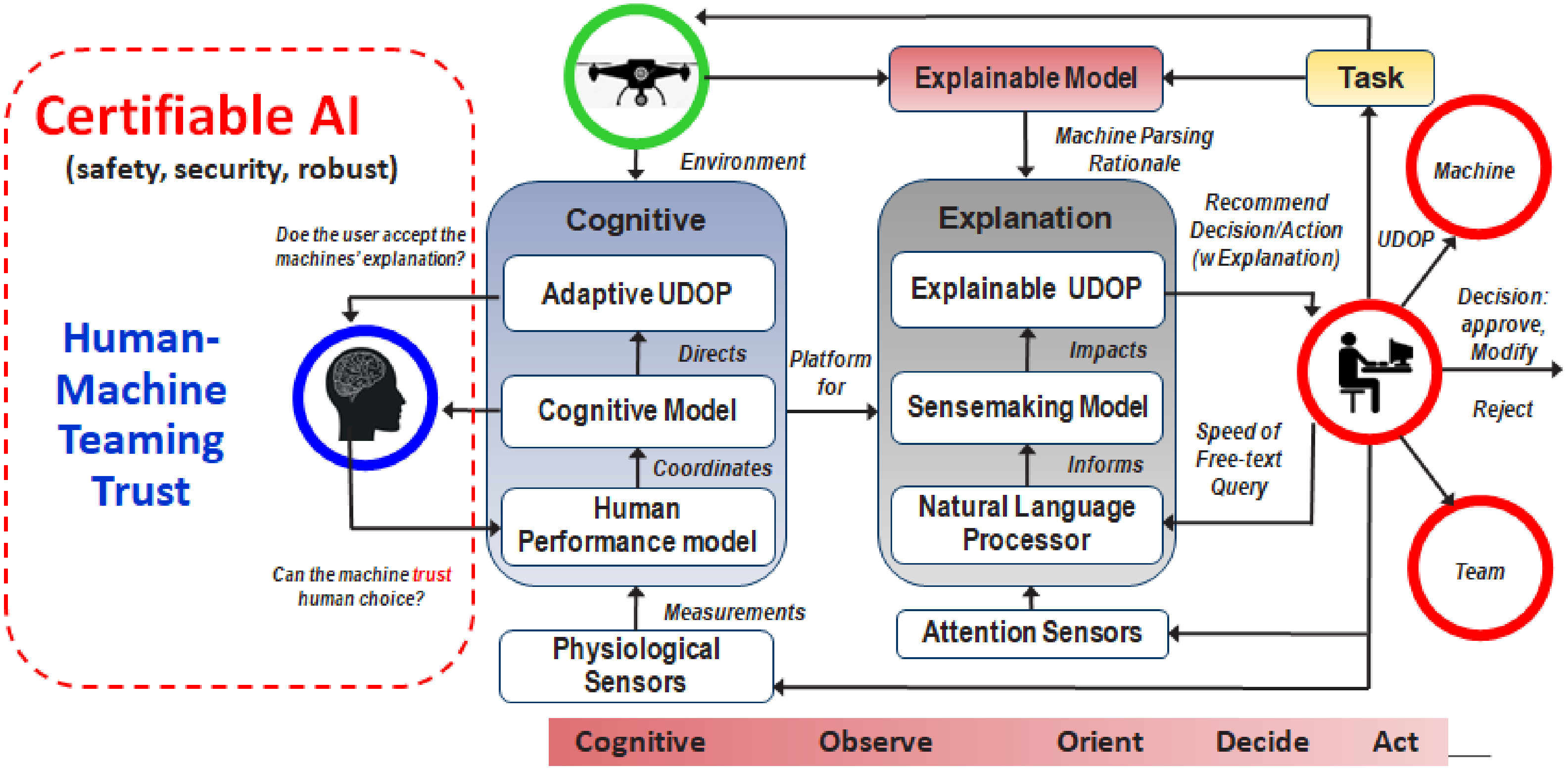
Solution

Adaptive HMI based on Explainable and Trusted AI

Cognitive Human-Machine Systems (CHMS)

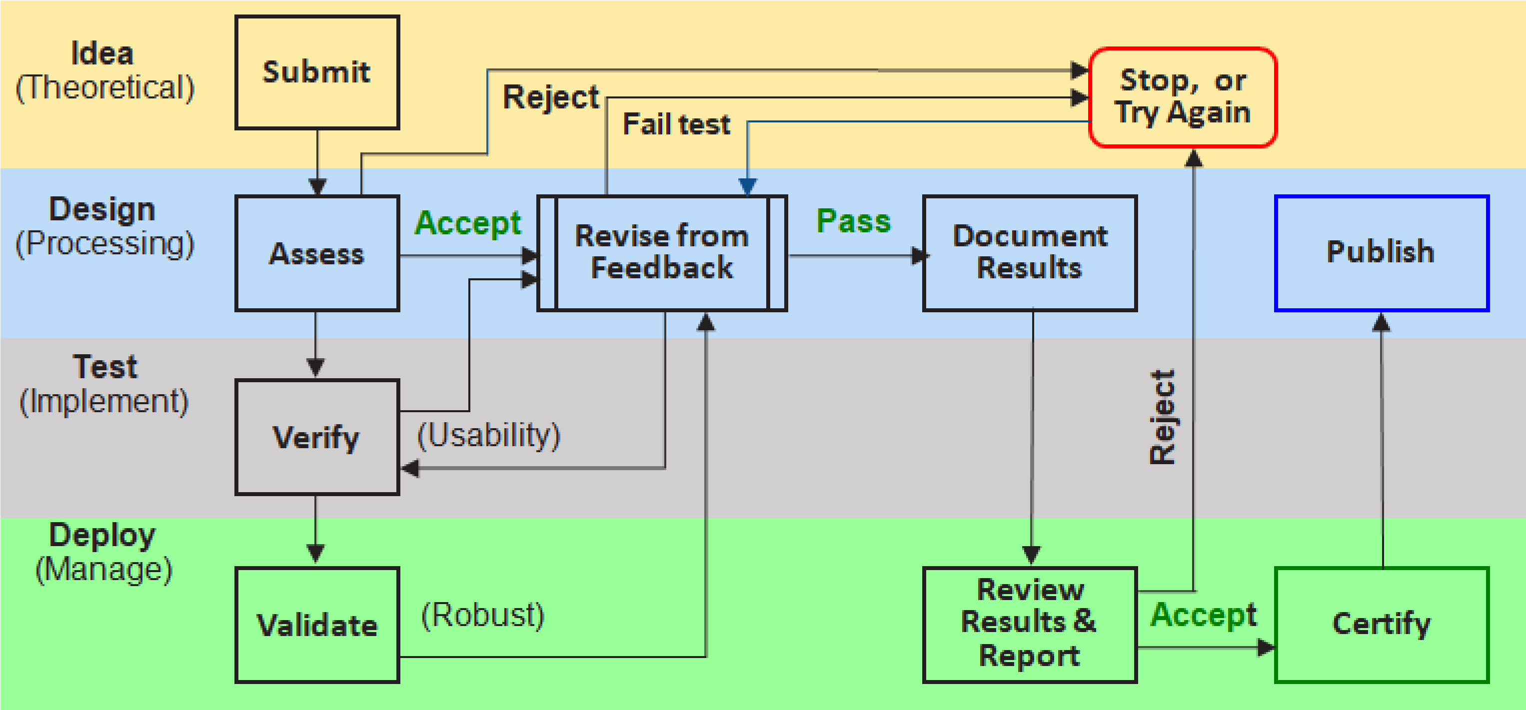
Kistan T., et al., "Machine Learning and Cognitive Ergonomics in Air Traffic Management: Recent Developments and Considerations for Certification", *Aerospace, 5(4), p. 103*, 2018.
Xie Y., Pongsakornsathien N., Gardi A., Sabatini R., "Explanation of Machine-Learning Solutions in Air-Traffic Management", *Aerospace, 8(8), no. 224*, 2022.
Asad Vakil, Erik Blasch, Robert Ewing, Jia Li, "Explainable Hybrid Decision Level Fusion for Heterogeneous EO and Passive RF Fusion via xLFER," *IEEE Nat. Aerospace and Electronics Systems Conf*, 2023.

Cognitive reasoning and task coordination



E. Blasch, et al, "Certifiable Artificial Intelligence Through Data Fusion," AAAI FSS-21, 2021. http://arxiv.org/abs/2111.02001

Certification Issues



E. Blasch, et al, “Certifiable Artificial Intelligence Through Data Fusion,” AAAI FSS-21, 2021. http://arxiv.org/abs/2111.02001

Regulatory Considerations in the Era of AAM: Approaches to Technology Maturity and Standardization

1. Introduction to the IEEE AESS Avionics Systems Panel	Giancarmine
2. Air and Space Transport Integration: Towards Multidomain Traffic Management	Rob
3. Aviation Noise Impact Assessment and Mitigation	Erik
4. ATM and Flight Management Systems	Erik / Alex
5. UTM, AAM, and Trusted Automation	Erik / Alex
6. Regulatory Considerations in the Era of AAM: Approaches to Technology Maturity and Standardization	Craig
7. Challenges and Advances in Space Domain Awareness and Space Traffic Management	Giancarmine

ASP
AESS IEEE Aerospace & Electronic Systems Society

Outline

- Drone Regulation
  - Foundational Concepts
  - Maturity Approach
  - International harmonization
- Standards Development
  - Operational Categorization
  - Organizations & Scope
  - Taskings

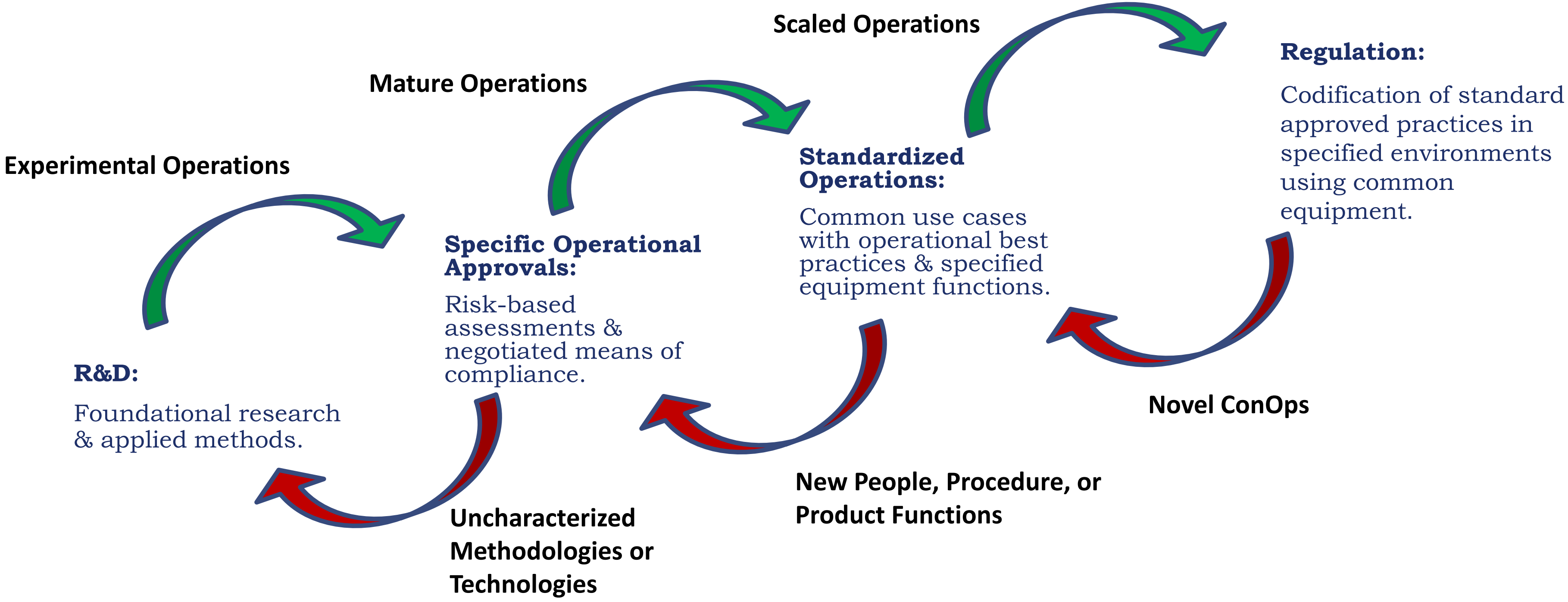
AESS IEEE Aerospace & Electronic Systems Society

Foundational Concepts for Drone Regulation

- Risk-appropriate:
  - Traditional aviation regulations are based on assumptions around people on-board and operating in aerodrome environments
  - Drones have a wide span of operational capability and provide solutions ranging from photography to human transportation.
  - Operational risk drives the requirements for products, procedures, personnel, and organizations.
- Performance-based:
  - To “future-proof” requirements in response to the rapid development of technologies traditional “prescriptive” requirements don’t serve to enable operations
  - Setting safety targets allows for multiple means of compliance, though good guidance is necessary to set expectations on acceptable solutions to evaluating safety.
- Informed Oversight:
  - Data collection for regulators to provide effective oversight of the industry as a whole and not single designs/operators.

Regulatory Maturity Approach

- ❖ New & novel operational concepts, system functions, and technology development are difficult to address within static regulatory frameworks.
- ❖ Flexible regulatory tools allow for the measured deployment of advances.



International Harmonization

- **ICAO:**
  - Provide a venue for Civil Aviation Authorities to share best-practices in regulation/oversight and enable common solutions for the global community.
  - Have a number of initiative to support common regulatory systems:
    - AAM SG: UA - Advanced Air Mobility Study Group (AAM SG)
    - UAS Model Regulations: UA/ICAO Model UAS Regulations
    - UTM guidance: UTM Guidance
    - RPAS SARPs: UA / Remotely Piloted Aircraft Systems Panel (RPASP)
- **JARUS:** Publications – JARUS
  - A community of like-minded regulators bringing industry & academia together to advance the state-of the art for regulatory approvals outside of certified aviation.
  - Develops and maintains the Specific Operational Risk-Assessment (SORA) process which many States use to authorize operations.
- **Bilateral Engagements:**
  - Coordination between authorities on approaches to drone safety assurance to support harmonization and product transferability.

ICAO

JARUS Joint Authorities for Rulemaking on Unmanned Systems

Organizations & Scope: Regulatory

Org	Group	Scope
ICAO	*RPAS Panel*	Certified International IFR Aerodrome-to-aerodrome RPAS Operations.
	FSM Panel	International Civil Aviation RPAS Spectrum coordination.
	AAM SG	Collecting information from States on all "non-traditional" aviation programs including RPAS, eVTOL, HAO, & UTM/U-Space/Automated CNS to inform future ANC work plans.
ITU	*WP 5.B*	International RPAS Spectrum Regulations.
JARUS	*AW WG*	Development and maintenance of performance-based airworthiness requirements for uncrewed aircraft (CS-UAS).
	SRM WG	Development and maintenance of risk-based operational approval framework (SORA).
	OOP WG	Development and maintenance of Personnel Licensing and Organizational requirements outside the Certified category.

Operational Categorizations

- Working Groups in general have approached the drone space by focusing on the development of materials for various risk classes of operation. The WGs generally stay within the risk-classifications established by the JARUS Operational concept (JAR Doc-09) as Category A, B, & C in increasing order of risk. Also recognized in ICAO Annex 6 Part IV as “Open”, “Specific”, and “Certified”.

Category A

Category B

Category C

Organizations & Scope: Industry

Org	Group	Scope
IEEE	*AESS*	Collaboration between aviation technology research and academic community.
FSF	*ARPAC WG*	Collaboration on BVLOS approval processes and operational experiences (e.g., RTM, SORA).
ISO	*SC-16/TC-20*	Development of industry consensus standards for uncertified RPAS & Infrastructure.
RTCA/ EUROCAE	*SC-228/WG-105*	Development of industry consensus standards for certified RPAS.
	SC-147/WG-75	Development of industry consensus standards for automated aircraft manuevering.
	SC-242/WG-124	Development of industry consensus standards for RPAS Spectrum.
	SC-238/WG-115	Development of industry consensus standards for Counter-RPAS.
SAE	*S-18*	Development of industry consensus standards for system safety assessment including automation.
	G-34	Development of industry consensus standards for AI/ML software development
ASTM	*F37*	Development of industry consensus standards for Light-Sport Aircraft/AULA
	F38	Development of industry consensus standards for uncertified RPAS & Infrastructure.
	F39	Development of industry consensus standards for Small Certified Aircraft Electrical Systems.
	F44	Development of industry consensus standards for Small Certified Aircraft.
	F47	Development of industry consensus standards for Aviation Personnel.
GUTMA/3GPP	*ACJA*	Development of standard approaches for Cellular industry serving aviation.

Tasking Breakdown: Work Areas

- When evaluating the scope of the various working groups each may be developing material along a number of major thematic lines:
  - Airspace Procedures/Flight Rules;
  - Operator Approvals/Procedures;
  - Safety Assurance Process/Procedures;
  - Airspace Classification;
  - Maintenance Personnel;
  - Engineering Personnel; and
  - Pilot Licensing.

Tasking Breakdown: Technical Topics

- When evaluating the outputs of the various working groups, each may be developing material for specific Technical Issues:
  - Aircraft Airworthiness;
  - Detect Alert and Avoid (DAA);
  - C2 Link;
  - Infrastructure;
  - Com/Nav/Surveillance (CNS);
  - Counter-UAS; and
  - Traffic Management (TM).

IEEE Aerospace & Electronic Systems Society

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Challenges and Advances in Space Domain Awareness and Space Traffic Management

Outline

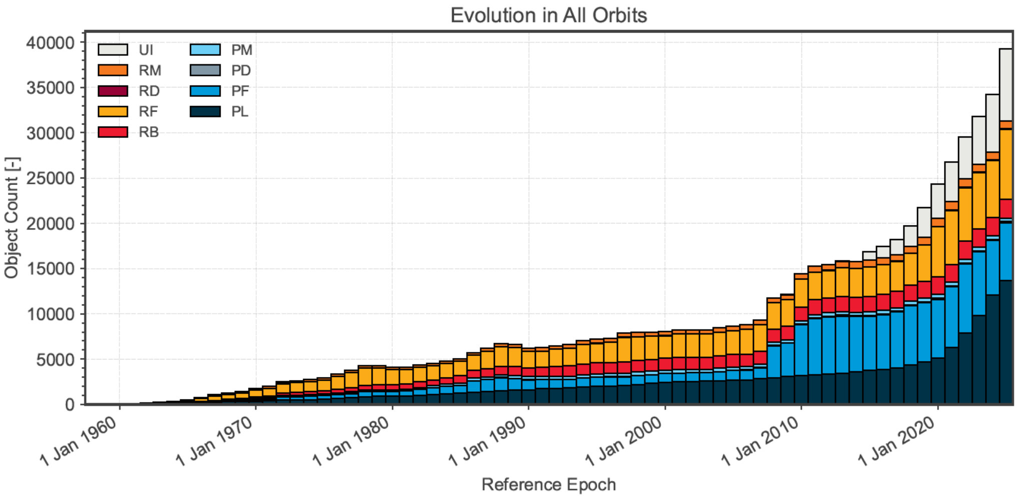
- Introduction & Space Environment Scenario
- Basics of Space Domain Awareness and Space Traffic Management
- Challenges and trends
- (Some) Research Paths
- Perspectives and conclusion

Introduction

- Last decade: rapid growth and change in the space industry, and explosion of commercial and private activity
- Space as a growing importance domain in the military field. Geopolitical tensions extending into the space environment
- Growing congestion in orbit, proliferation of space debris, increasing complexity of space operations, interference with astronomical observations, emergence of large constellations of satellites, and space threats posing increasing concerns for safety, security, and long-term sustainability of space
- This has increased the interest towards space surveillance and coordination of space operations, leading to new concepts such as Space Traffic Management
- Scopes of these slides: provide basics about space surveillance and STM, and discuss some emerging trends and research paths

Space Environment Scenario

❖ Source: ESA Space Environment Report 2025 (March 2025)
https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025



Type	Description
PL	Payload
PF	Payload Fragmentation Debris
PD	Payload Debris
PM	Payload Mission Related Object
RB	Rocket Body
RF	Rocket Fragmentation Debris
RD	Rocket Debris
RM	Rocket Mission Related Object
UI	Unidentified

Space Environment Scenario

- Source: ESA Space Environment Report 2025 (March 2025)
https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025

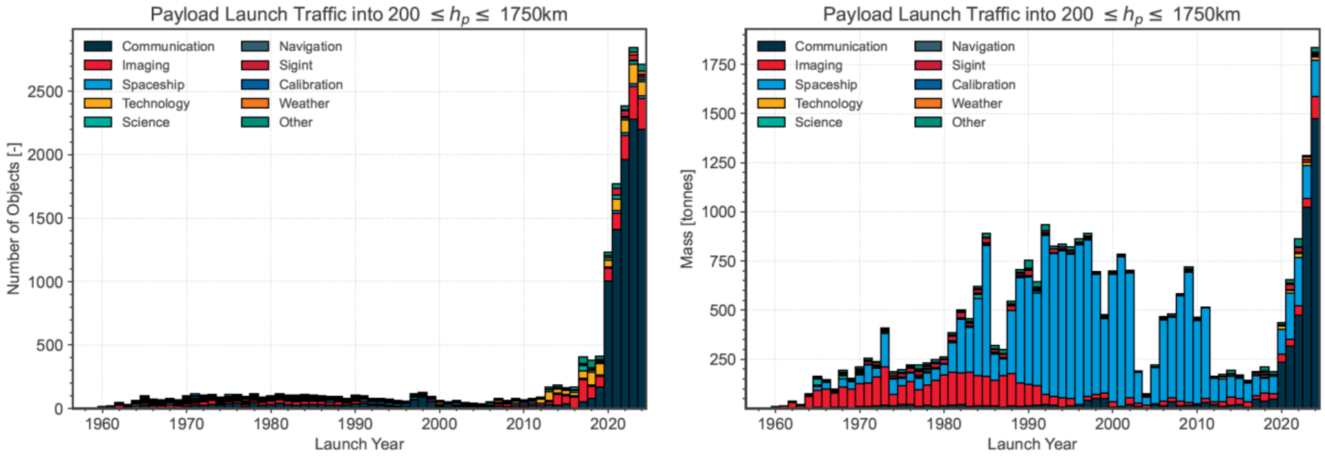


Figure 2: Evolution of the launch traffic near LEO_{IADC} per mission type in object number (left) and mass (right).

Space Environment Scenario

- Source: ESA Space Environment Report 2025 (March 2025)
https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025

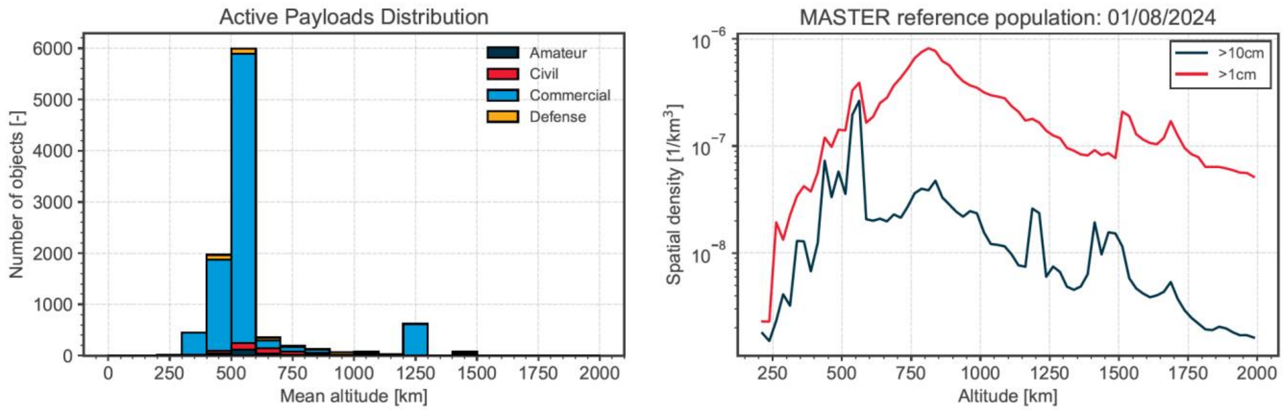


Figure 3: Distribution of active payloads with altitude (left) and density profiles in LEO_{IADC} for different space object size ranges from the 01/08/2024 MASTER reference population (right).

Space Environment Scenario

❖ Source: ESA Space Environment Report 2025 (March 2025)
https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025

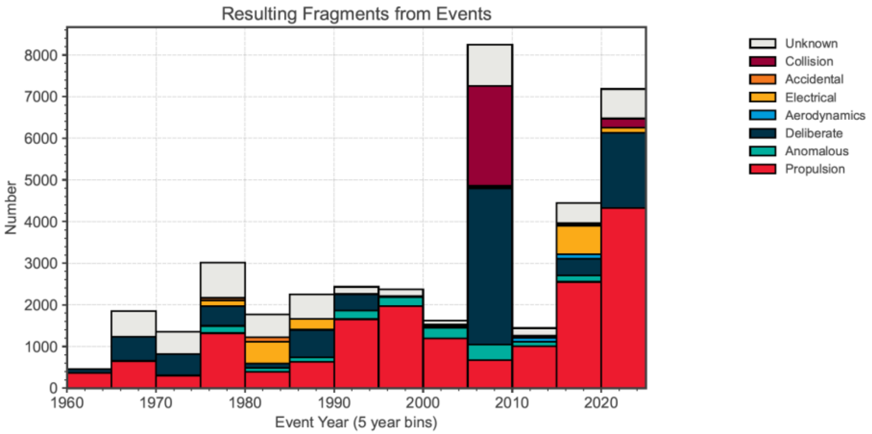


Figure 4: Historical trend of numbers of fragments produced by fragmentation events. The last bin covers until the end of 2024.

Space Environment Scenario

- Source: ESA Space Environment Report 2025 (March 2025)
https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2025

- Despite debris mitigation efforts, the **extrapolation** of the current changing use of orbits and launch traffic, combined with continued fragmentations and limited post mission disposal success rate could lead to a **cascade of collision events** over the next centuries. Even in case of **no further launches** into orbit, it is expected that collisions among the space debris objects already present will lead to a **further growth** in space debris population in Low Earth Orbit.

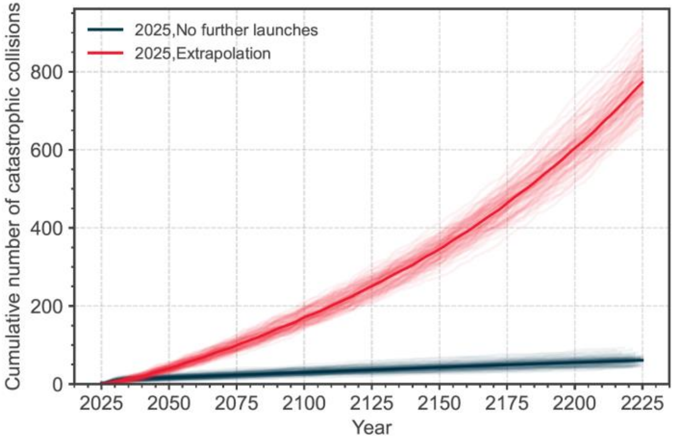
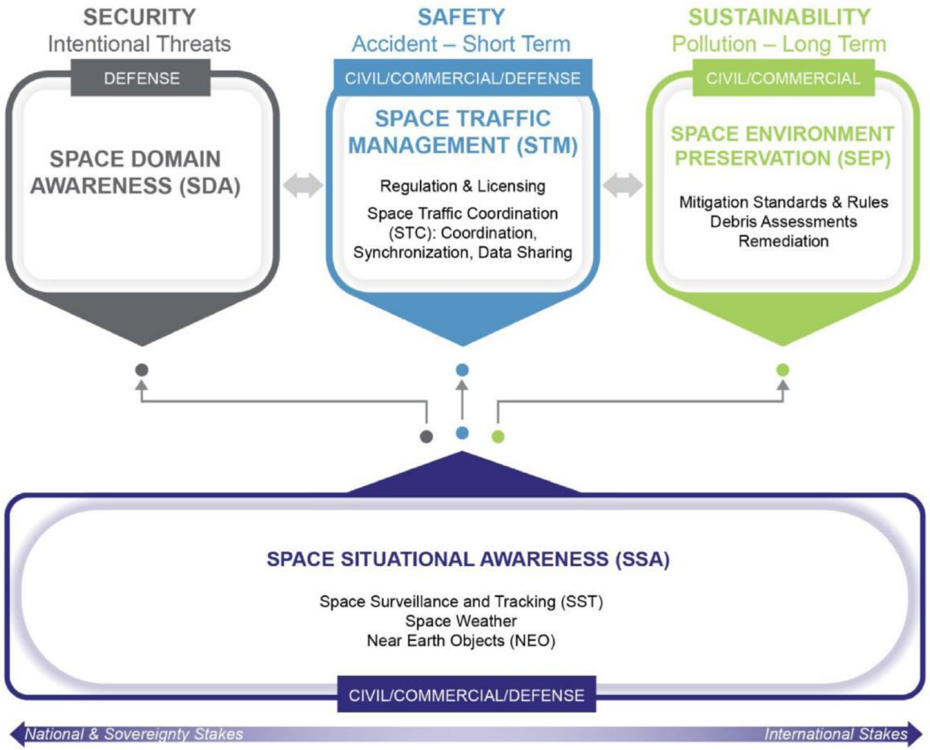


Figure 9: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

Some keywords

- Space sustainability challenges
- Debris mitigation and remediation
- Need of persistent monitoring to take timely actions and to preserve safety and security of space assets. Scalability, efficiency, context-based information and high level understanding
- Need of advanced coordination
- Technological, legal and geopolitical aspects

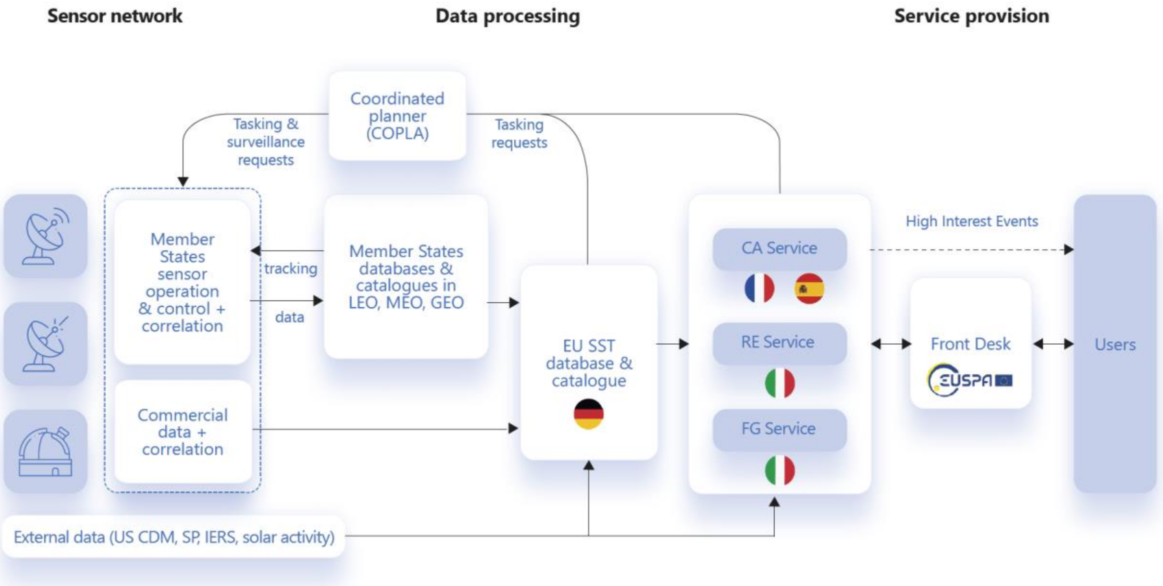
Basics – General definitions



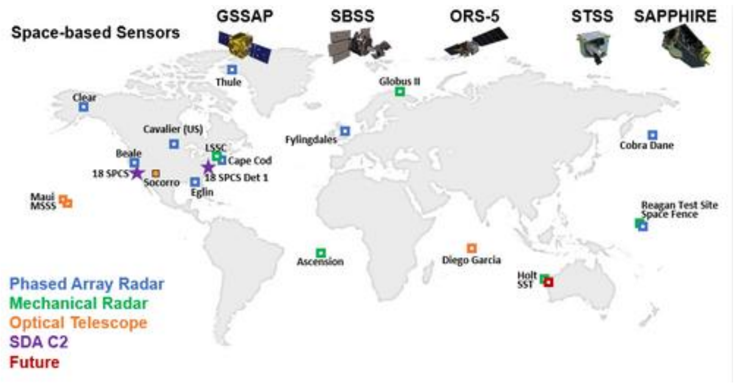
(* Skinner et alii, Space traffic management terminology, Journal of Space Safety Engineering, 2022)

SST Architecture and Services

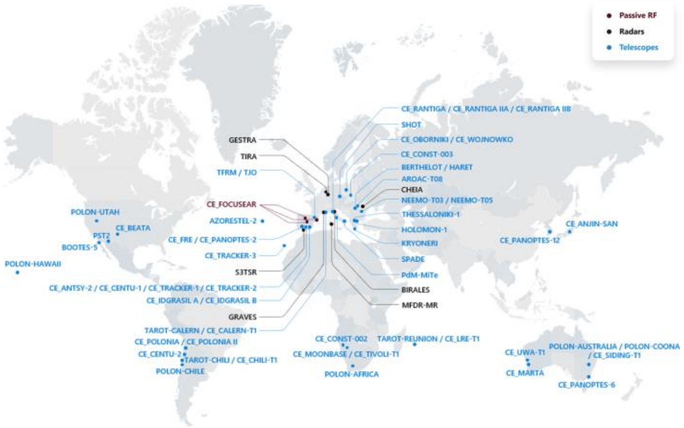
- Example architecture from EU-SST Consortium (https://www.eusst.eu/)
  - Sensors (ground-based and space-based) and other sources
  - Key processing functions: correlation & orbit determination to retrieve the orbital state. Need of catalogue build-up and maintenance
  - Sensor tasking
  - Basic services
    - Conjunction Analysis
    - Re-entry
    - Fragmentation



SST Sensor Networks



(US Space Surveillance Network)



(EU SST Network)

Correlation and Orbit Determination

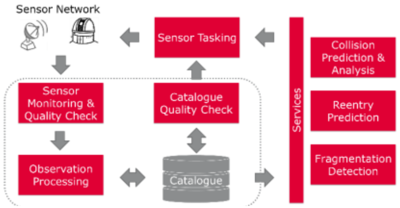
- Sensor measurements feed correlation and orbit determination pipelines

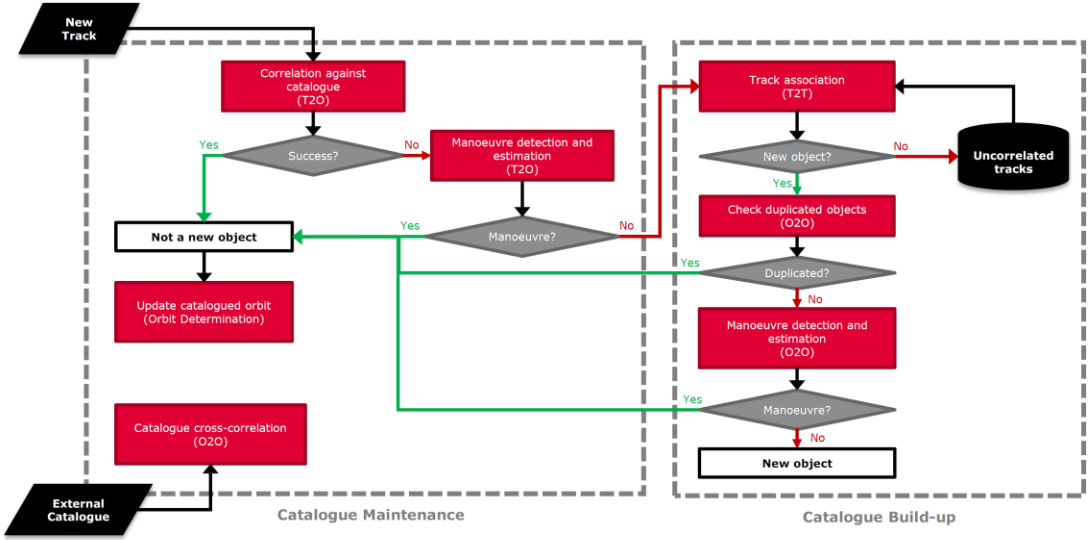
- Multi-target tracking problem
  - Measurements frequency
  - Dynamic model – uncertainties
  - Maneuvers

- Correlation and orbit determination needed for catalogue build up and maintenance

Catalogue build up and maintenance

- Mahalanobis distance usually adopted: role of uncertainties
- Maneuvers. Correlation and track-to-orbit maneuver detection and estimation

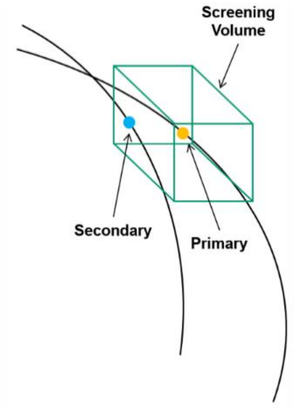


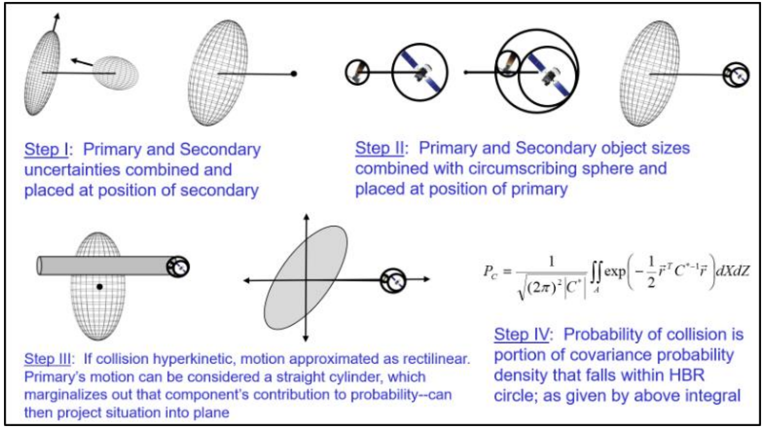


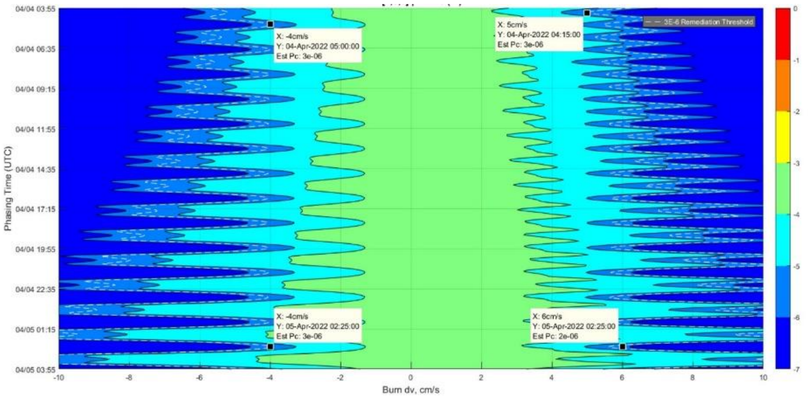
(Pastor et alii, DATA PROCESSING METHODS FOR CATALOGUE BUILD-UP AND MAINTENANCE, NEO and Debris Detection Conference 2019)

SST Services: Conjunction Analysis

- Major steps
  - Close conjunction identification
  - Collision risk assessment
    - Generates Conjunction Data Messages (CDMs)
  - Conjunction mitigation
    - Suggests Collision Avoidance Maneuvers (CAMs)
- «Classic» procedures based on human-in-the-loop information exchange and decision-making



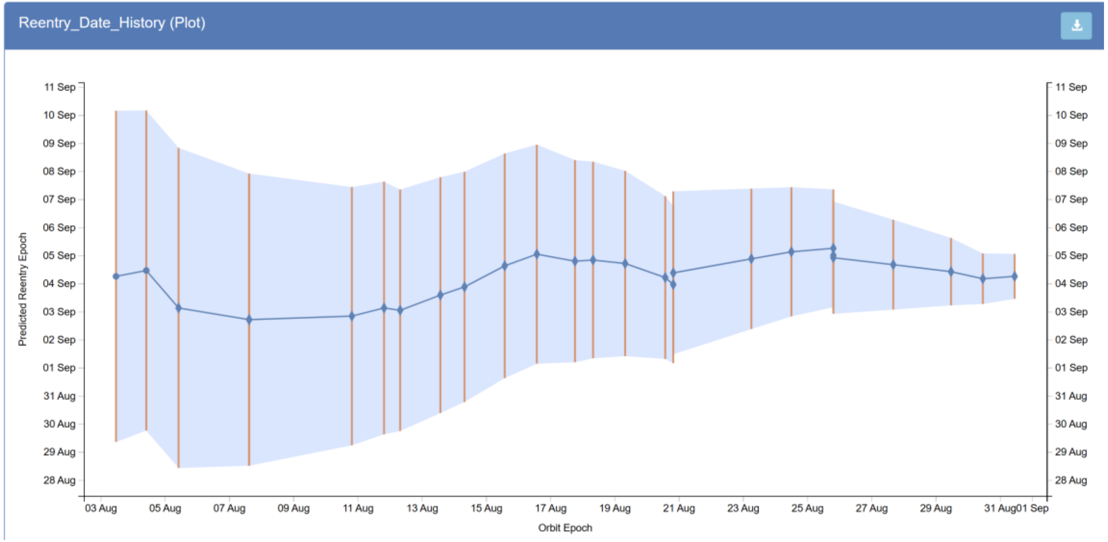




https://www.nasa.gov/cara

Services: Re-entry

- Provide information on Space Objects which should re-enter without control
  - “30 Day Re-entry List”
  - “Re-entry Reports”
- Space objects of interest
  - mass greater than 2.000 kg or, if no mass information is available, RCS larger than 1m².
  - all rocket bodies (R/B)
- Sensor tasking requests
- Decay notification
- Uncertainty and complex dynamics



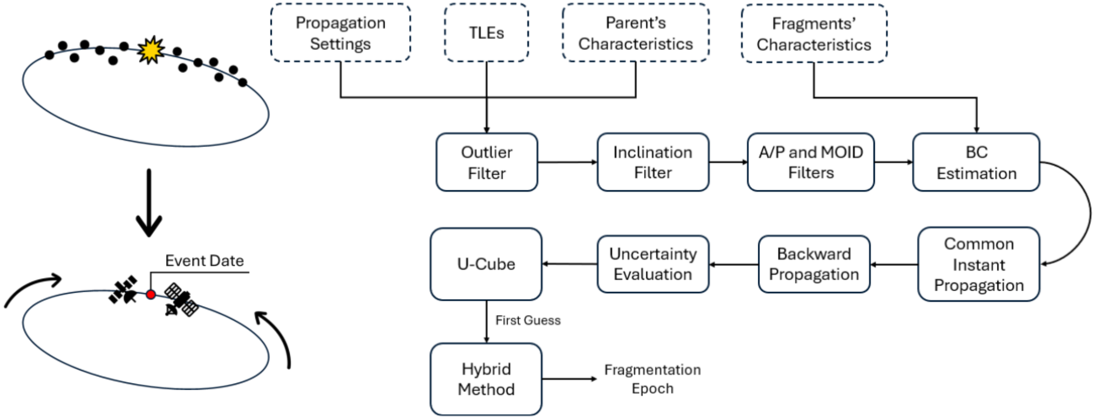
Cosmos-1455

SATNO : 14032
Name : Cosmos-1455
Reentry Date : 04 Sep 2025
Uncertainty : 0.800 day(s)
Mass : 1982.160 kg
Class : Payload
Inclination : 82.500 deg
Perigee : 224.900 km
Apogee : 230.400 km
Tool : RAPID
Country : USSR, Union of Soviet Socialist Republics

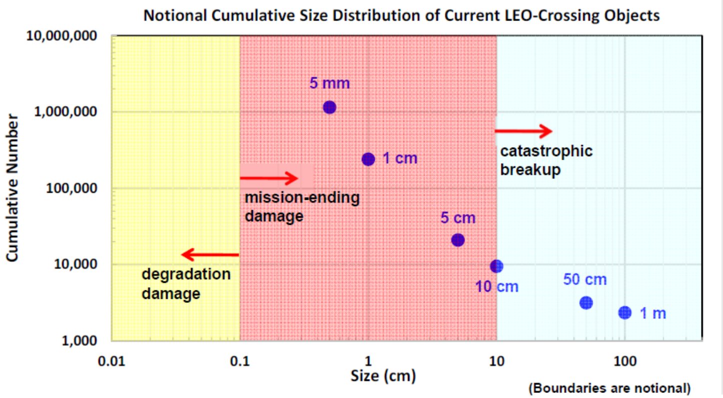
https://reentry.esoc.esa.int

Services: Fragmentation

- ❖ Provides detection and characterisation of in-orbit fragmentations
  - Event detection, parent(s) identification
  - Fragment distribution and evolution
  - Early impact risk assessment
  - Event modeling and simulation
- ❖ Breakups and Anomalous events



(Ostrogovich et alii, INTEGRATING PERTURBATION-AWARE BACKWARDS PROPAGATION AND FRAGMENT CHARACTERIZATION FOR IMPROVED FRAGMENTATION DETECTION AND PARENT IDENTIFICATION, ESA Space Debris Conference 2025)

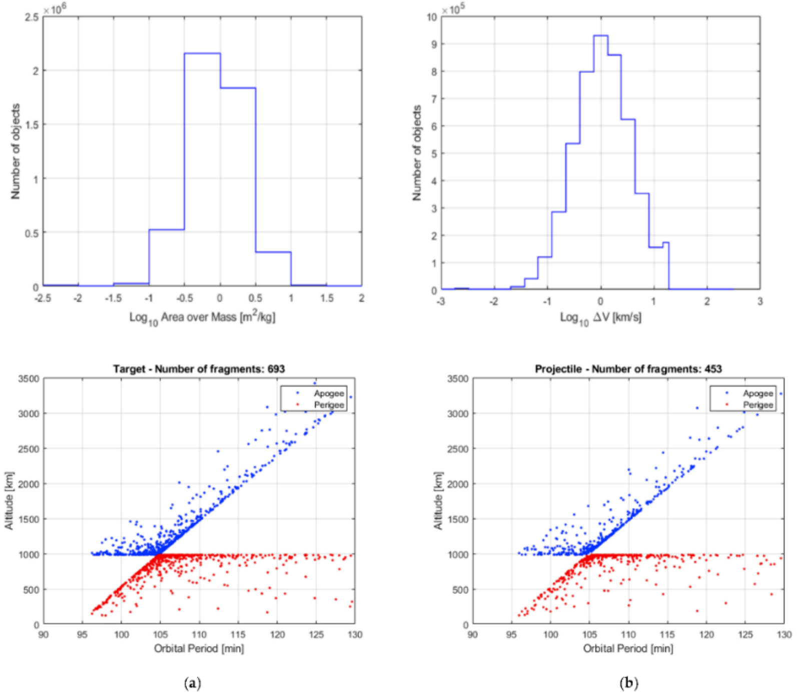


(Liou, 2020, https://ntrs.nasa.gov/api/citations/20205001509/downloads/20200513%20Brookings%20OD%20presentation%20rev1%20(Liou).pdf)

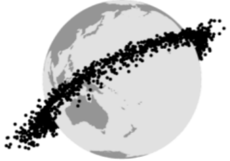
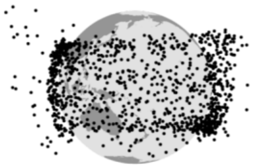
Services: Fragmentation

- Fragments evolution: driven by keplerian dynamics + perturbations (J2 and drag in LEO, J2 third body and solar radiation pressure in GEO). Cloud → Toroid → Band

- Breakup modeling: NASA Standard Breakup Model
  - Other models under development or in usage
  - They provide fragment distribution in terms of number, size/area, mass, velocity variation



(Cimmino et alii, Tuning of NASA standard breakup model for fragmentation events modelling, Aerospace 2021)

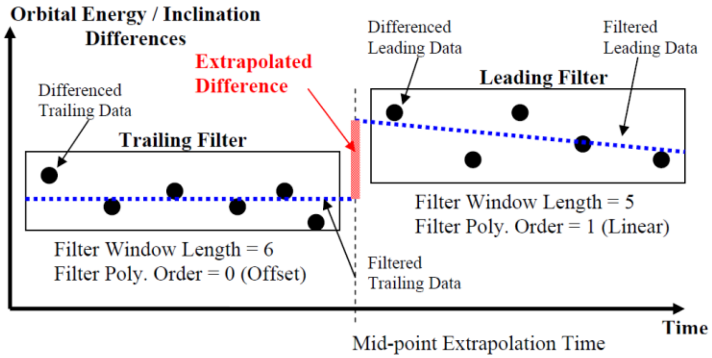




Other Key functions for SSA

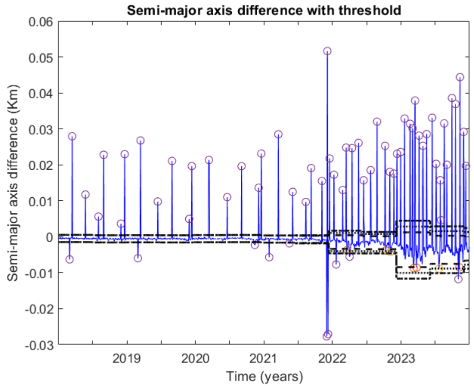
- Maneuver detection
- Pattern of life estimation
- Anomaly Detection
- Resident Space Object Characterization
- Threat and proximity detection
- Spawning Detection

Maneuver Detection

- Based on orbital state or sensor measurements (interface with correlation and orbit determination)
- Techniques based on orbital state: maneuvers detected with propagation-based or parameter-based approaches
- Sensitivity to small maneuvers vs sensor/orbit determination noise
- Orbit determination latency
- Measurement-based approaches and observability challenges
- Rise of AI-based approaches

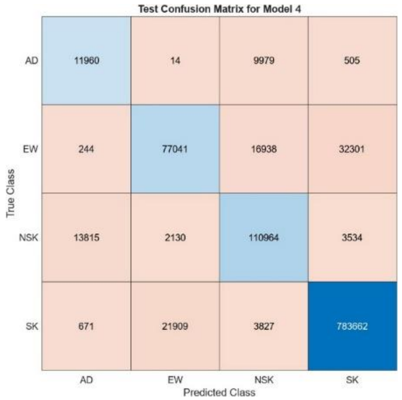


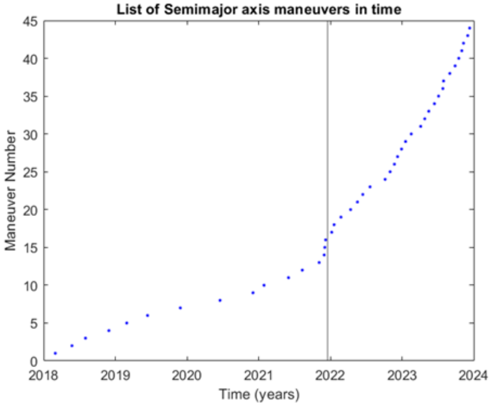
(Kelecy et alii, Satellite Maneuver Detection Using Two-line Element (TLE) Data, 2007)



Pattern of Life Estimation

- Definition of typical satellite behaviors, to support predictions and anomaly detection
- Linked to time statistics and entity of maneuvers
- Example GEO modes
  - Station Keeping (SK): satellite controlled on both EW and NS directions;
  - East-West Stabilization (EW): satellite controlled on EW direction only;
  - Not Station Keeping (NSK): satellite not controlled on both directions;
  - Adjust Drift (AD): satellite performing a repositioning maneuver.
- Wide usage of AI-based approaches





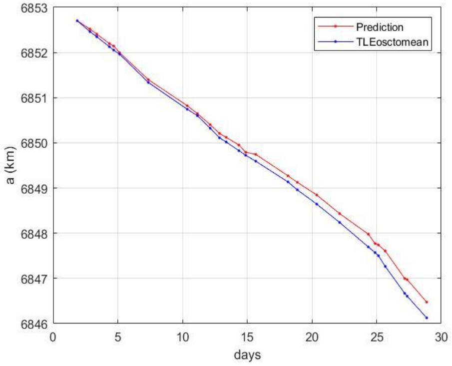
(Perugino et alii, Statistical Approach for the Definition of Satellite Pattern of Life, IEEE MetroAerospace 2025)

Resident Space Object Characterization

- Astrometric characterization: exploits non-conservative perturbation effects to derive information about ballistic coefficient and effective ballistic coefficient

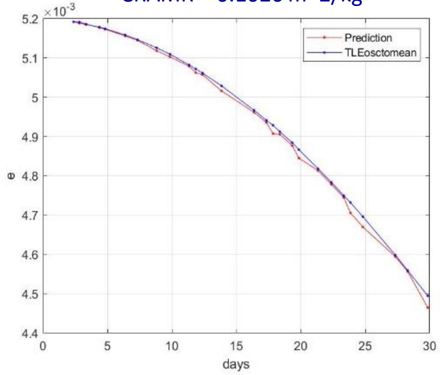
NORAD ID 32075 (LEO)

CDAMR = 0.3610 m^2/kg



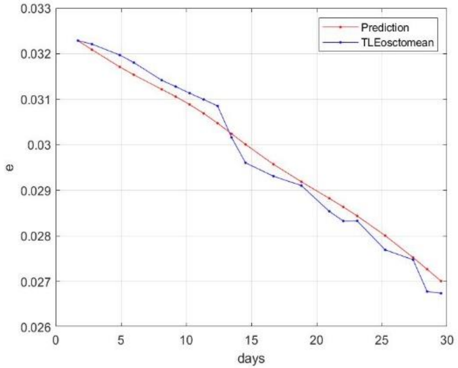
NORAD ID 42515 (MEO)

CRAMR = 0.1026 m^2/kg



NORAD ID 43285 (GEO)

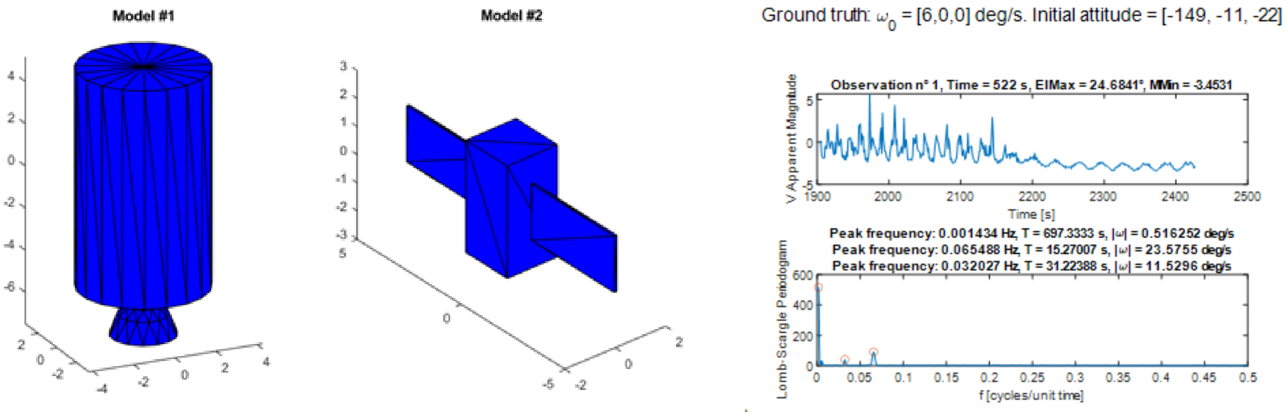
CRAMR = 1.2549 m^2/kg



(Cimmino et alii, Earth Orbiting Resident Space Objects Characterization based on Astrometric Data, IEEE MetroAerospace 2023)

Resident Space Object Characterization

❖ Sensor-based characterization: uses sensor measurements for shape/attitude/surface properties characterization
- Light curve analysis: important for operational status
- Multi-sensor-based techniques (optical, radar, laser)



(Isoletta et alii, Attitude motion classification of resident space objects using light curve spectral analysis, Advances in Space Research 2025)

Challenges and Needs

- More resident space objects
- Many more active objects - High spatial density in specific orbit domains, substancial increase of collision avoidance maneuvers
- Business as usual meets challenges: it is not scalable
  - Human in the loop
  - Limited quality of situational awareness information, limited data sharing – unacceptable trade-offs
  - Limited responsiveness with respect to threats
  - New operational procedures are already being applied (e.g. collision avoidance for large constellations)

Challenges and Needs

- Collision avoidance for large constellations - STARLINK

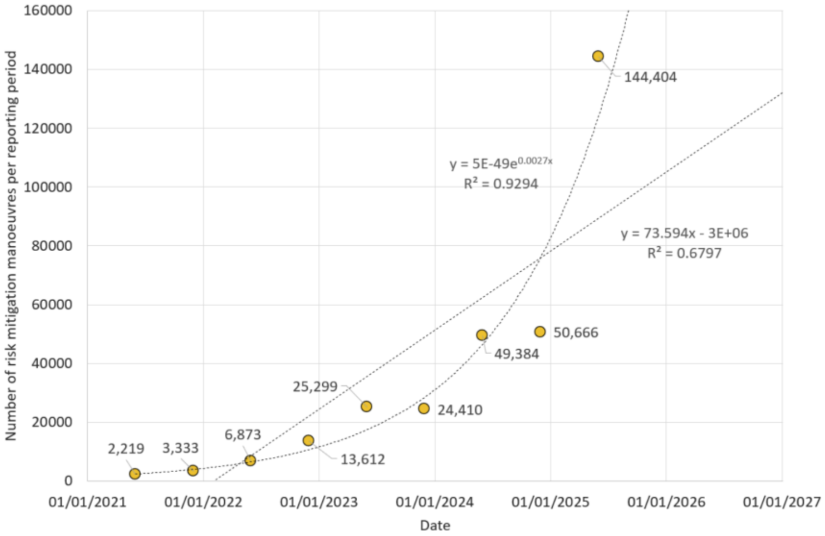


Figure 3. Number of conjunction risk mitigation manoeuvres reported by SpaceX for each reporting period.

https://www.linkedin.com/pulse/starlink-manoeuvre-update-july-2025-hugh-lewis-utkhe/

Needs

- More Accurate and More Frequent Sensing Information
  - More Sensors
  - Devices for Enhanced Tracking
  - Cooperative and Non-cooperative Sources
  - Coordination and Data sharing
    - Including maneuver plans
  - Data Fusion

- Rules of the road and maneuver coordination

- Assessment of Orbital capacity and capacity-oriented design

- Adherence to mitigation «guidelines»

Needs – Data Fusion

Sensor type:	GEO coverage	LEO coverage	Not lighting-dependent	All weather	Range	Range rate	Angles
Monostatic Radar	◒	●	●	●	●	◒	◒
Bistatic/multi-static Radar	◒	●	●	●	●†	◒	◒
Optical Telescopes	●	◒	○	○	○	○	●
Passive RF (TDOA/FDOA)	●	●	●	●	●†	●	○
LIDAR	●	●	◒	○	●	○	◒

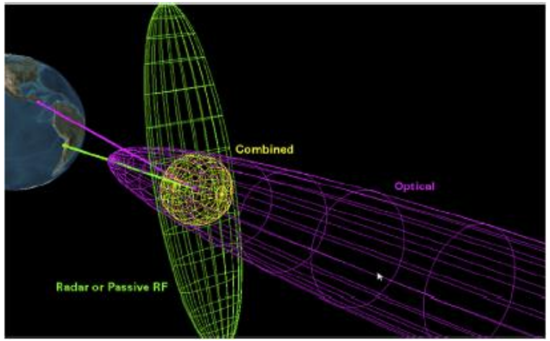
† Derived quantity ●=full, ◒=partial and ○=little or no capability

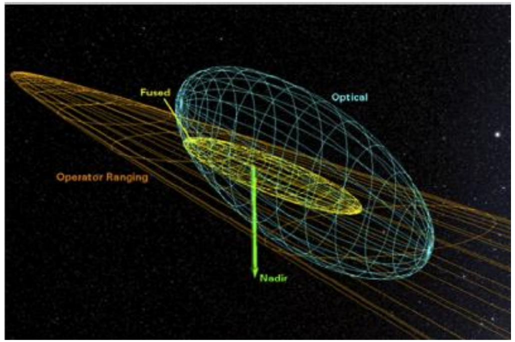
Fig. 2. General performance comparison of sensors that can track both space debris and spacecraft.

Sensor type:	Doesn't require operator cooperation	GEO coverage	LEO coverage	Not lighting-dependent	All weather	Range	Range rate	Angles
Spacecraft transponder ranging and range rate	○	●	○	●	●	●	●	◒
1-way Doppler	●	●	●	●	●	○	●	○
Radio Telescopes	●	●	●	●	●	○	○	●
Passive RF (TDOA/FDOA)	●	●	●	●	●	●†	●	○
Onboard GNSS	○	●	●	●	●	●†	●†	●†

† Derived quantity ●=full, ◒=partial and ○=little or no capability

Fig. 3. General performance comparison of sensors that can only track actively-transmitting spacecraft.

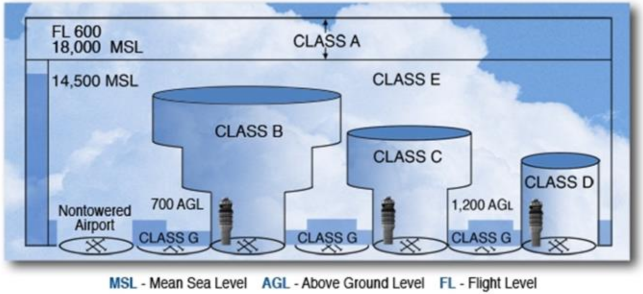


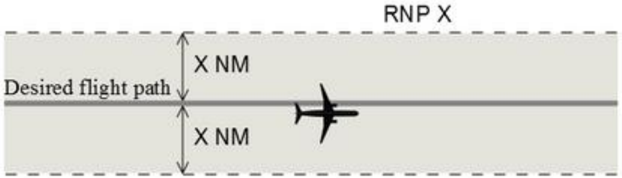


(Oltrogge et alii, Space traffic management: Data fusion, Acta Astronautica 2025)

A parallel with Air Traffic Management

- Cooperative surveillance – non cooperative surveillance often used as a backup layer
- Rules of the air
  - Predictability
  - Helps deconfliction with limited situational awareness information
- Airspace capacity
- Airspace classes
  - Clearance requirements
- Required navigation performance
- Flight plan, strategic deconfliction, intent



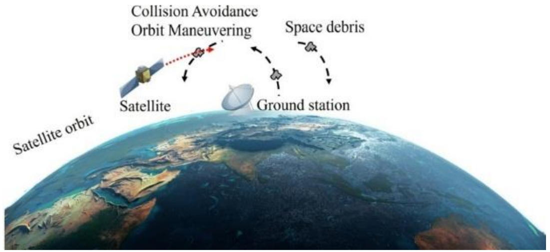


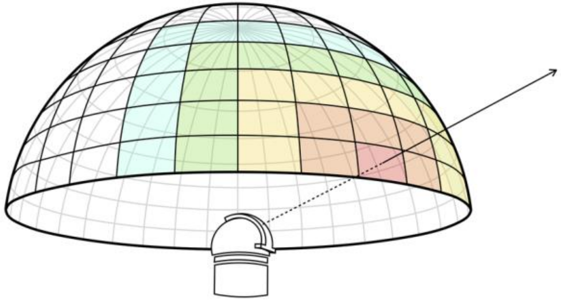
Trends and Opportunities

- Automation and onboard autonomy
  - Independence from ground control
  - Data exchange, Sensor Tasking
  - Onboard collision avoidance
  - Human high level supervision

- Artificial Intelligence
  - Useful to process significant quantities of information and/or to make decisions
  - Real vs synthetic datasets? Generalization? Explainability?

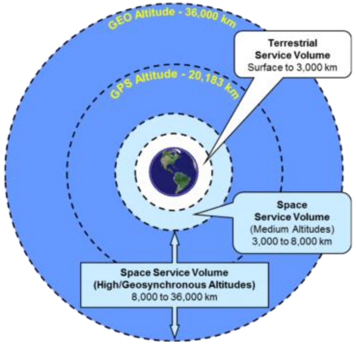
- New sensors and processing pipelines
  - Opportunities for commercial SSA operators





Trends and Opportunities

- Space-based solutions
  - Ad hoc systems
  - Opportunistic payloads
  - Crowdsensing policies – system-level perspective
  - Local sensing
  - Distributed space-based sensing
- Cooperative Approaches
  - Role of GNSS
  - Resiliency? Vulnerabilities?
- Debris Remediation and In Orbit Servicing



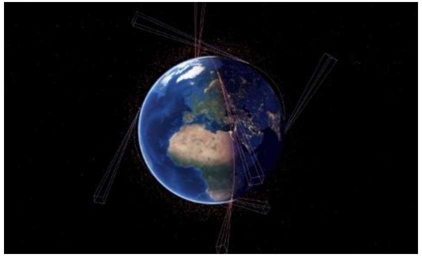
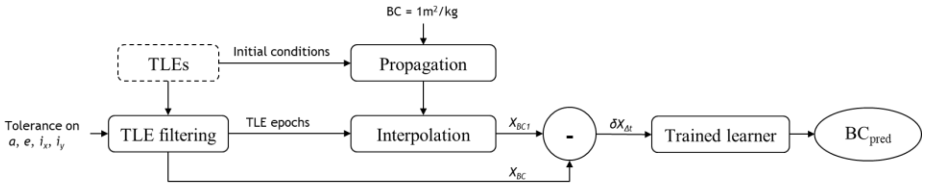


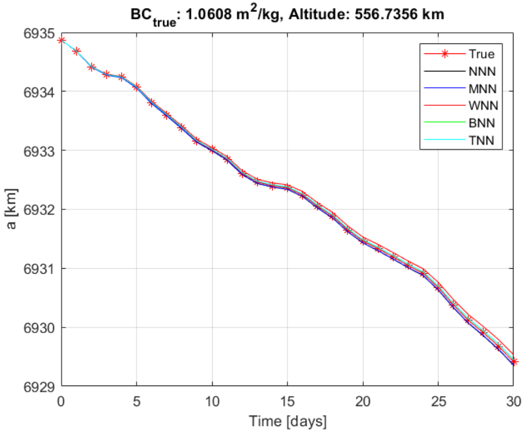
Image credits: Vyoma Space

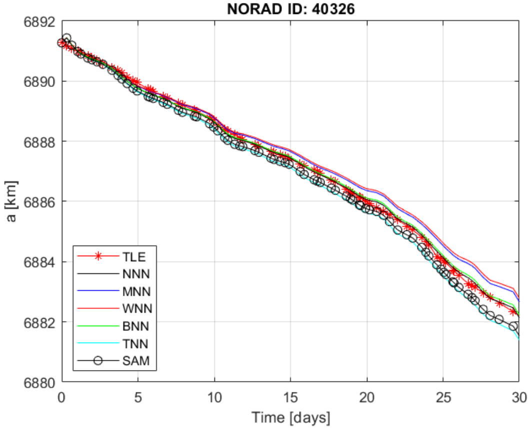
Research Paths: Artificial Intelligence for RSO Characterization

Machine Learning-based astrometric characterization

- Ballistic coefficient estimation using neural networks
- Based on mean orbital elements derived from TLEs
- Tested on synthetic and real space objects for LEO, MEO and GEO objects
- Comparison and potential combination with conventional methods



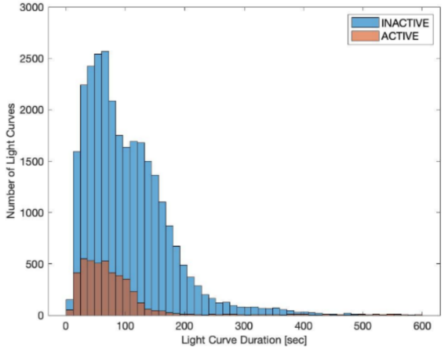


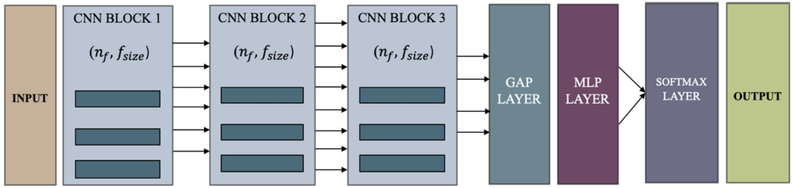


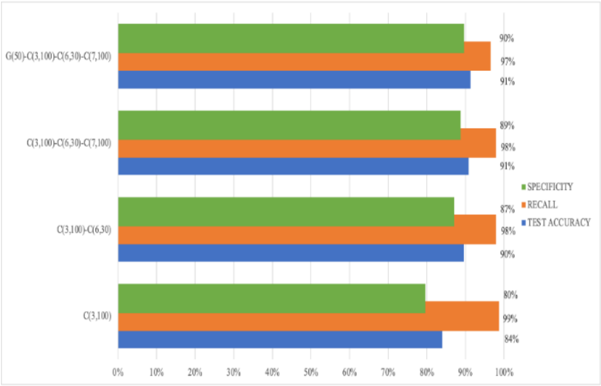
(Cimmino et al., ASR 2024)

Research Paths: Artificial Intelligence for RSO Characterization

- ML-based light curve analysis
- Promising performance figures, but significant impact of the dataset characteristics



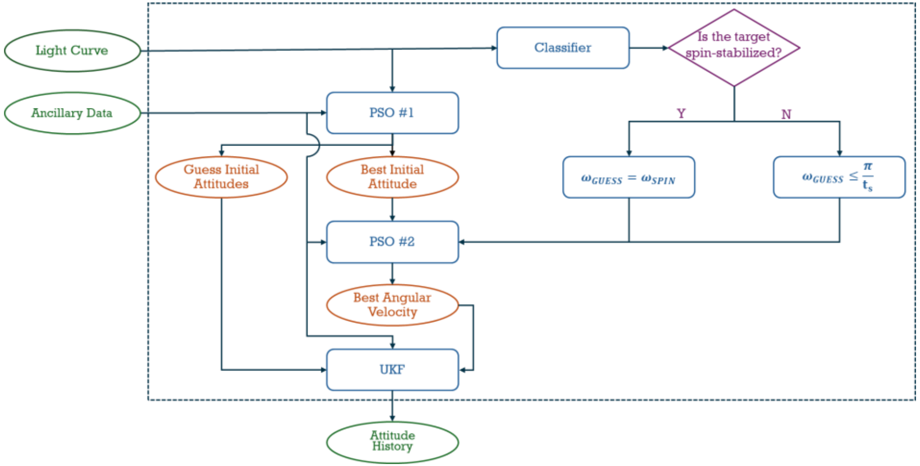


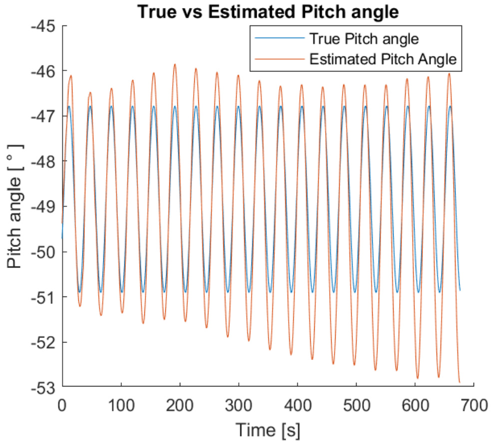


(Bencivenga et al., IEEE MetroAerospace 2025)

Research Paths: Data Fusion for RSO Characterization

- Data fusion for light curve analysis
  - Combination of multi-temporal multi-spatial light curves for attitude motion classification
  - Combination of multi-temporal information with UKF and PSO for attitude estimation
- On-going: fusion of heterogeneous sensors



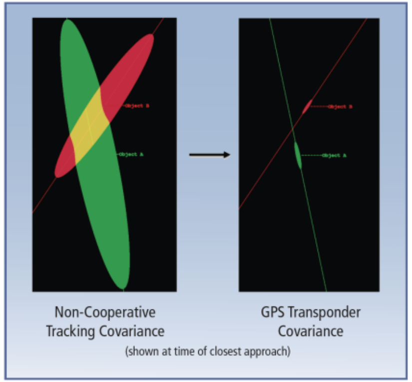


(Bencivenga et al., ESA Space Debris Conference 2025)

Research Paths: Cooperative STM

- Role of GNSS for STM
- Challenge: failures /end of life

Advantages	Drawbacks
High accuracy (about 100 times better than Two Line Elements)	Only for cooperative satellites with a GNSS receiver onboard.
Global and continuous coverage provided by GNSS satellites	Potential limitations in terms of size, weight, power and cost.
	Earth-Satellite communication is possible only when the satellite is in view of the ground station



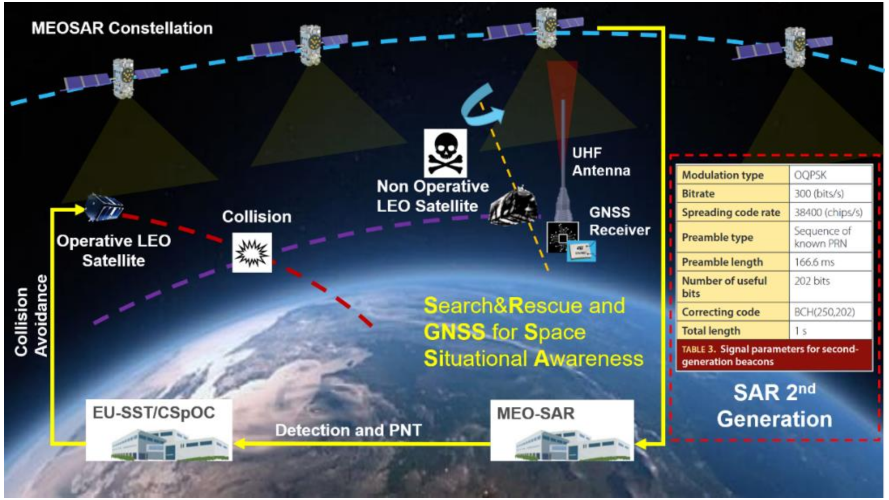
(Abraham, 2018)

Research Paths: Cooperative STM

New solution being developed by the *European Commission's Joint Research Centre* in collaboration with *University of Naples Federico II*: **SARGASSIA** *(Search & Rescue and GNSS for Space Situational Awareness).*

- **SARGASSIA CORE**: use of snapshot GNSS receivers integrated with Galileo SAR (Search And Rescue) system.

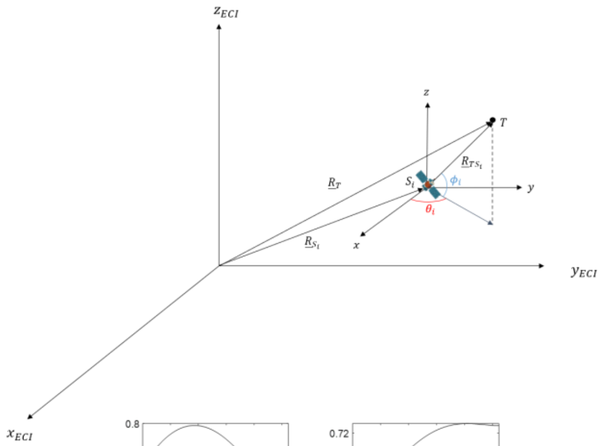
- **SARGASSIA CONCEPT**: The satellite activates the GNSS receiver under specific conditions, such as failure or end-of-life, and transmits data on ground via SAR communication link. This reduces onboard power consumption and processing while overcoming ground coverage limitations. The system allows for intermittent but power-efficient position updates, making even inactive satellites temporarily cooperative for SSA purposes.

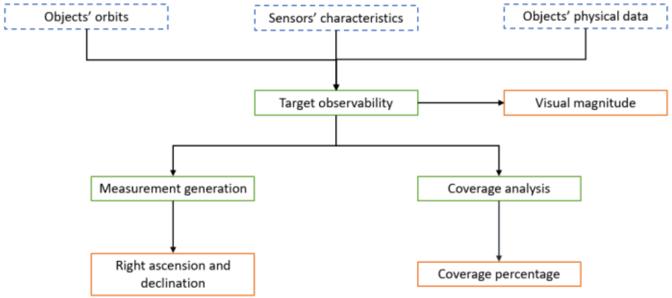


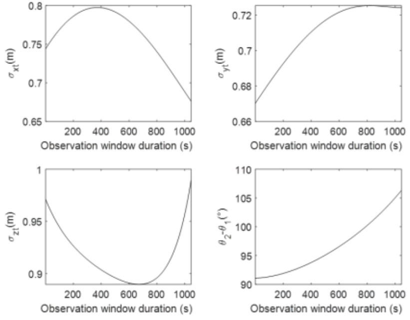
(Russo et alii, ION GNSS+, 2025)

Research Paths: Space-based SSA

- Added value of space-based sensing
- Distributed space systems for SSA
  - Triangulation of optical measurements
  - Multilateration based on RF signals
  - Coordination and control
  - Highly Automated tasking







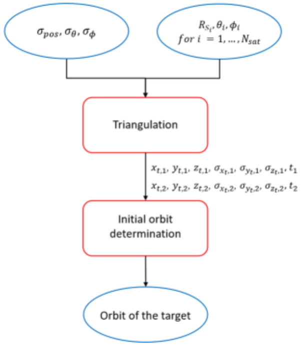
Trend of σ_{x_t},σ_{y_t}, σ_{z_t} and $\theta_2 - \theta_1$ during the observation window, when $\Delta v = 3°$ and $\sigma_{pos} = 0.5\ m$, $\sigma_\phi = 0.0022°$ and $\sigma_\theta = 0.0022°$.

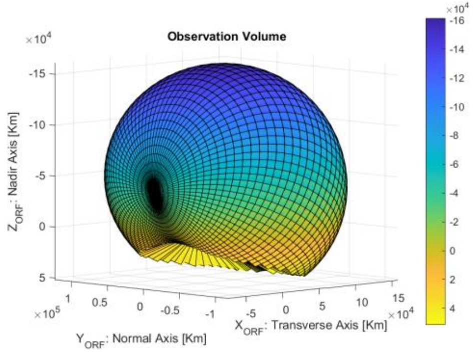
(Argirò et alii, ESA Space Debris Conference 2025)

Research Paths: Space-based SSA

Focus on large-baseline satellite systems

- Accurate triangulation and thus range estimation of the objects of interest
- Possibility to exchange information and coordinate observations, allowing near real-time fusion and processing without excessive requirements on Inter Satellite Link
- Reconfiguration possibilities
- The relatively large separation and the implementation of passive safety concepts enable less stringent requirements in terms of guidance, navigation, and control





(Argirò et alii, 2025)

Perspectives and Conclusion

- Evolution of the space environment leading to significant paradigm changes
- Technological advances to improve situational awareness
- Importance of coordination and data exchange
- Necessity to support civilian and defense applications of space. Dual use technologies
- Need to ensure safe and secure space operations, and space sustainability as a whole

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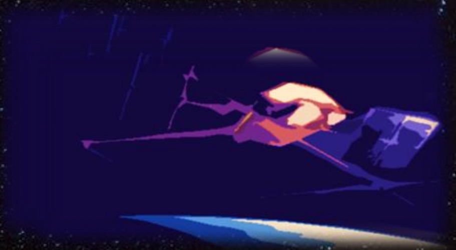

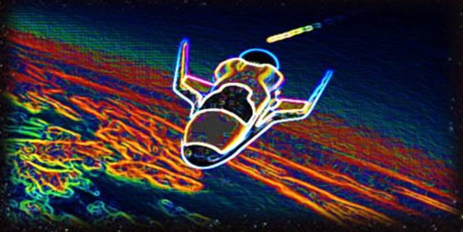

Thank you!

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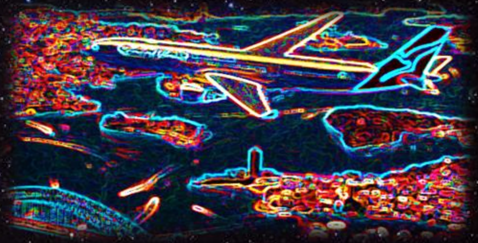

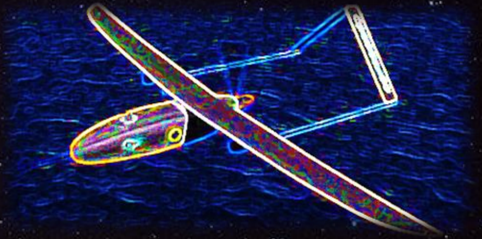

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