جامعــة خليفــة
Khalifa University

IEEE
Advancing Technology
for Humanity

Advanced in Digital Avionics and Space Systems

Dr Roberto Sabatini
Professor of Aerospace Engineering
Khalifa University of Science and Technology
Chair, IEEE AESS Avionics Systems Panel
P.O. Box 127788, Abu Dhabi, UAE
T: +971 2 312 5656
E: roberto.sabatini@ku.ac.ae

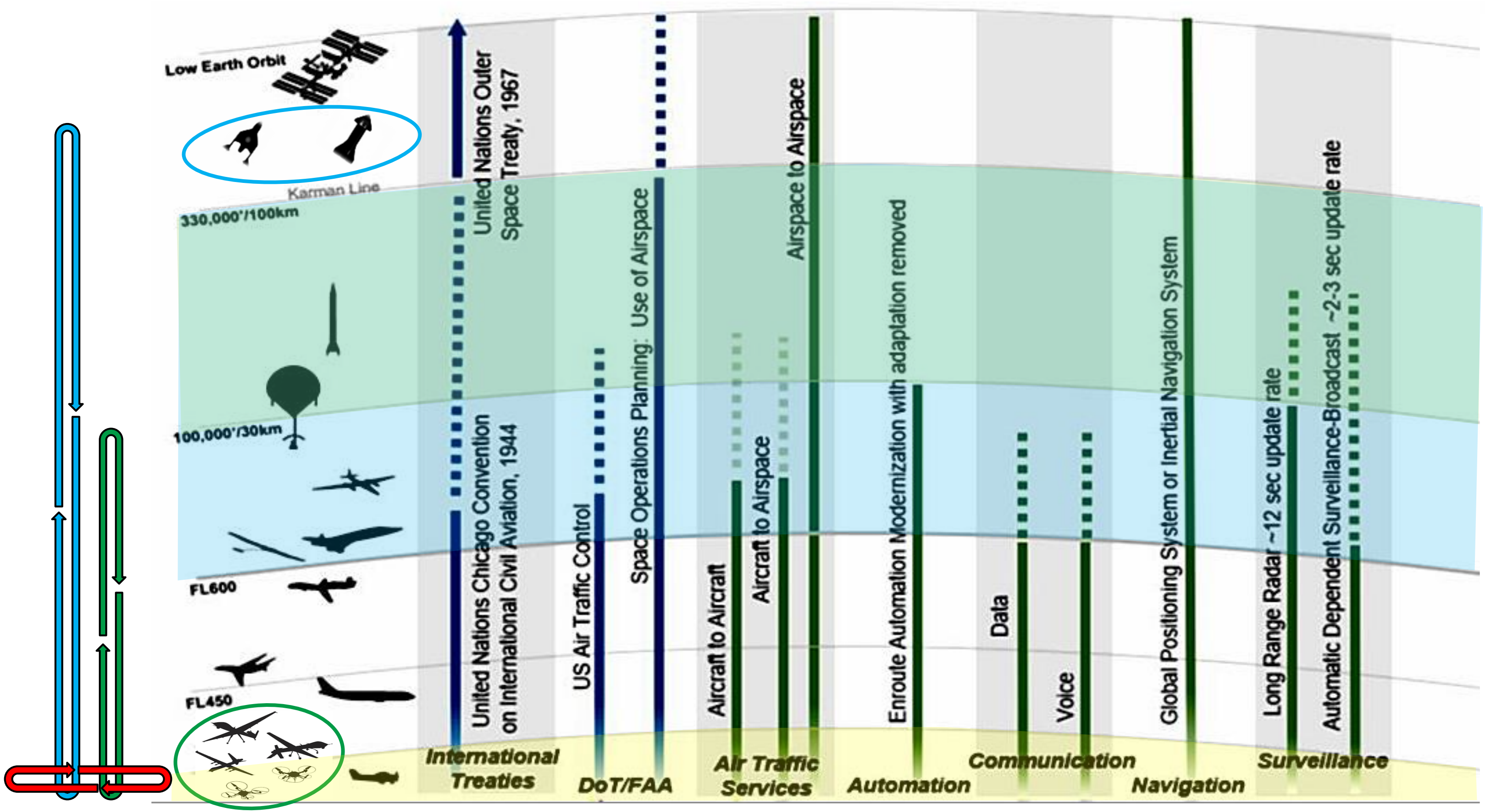
22nd June 2023


AESS 50th Anniversary IEEE Aerospace and Electronic Systems Society

IEEE Aerospace and Electronic Systems Society
VIRTUAL DISTINGUISHED LECTURE SERIES

ASP
AESS IEEE Aerospace & Electronic Systems Society

Evolving Flight Domains



Credit: FAA

Air Transport Industry Snapshot

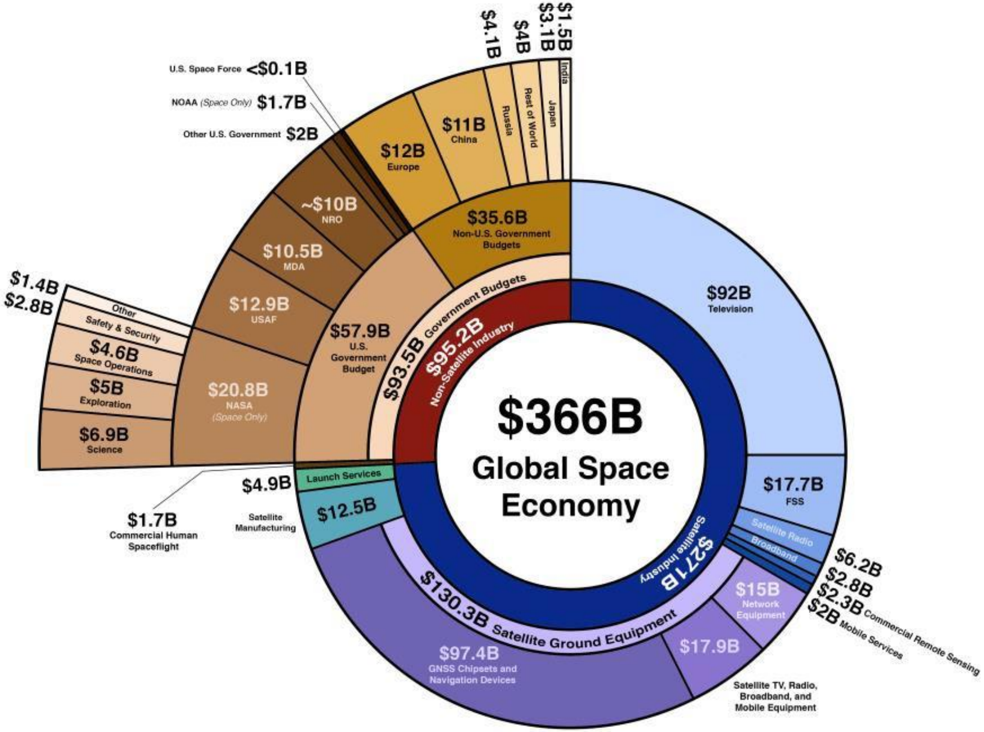
- The Aerospace and Aviation (A&A) industries play an important role in the global economy. Before the recent crisis caused by the COVID-19 pandemic, air transport alone contributed US$2.7 trillion to the world GDP (3.6%) and supported 65.5 million jobs globally

- Despite the temporary reduction of air transport due to COVID-19, forecasts show that demand for aviation will continue to rise in the period up to 2050. So, its growth must be sustainable – with affected communities supported and the environment protected

- Key drivers post-COVID include Advanced Air Mobility and low-level ATM evolutions (UAS Traffic Management and Urban/Regional Air Mobility), flight above FL600 (stratospheric flight) and sub-orbital space transport

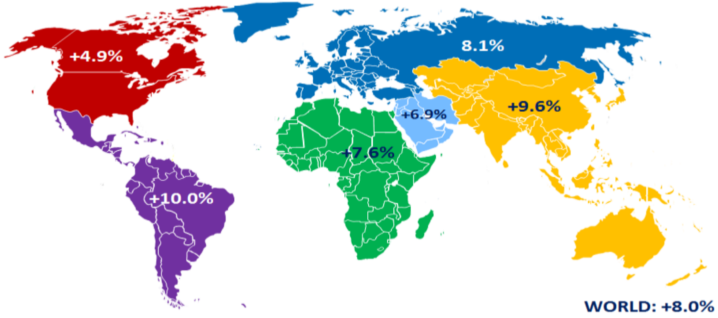
Space Industry Snapshot

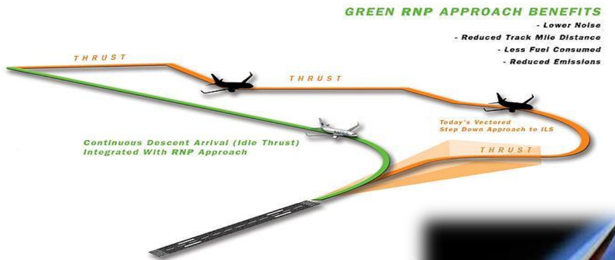
- The <u>global space economy is worth approximately 366 billion USD</u>
- One quarter attributed to non-satellite industries (government budgets and a very small portion allocated to commercial human spaceflight) and three quarters to commercial satellite and launch services.
- While satellite manufacturing and launch services account for a total of 17.4 billion USD, the satellite systems industry (space, ground and user segments) holds the majority of the market share, with a staggering 253.4 billion USD.
- The entire human spaceflight market volume accounts for a mere 1.7B.

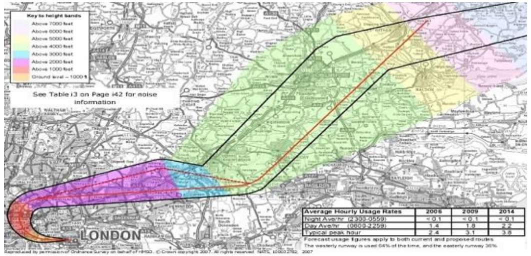


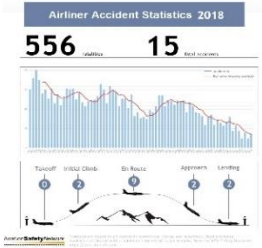
Current Challenges

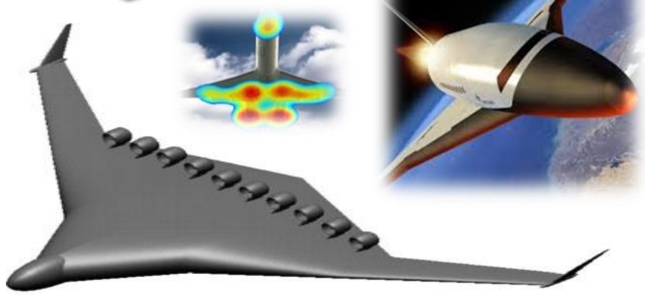
- **Enhancing <u>Safety, Efficiency and Environmental Sustainability</u> of air and space transport to support the anticipated growth of the sector**
- **Research and Innovation Areas**
  - Next Generation ATM Communications, Navigation, Surveillance (CNS) & Avionics (A) Systems (CNS+A)
  - UAS access 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



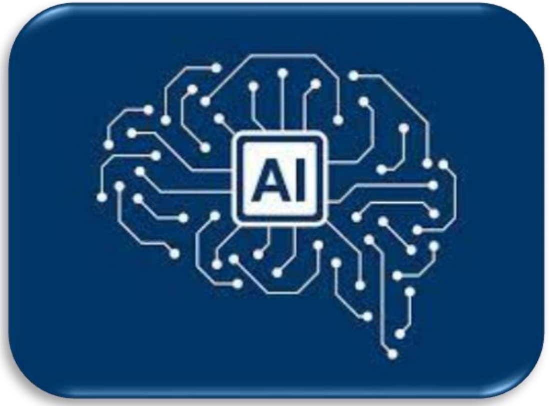








Automation and AI in Aerospace Systems



- 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

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

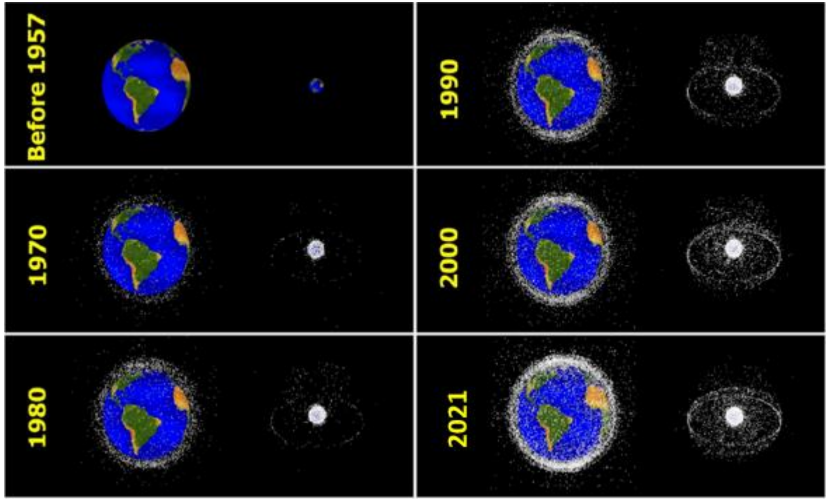
Virgin Galactic Space Ship 2
Credit: Virgin Galactic

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

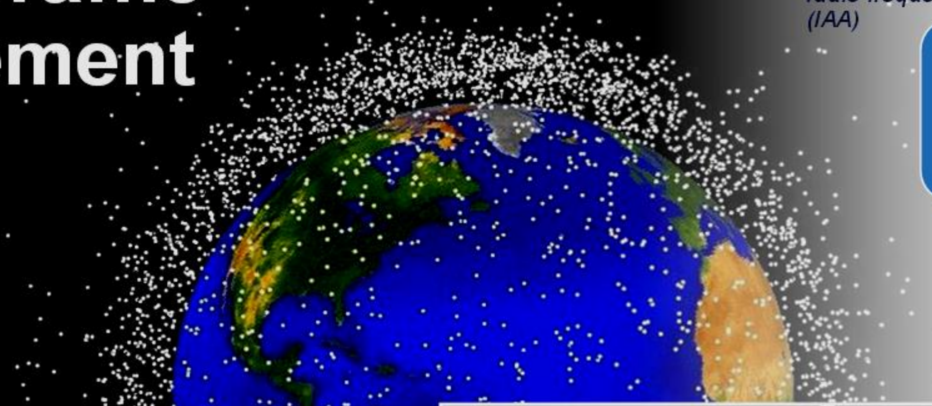
https://www.esa.int/ESA_Multimedia/Images/2019/10/Distribution_of_space_debris_around_Earth

Collision Events

IRIDIUM vs. KOSMOS collision event (2009)

PRC Anti-Satellite Missile Test (2007)

Space Traffic Management

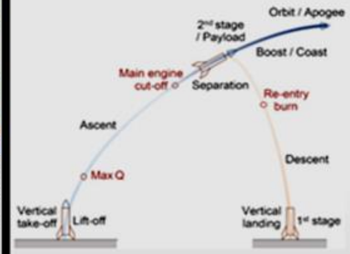


"Space traffic management is the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference." - International Academy of Astronautics (IAA)

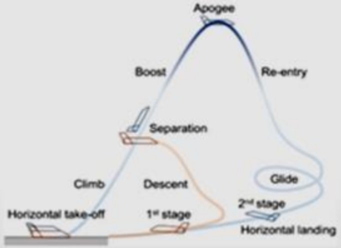
Only a few organisations have the global sensor networks and computational capability to perform this task

- 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.

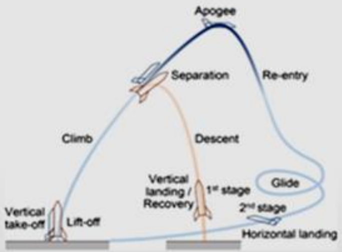
- **Vertical Take-off and Landing** (VTOL) - E.g., SpaceX Falcon 9 - Figure (a)
- **Horizontal Take-off and Landing** (HTOL) - NASP and HOTOL - Figure (b)
- **HYBRID**-Space Shuttle Orbiter and Sierra Nevada Corporation's Dream Chaser platforms - Figure (c)



VTOL platform schematic
(a)

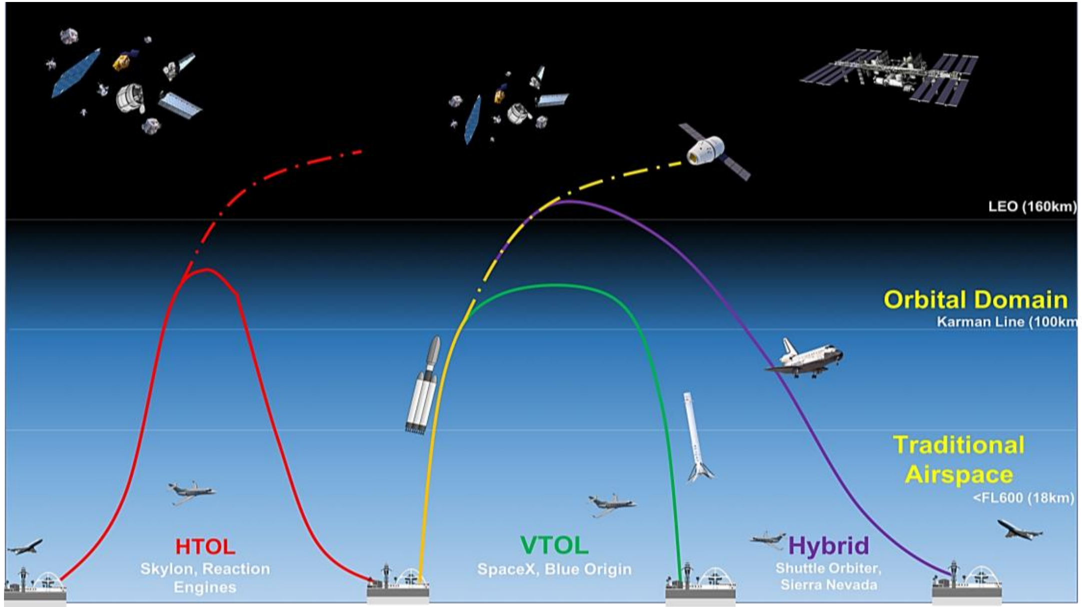


HTOL platform schematic
(b)



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
- <u>Minimized time in atmosphere</u> 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)
- <u>Promising concept for Suborbital Point-To-Point transportation</u>

Hybrid

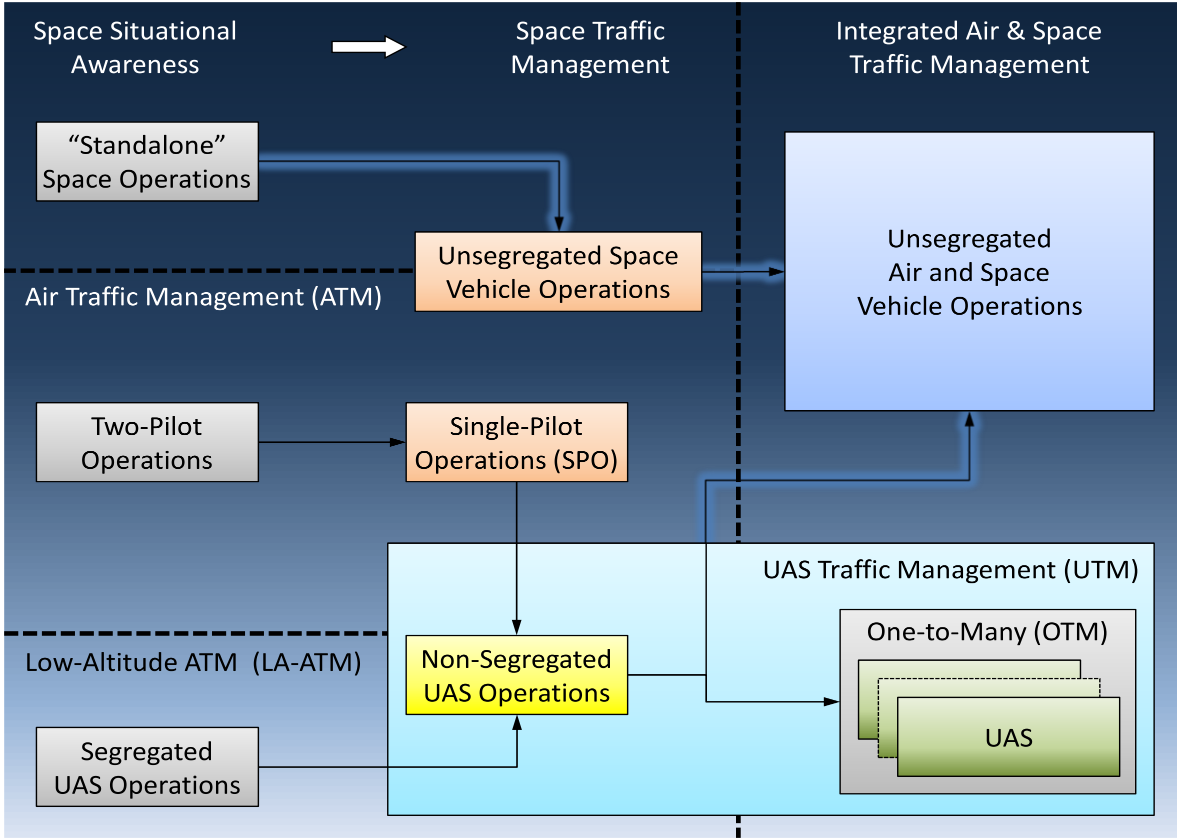
- Typically carrier aircraft taking space vehicle to launch altitude
- Gliding flight most commonly performed after re-entry
- <u>Promising for reduced environmental impact</u>

Emerging Autonomous Vehicle Concepts

New York to Shanghai in 36 min

Bangkok to Dubai in 27 min

Aerospace Systems Evolution



Space Situational Awareness

Space Traffic Management

Integrated Air & Space Traffic Management

"Standalone" Space Operations

Unsegregated Space Vehicle Operations

Unsegregated Air and Space Vehicle Operations

Air Traffic Management (ATM)

Two-Pilot Operations

Single-Pilot Operations (SPO)

UAS Traffic Management (UTM)

One-to-Many (OTM)

Low-Altitude ATM (LA-ATM)

Non-Segregated UAS Operations

UAS

Segregated UAS Operations

AESS IEEE Aerospace & Electronic Systems Society

R. Sabatini, A. Roy, E. Blasch, K. A. Kramer, G. Fasano, I. Majid, O. G. Crespillo, D. A. Brown and R. Ogan, "Avionics Systems Panel Research and Innovation Perspectives." IEEE Aerospace and Electronic Systems Magazine, Vol. 35, Issue 12, pp. 58-72, December 2020.

http://dx.doi.org/10.1109/MAES.2020.3033475

Sustainable Aviation Technology

Global Aviation Challenges

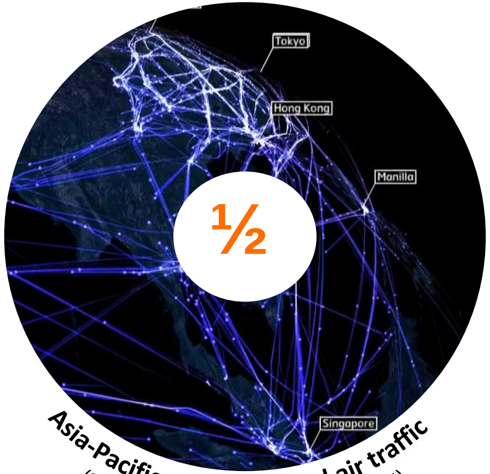
FORECAST 2050


×4

Global Air Traffic


5-10%

Aviation-induced global warming
(climate change impacts)

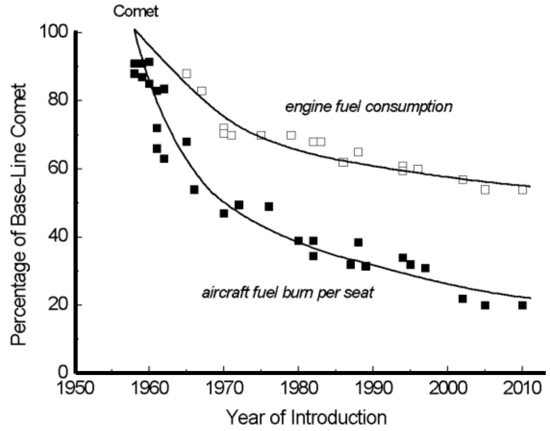


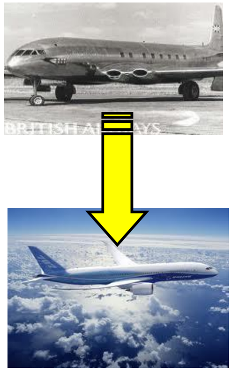
½

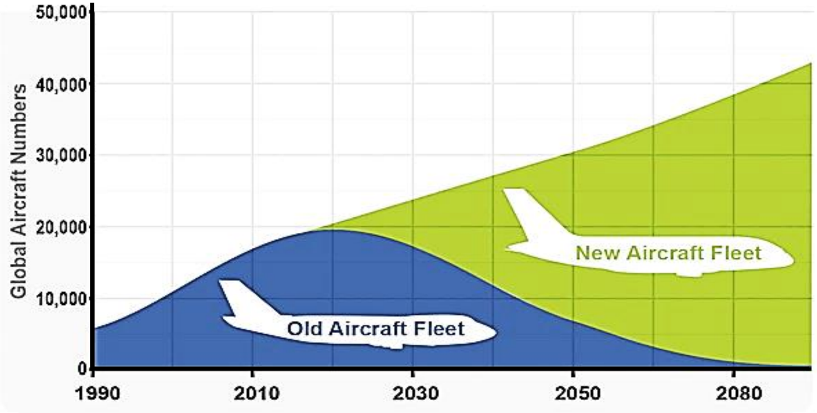
Asia-Pacific share of global air traffic
(215 new airports in China alone by 2035)

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**

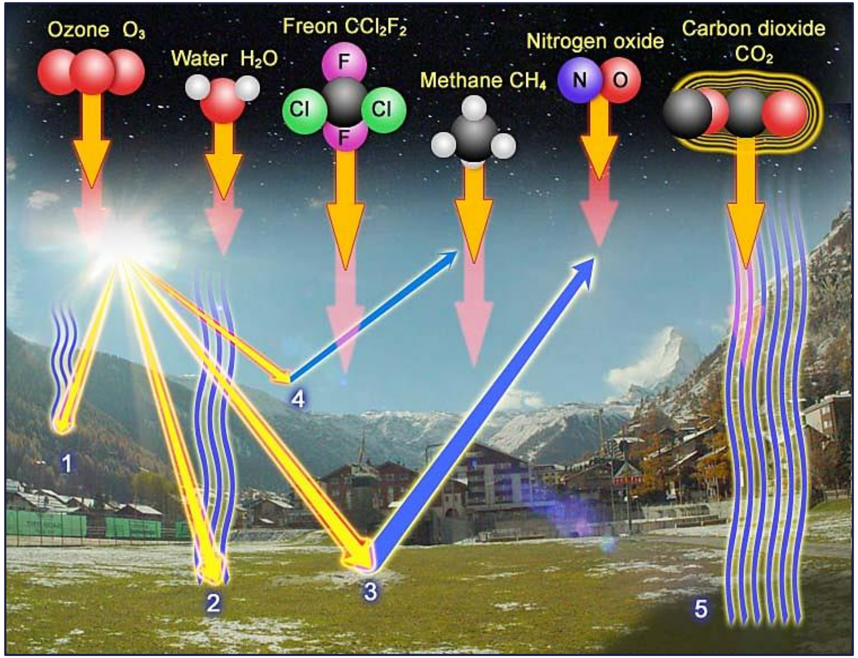


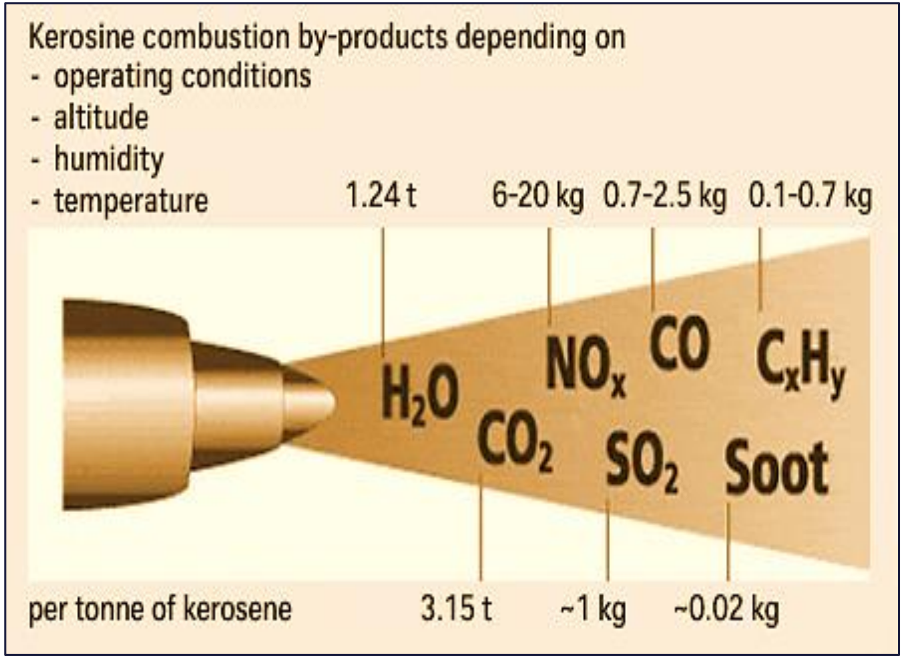




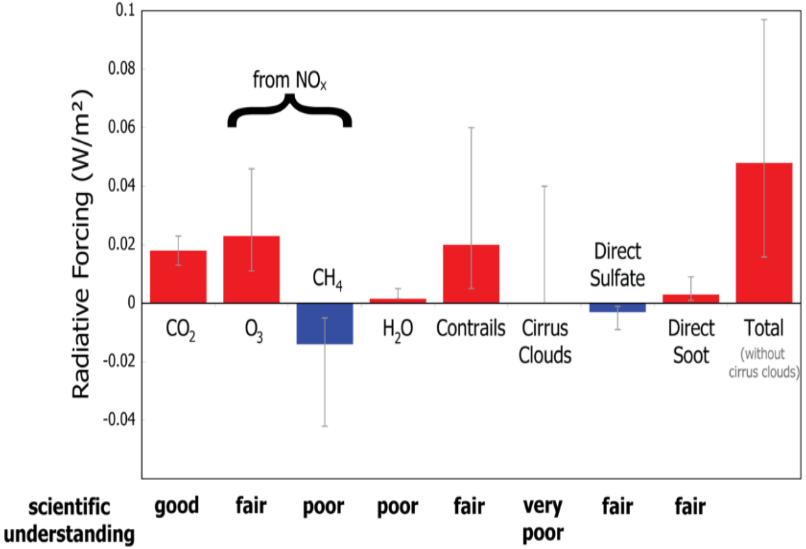
Greenhouse Pollutants and Aircraft Emissions

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

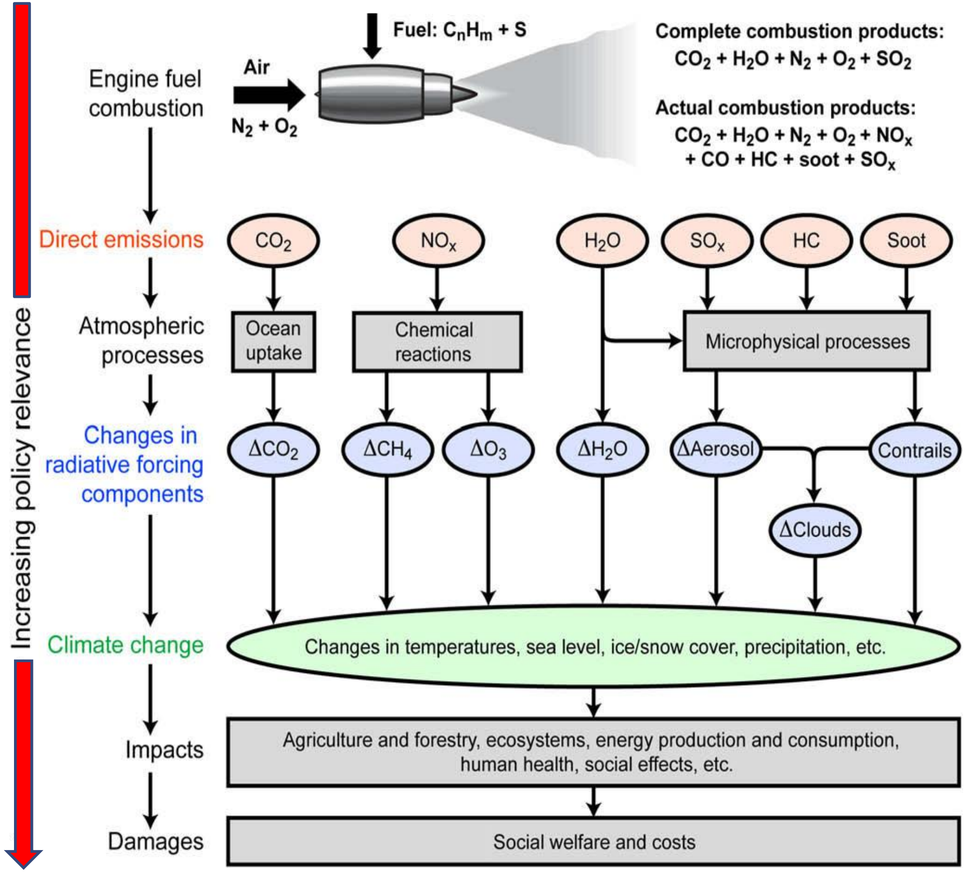




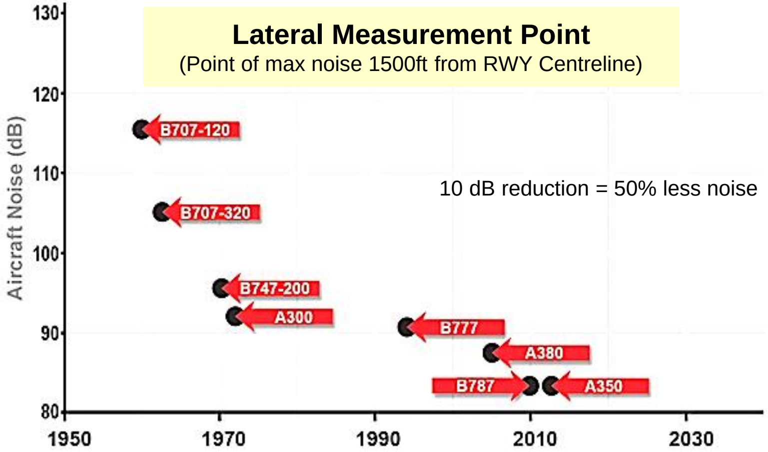
Impacts of Aviation Greenhouse Emissions



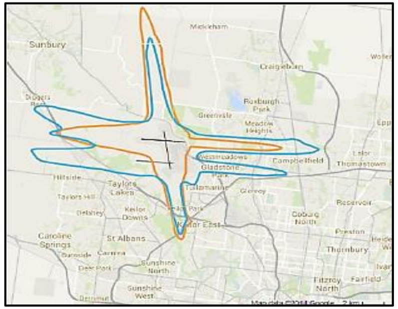
Radiative forcing (RF) is the change in the net vertical irradiance (Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system

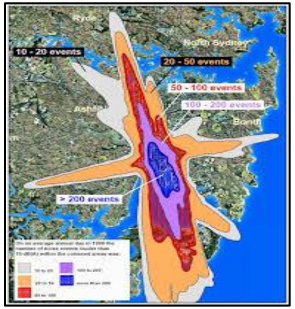


Aircraft Noise



- 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





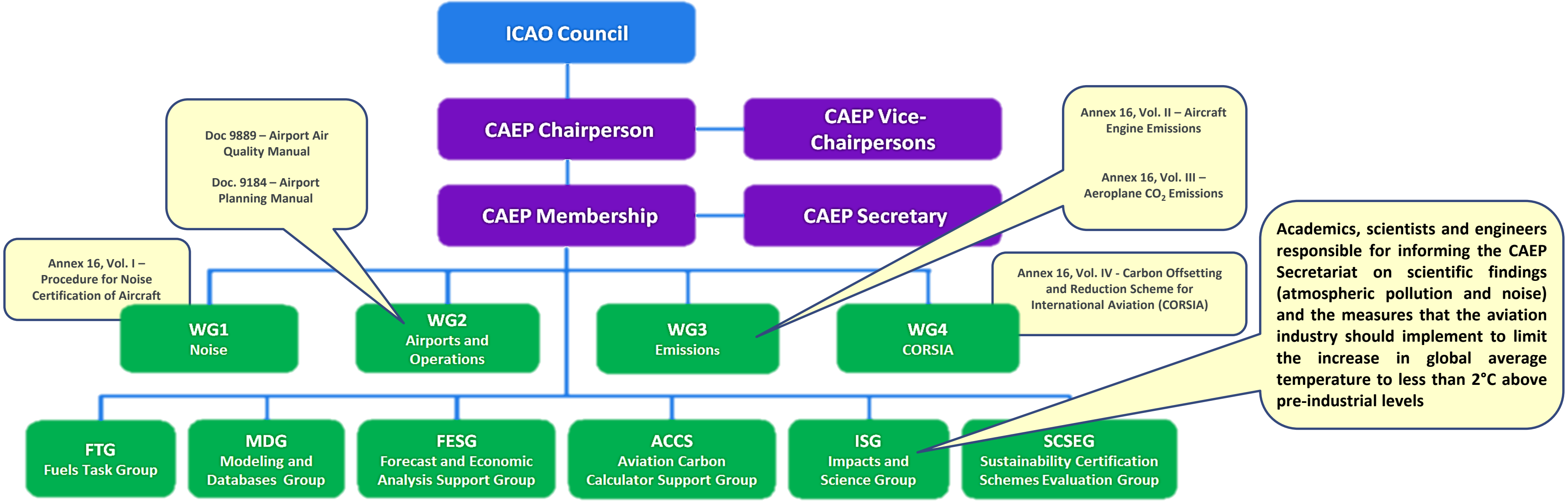
International R&I Priorities

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



ICAO Council

CAEP Chairperson

CAEP Vice-Chairpersons

CAEP Membership

CAEP Secretary

WG1
Noise

WG2
Airports and Operations

WG3
Emissions

WG4
CORSIA

FTG
Fuels Task Group

MDG
Modeling and Databases Group

FESG
Forecast and Economic Analysis Support Group

ACCS
Aviation Carbon Calculator Support Group

ISG
Impacts and Science Group

SCSEG
Sustainability Certification Schemes Evaluation Group

Annex 16, Vol. I – Procedure for Noise Certification of Aircraft

Doc 9889 – Airport Air Quality Manual

Doc. 9184 – Airport Planning Manual

Annex 16, Vol. II – Aircraft Engine Emissions

Annex 16, Vol. III – Aeroplane CO_2 Emissions

Annex 16, Vol. IV - Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

Academics, scientists and engineers responsible for informing the CAEP Secretariat on scientific findings (atmospheric pollution and noise) and the measures that the aviation industry should implement to limit the increase in global average temperature to less than 2°C above pre-industrial levels

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

	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**

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

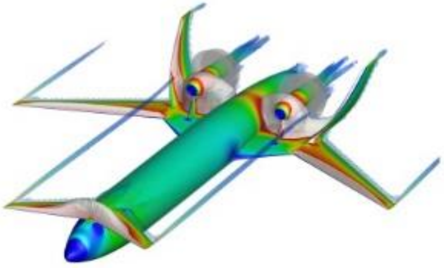
- Assessing aviation environmental impacts
- Forecasting, modelling and analysis

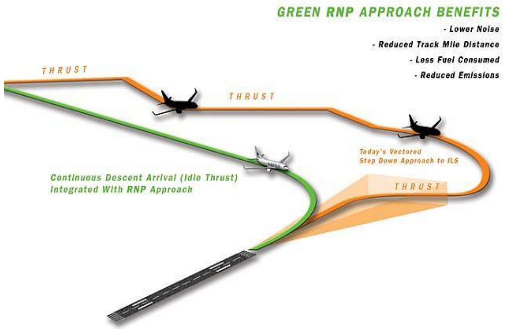
❖ Technology and Operations

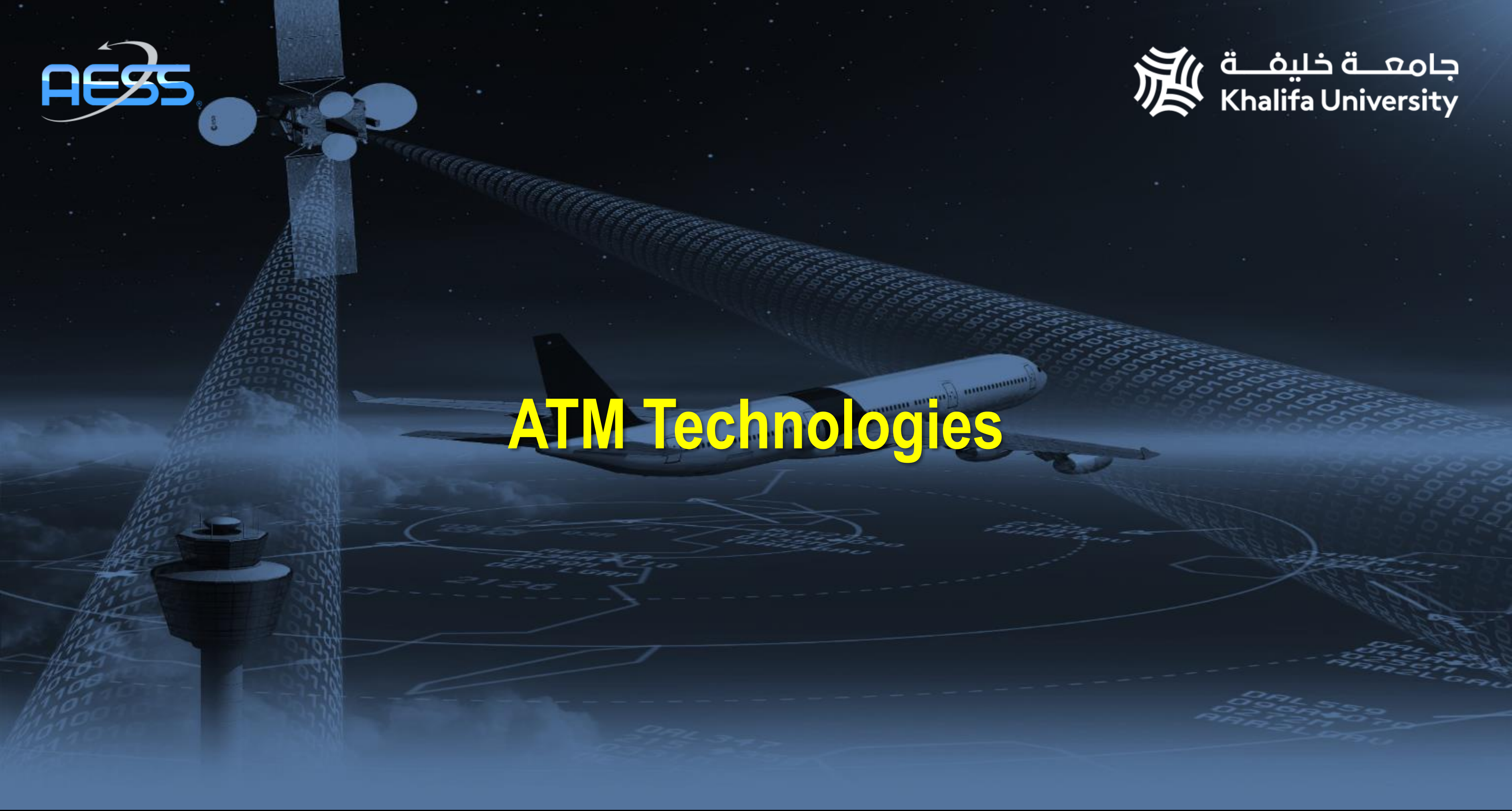
- Aircraft and propulsive technologies
- Flight operations, avionics and air traffic management
- Airport design, upgrade and operations
- Advanced manufacturing and logistics

❖ Policy and Regulations

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



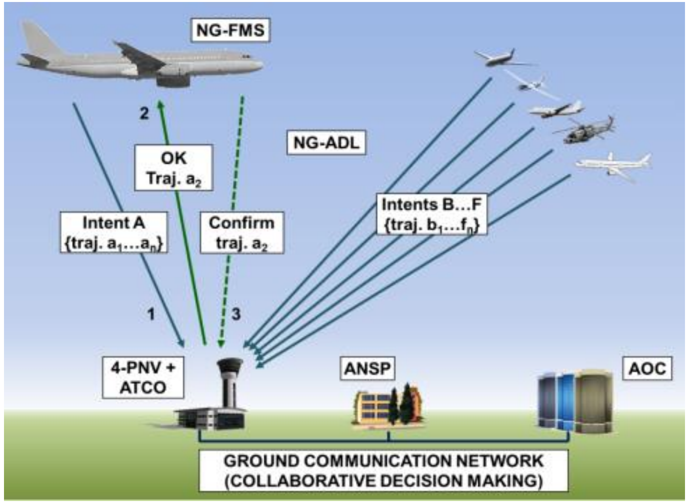


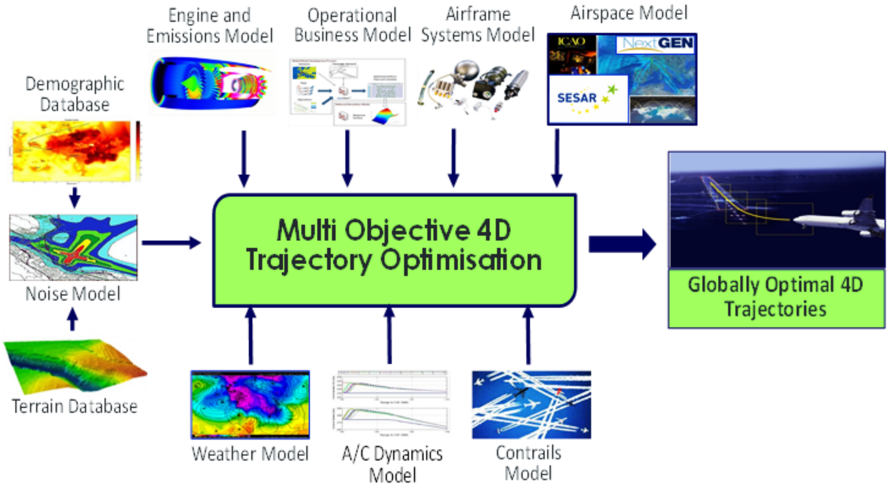


ATM Technologies

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)



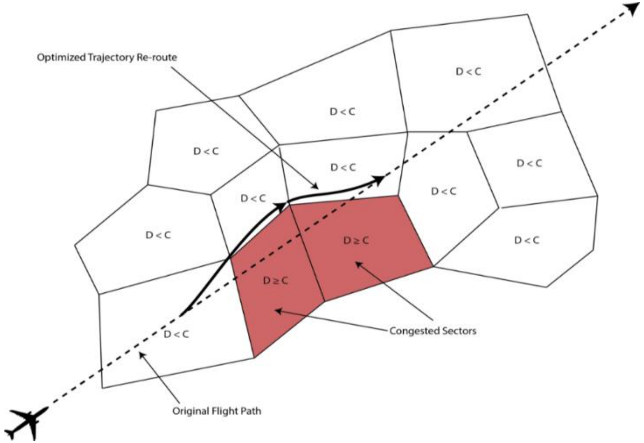


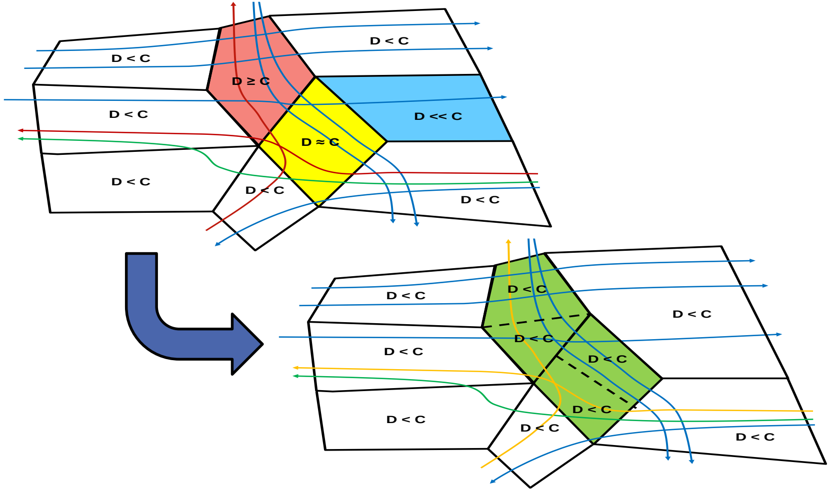
Ref.: A. Gardi, R. Sabatini, and S. Ramasamy, "Multi-objective optimisation of aircraft flight trajectories in the ATM and avionics context", Progress in Aerospace Sciences, vol. 83, pp. 1-36, 2016. DOI: 10.1016/j.paerosci.2015.11.006

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

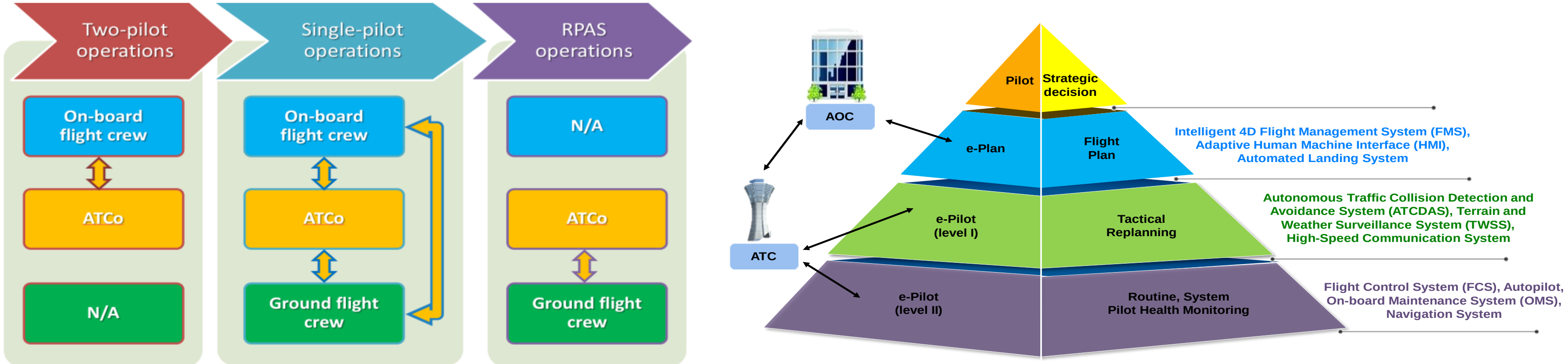




Ref.: T. Kistan, A. Gardi, R. Sabatini, S. Ramasamy, and E. Batuwangala, "An evolutionary outlook of air traffic flow management techniques", Progress in Aerospace Sciences, vol. 88, pp. 15-42, 2017. DOI: 10.1016/j.paerosci.2016.10.001

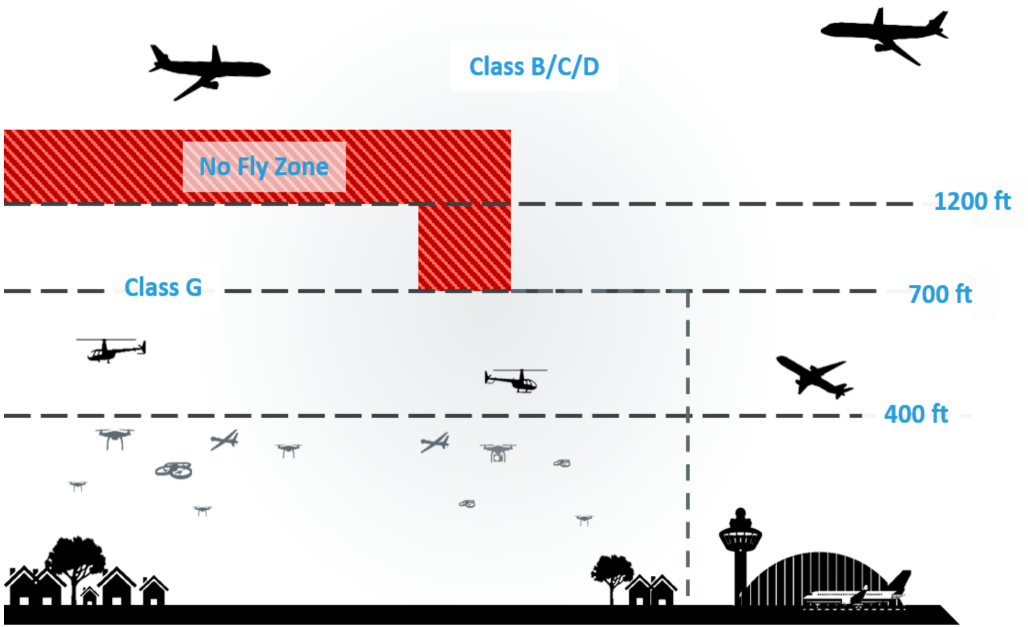
SiPO to RPAS in Conventional Airspace

- 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

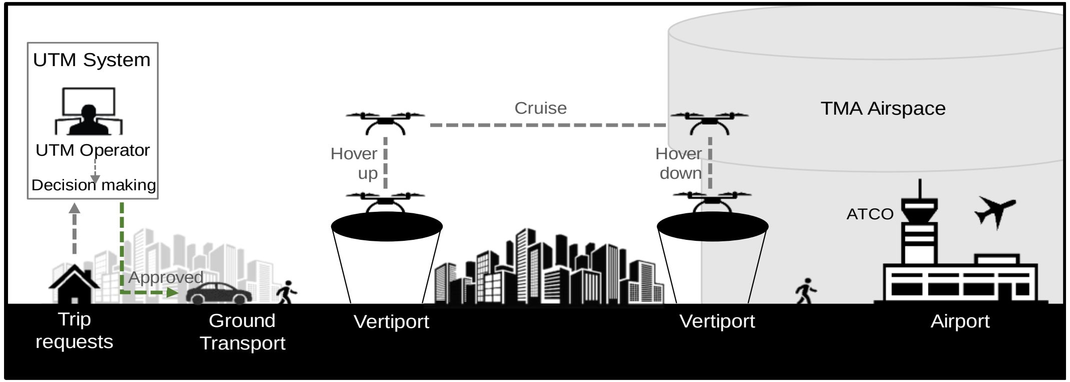
UAS Traffic Management – Key Challenges



- 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

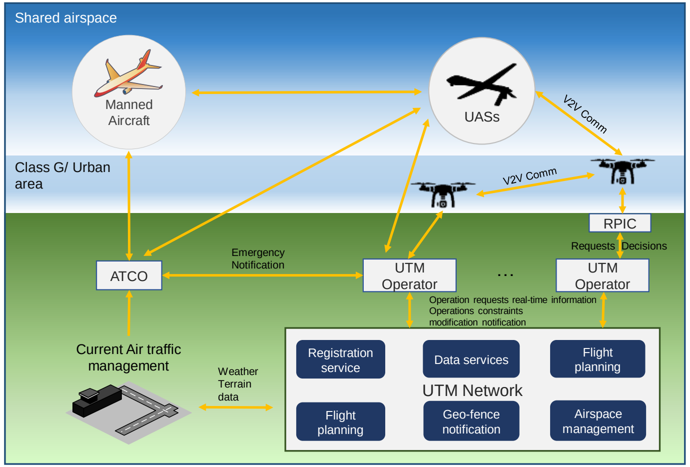
UAS Traffic Management and UAM



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)

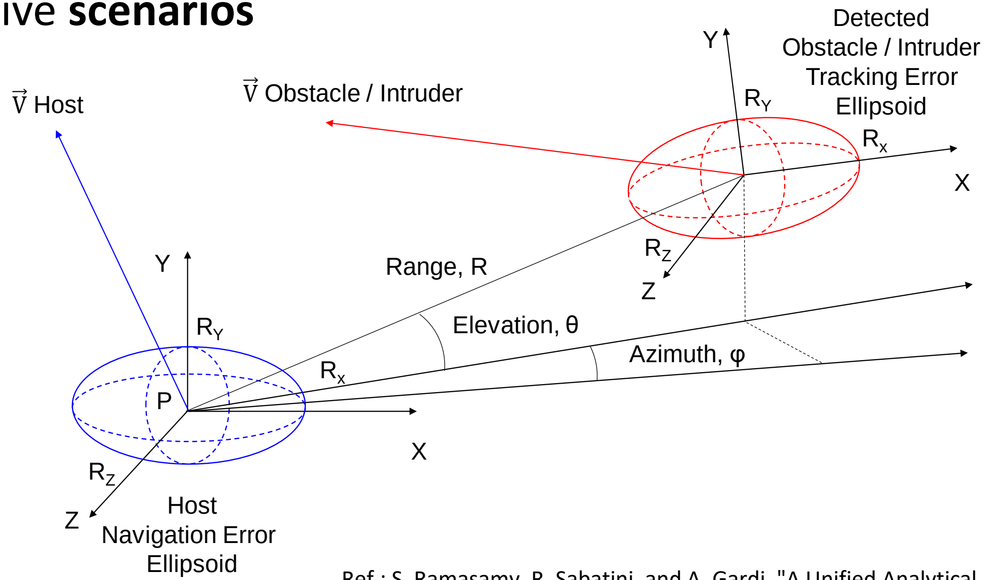
The tasks and responsibilities of humans and AI agents in UTM/AAM are yet to be defined

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

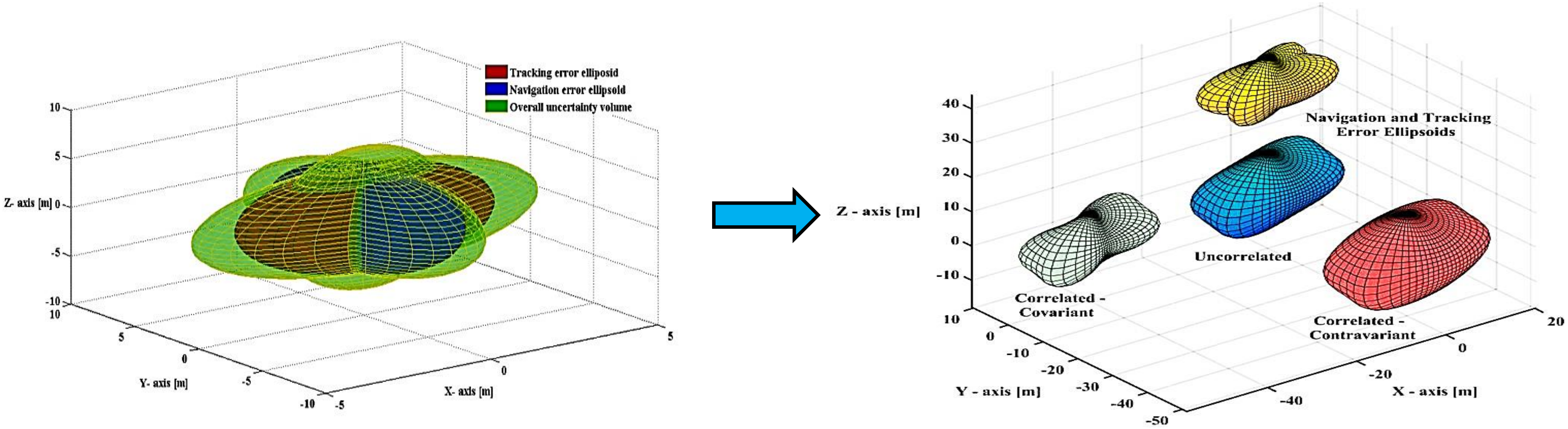
- **Avoidance volume** in the space surrounding each track is determined
- Accomplished by **continuing estimating both navigation and tracking errors** affecting the measurements (plus perturbations) and translating them to **unified range and bearing uncertainty descriptors**, which apply both to cooperative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

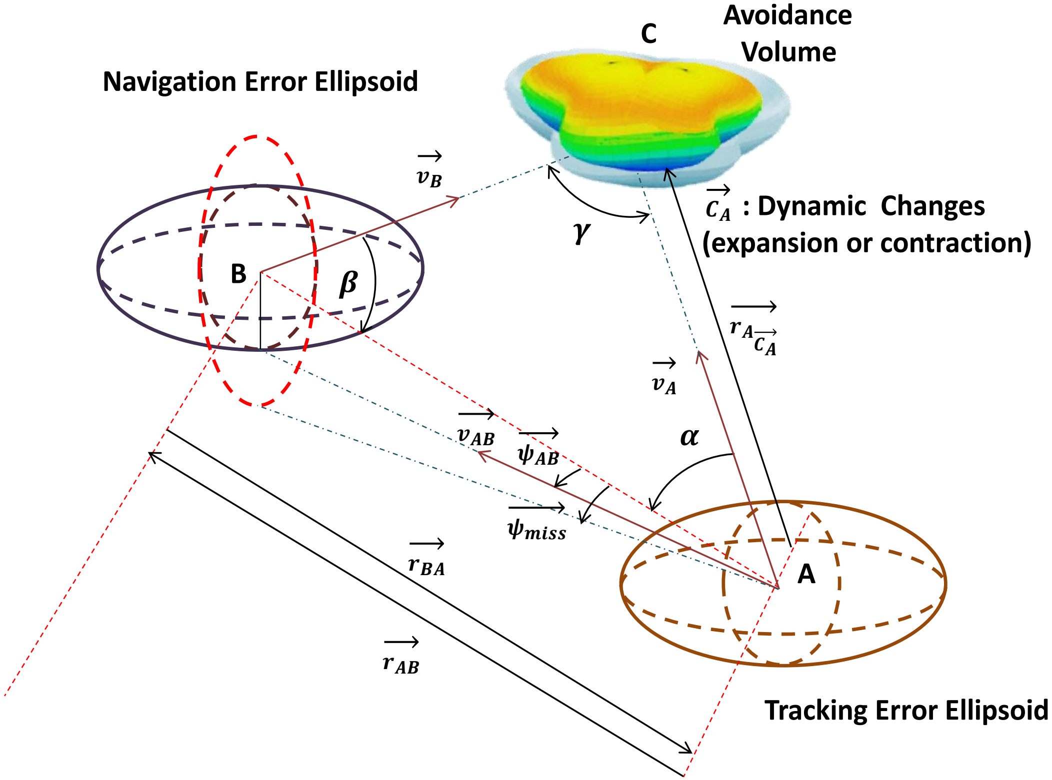
SA/CA – Error Analysis

- 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



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.

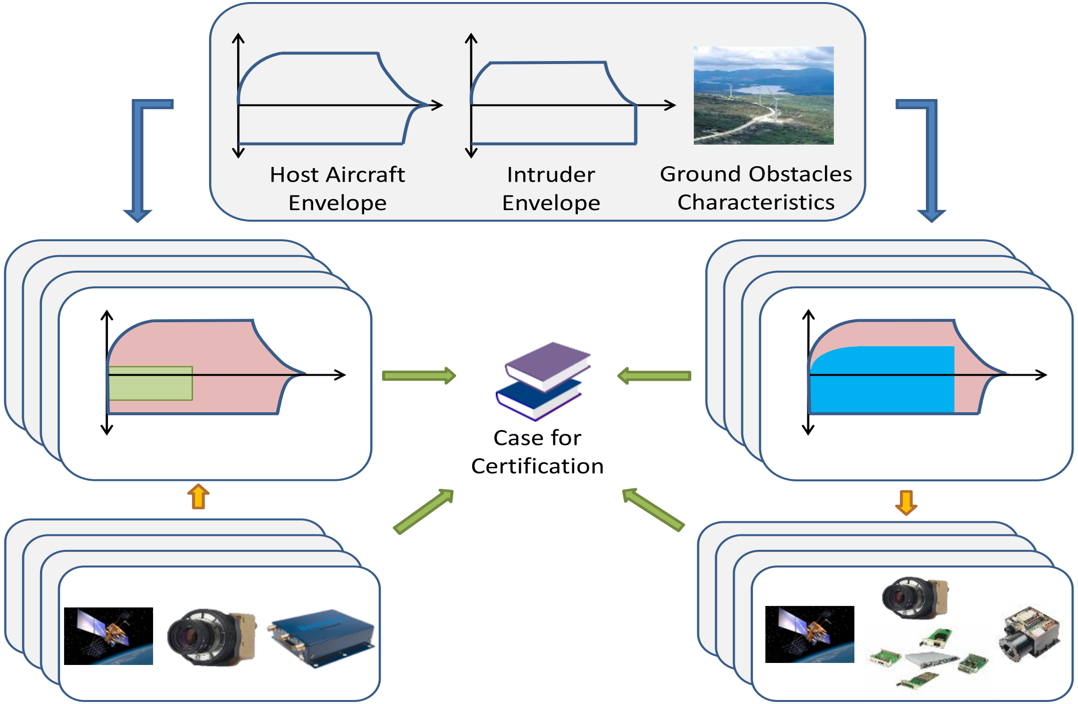
SA/CA – Relative Dynamics and Disturbances



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



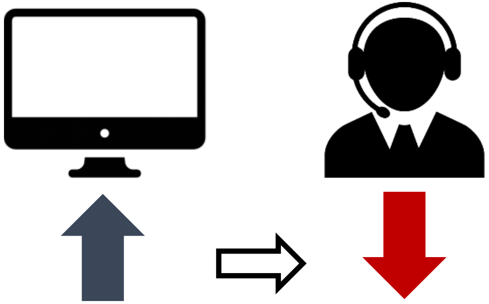
Ref.: S. Ramasamy, R. Sabatini, and A. Gardi, "A Unified Analytical Framework for Aircraft Separation Assurance and UAS Sense-and-Avoid", Journal of Intelligent & Robotic Systems, 91, pp. 735-754, 2018.

HOTL Dynamic Interactions

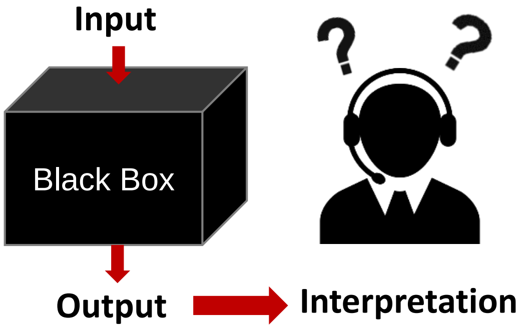
Challenges

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

- Lower cognitive capability
- Progressive deskilling
- Lower situational awareness



Human Factors



Input

Black Box

Output

Interpretation

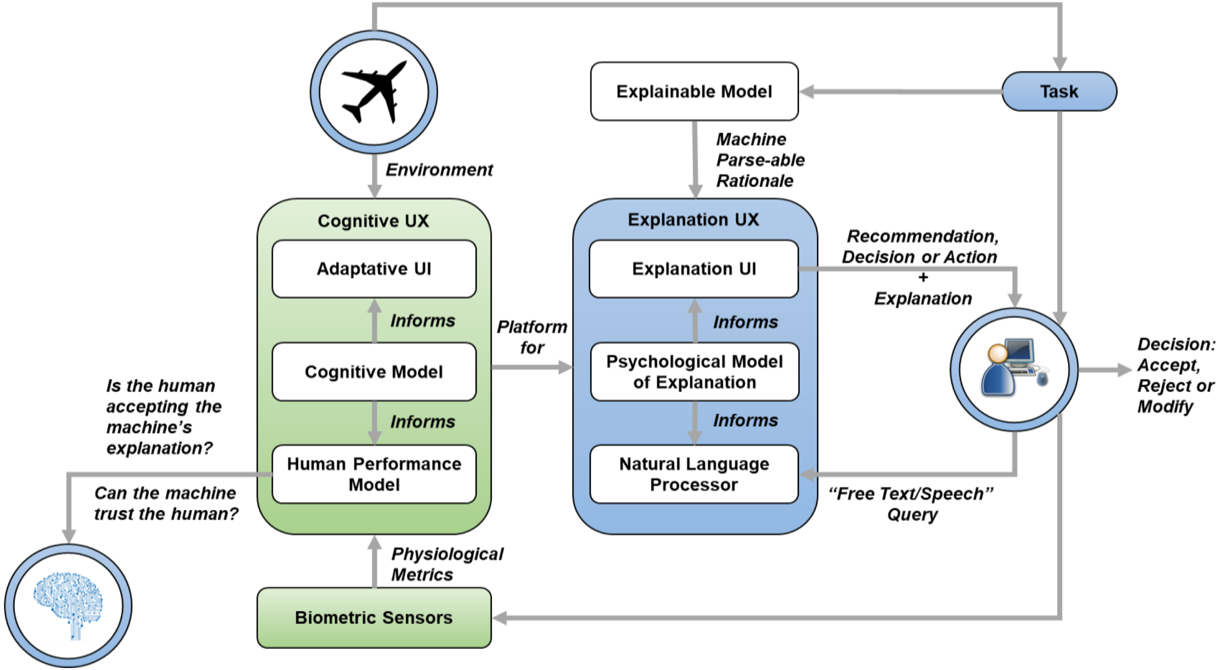
AI Explanation

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**

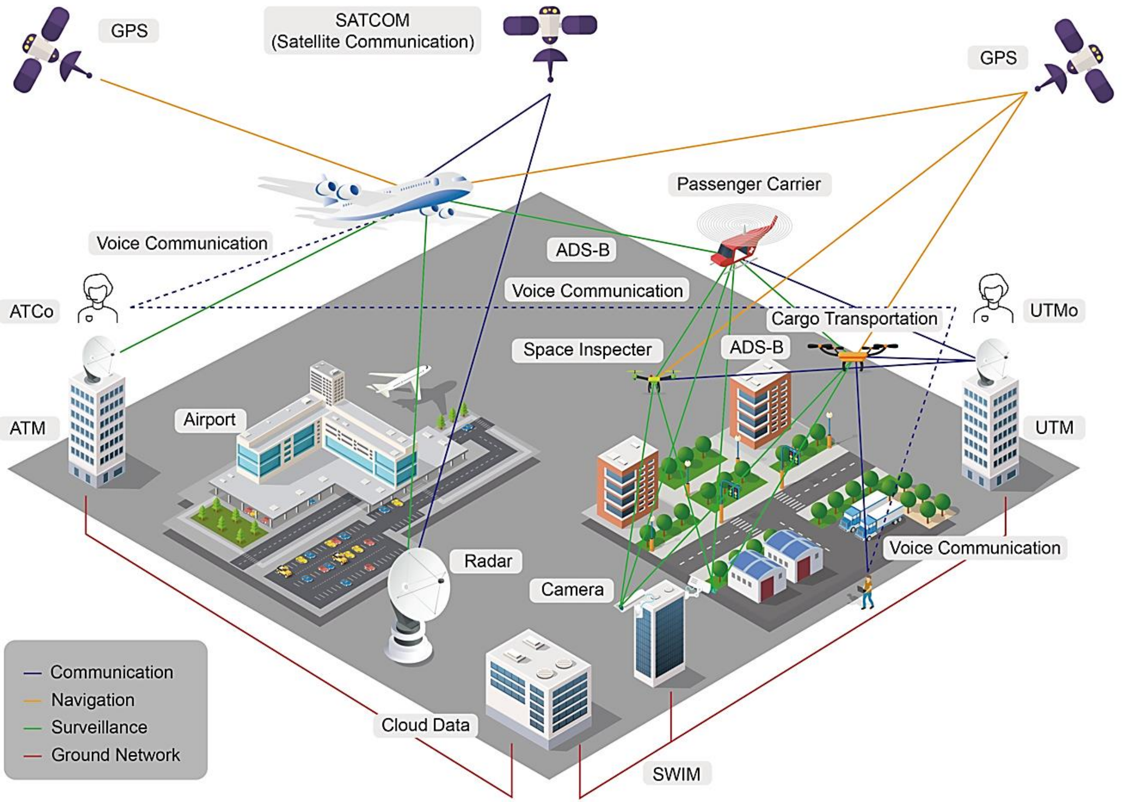
Ref: T. Kistan, A. Gardi, and R. Sabatini, "Machine Learning and Cognitive Ergonomics in Air Traffic Management: Recent Developments and Considerations for Certification," Aerospace, vol. 5, p. 103, 2018.

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

Cybersecurity Vulnerabilities in ATM and UTM

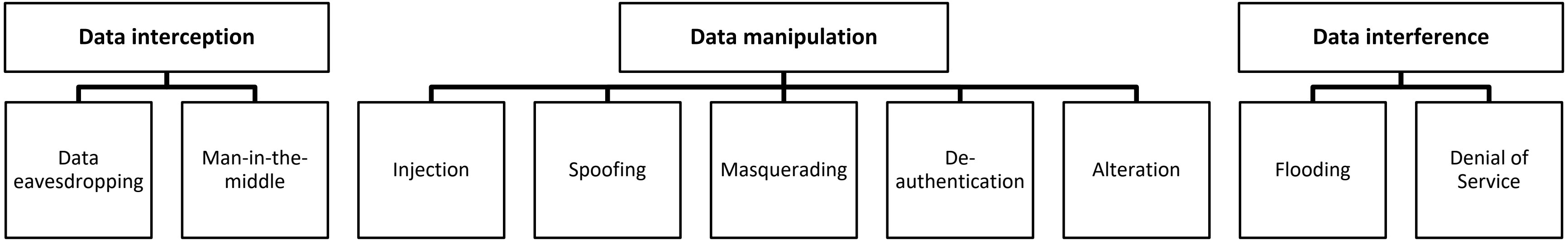
- Communication
  - HF/VHF voice, CPDLC, L-DACS, ACARS, SATCOM, Wireless communication networks
- Navigation
  - TRNAs, GNSS
- Surveillance
  - PSR, SSR, WAM, TACS, ADS-B
- Ground Network
  - SWIM



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

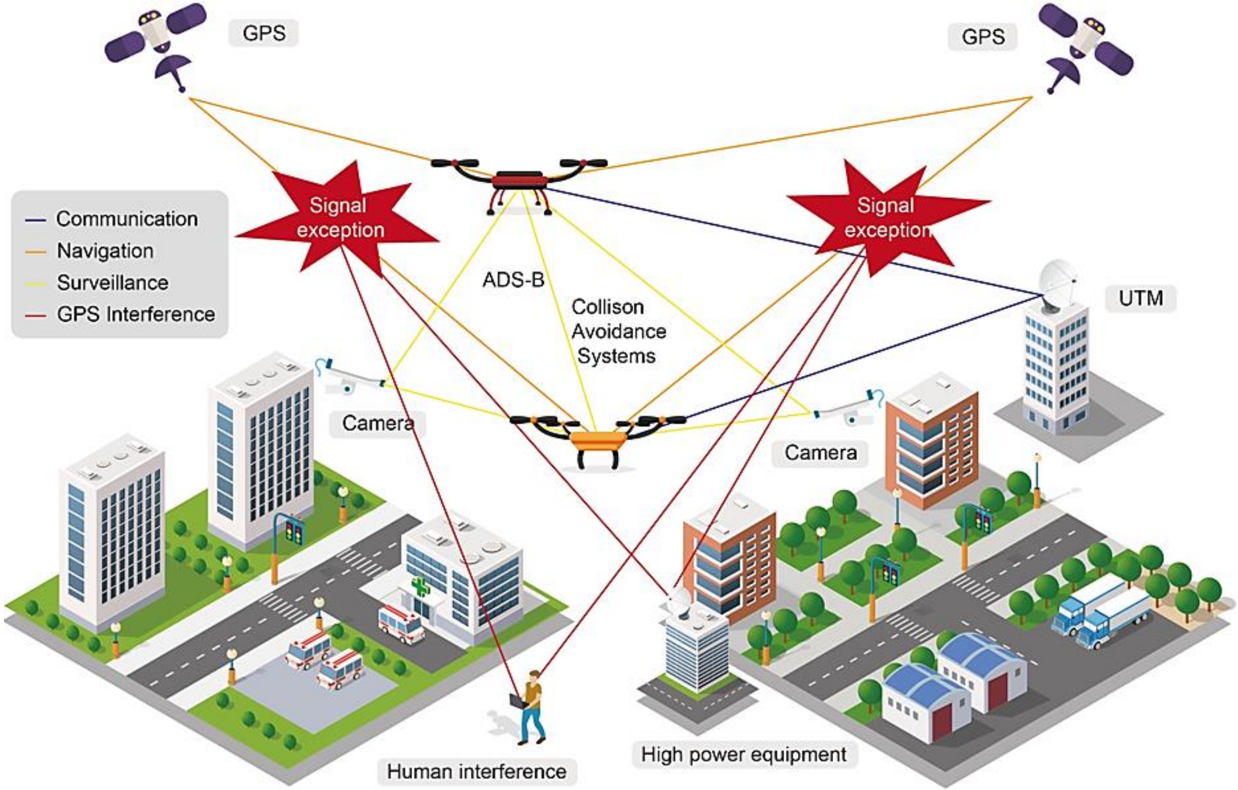


- **Data interception**
  - Data eavesdropping
  - Man-in-the-middle
- **Data manipulation**
  - Injection
  - Spoofing
  - Masquerading
  - De-authentication
  - Alteration
- **Data interference**
  - Flooding
  - Denial of Service

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.

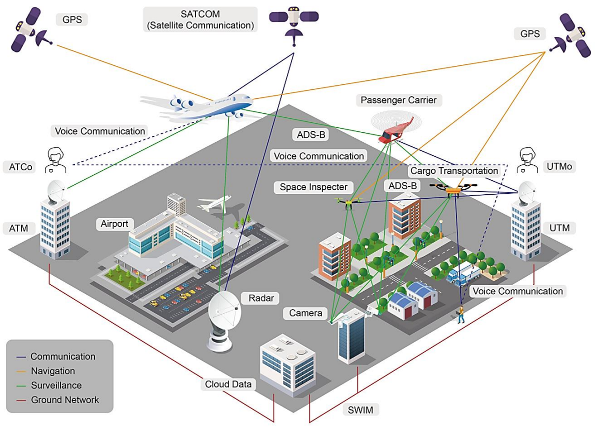
GPS and ADS-B Case Study

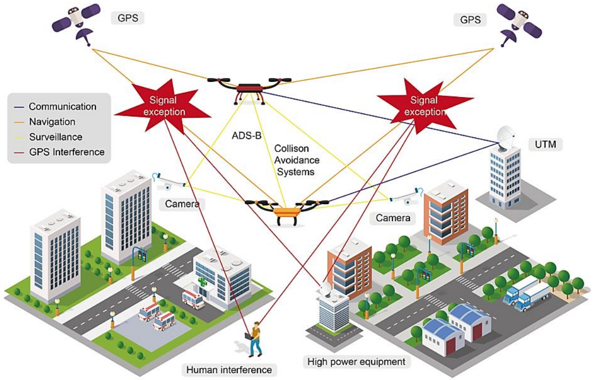


Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

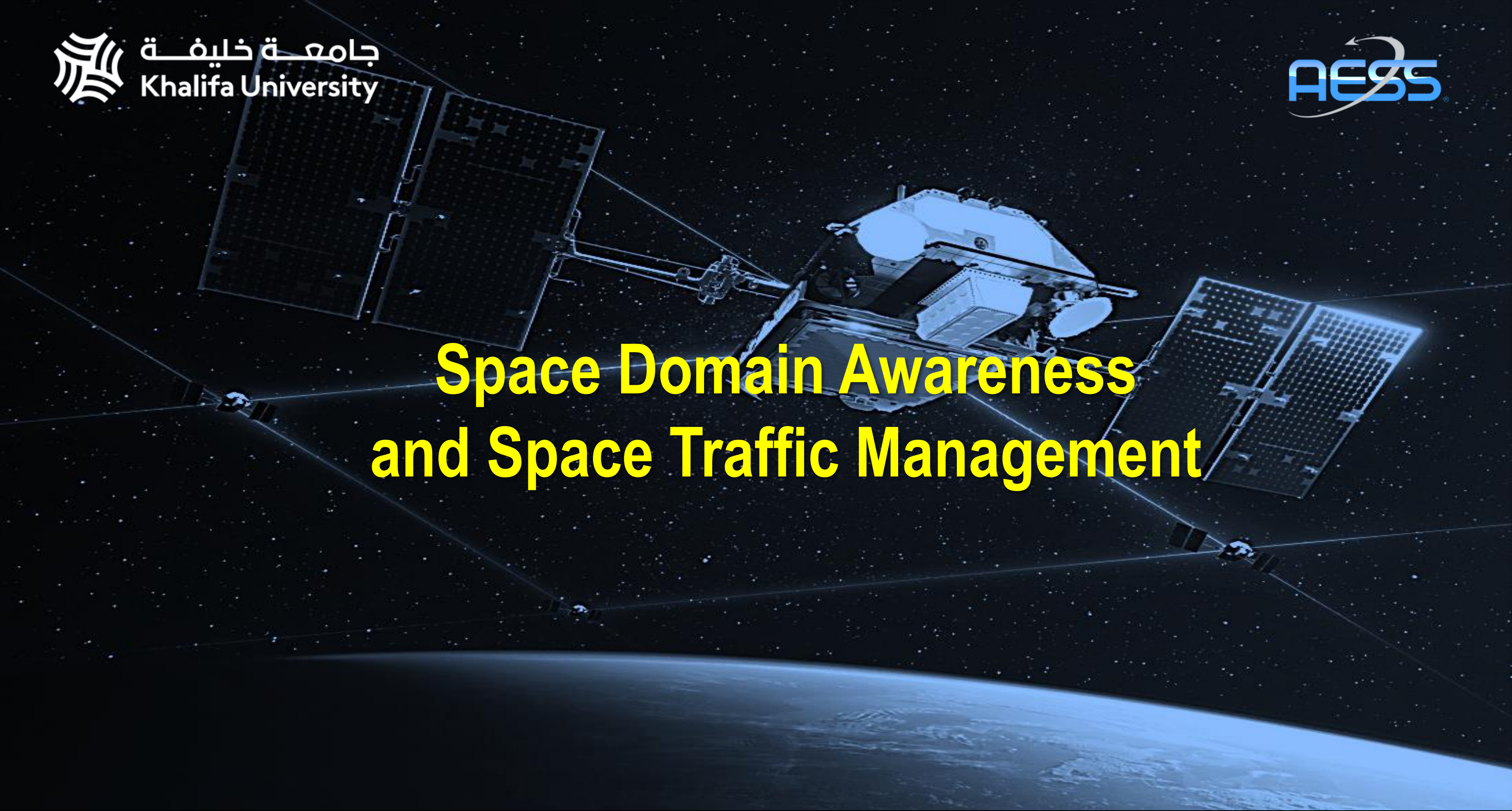
GPS Interference Case Study

- 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





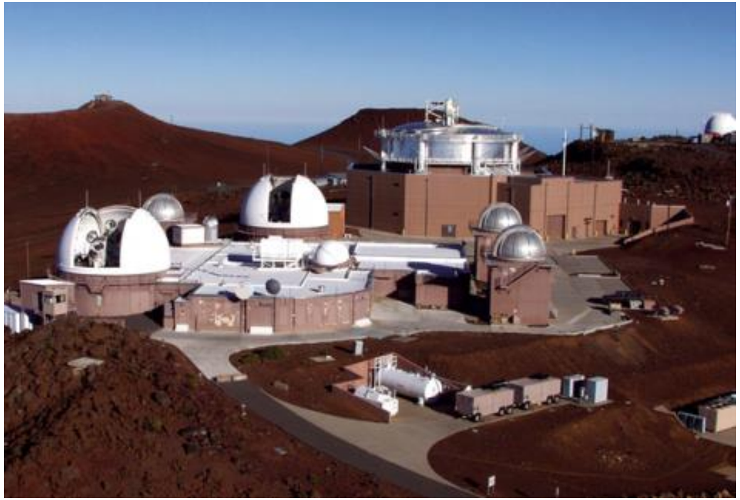
Y. Xie, A. Gardi, and R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", AIAA/IEEE Digital Avionics Systems Conference, DASC 2022.

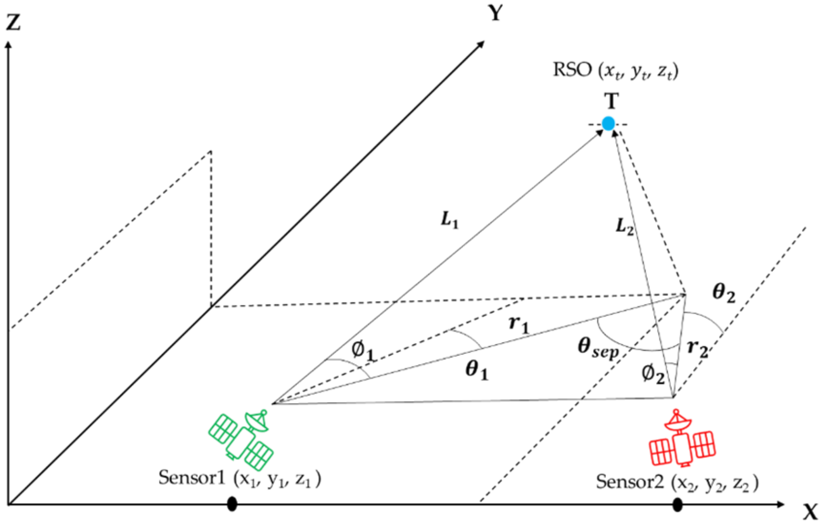


Space Domain Awareness and Space Traffic Management

Multi-Sensor RSO Tracking

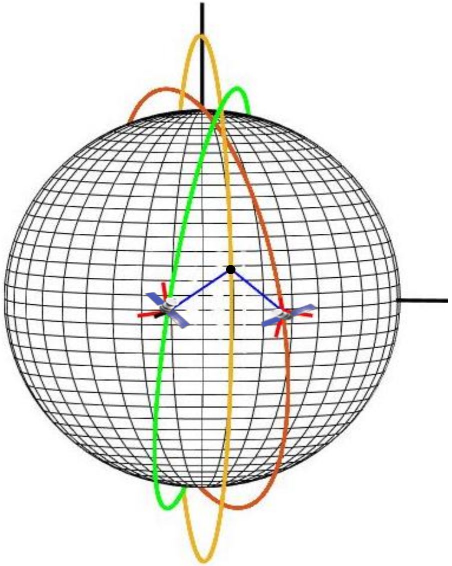
- Cooperative and Non-Cooperative Surveillance for SDA and STM
- Ground-Based Surveillance (GBS) and Space-Based Space Surveillance (SBSS)
- Tracking of <10cm RSO elusive to GBS infrastructure – STM Requires SBSS Integration



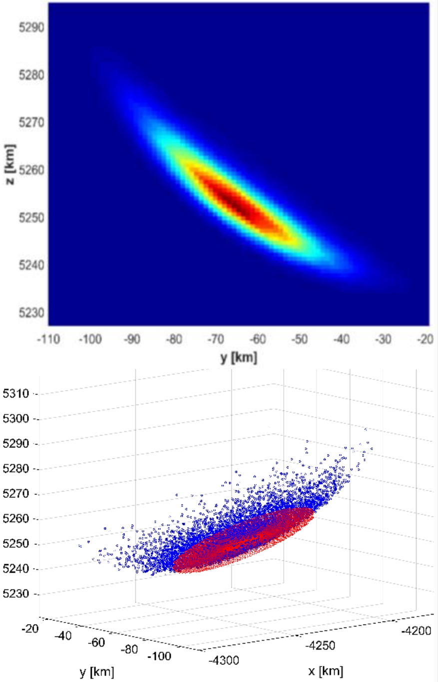


Space Traffic Management

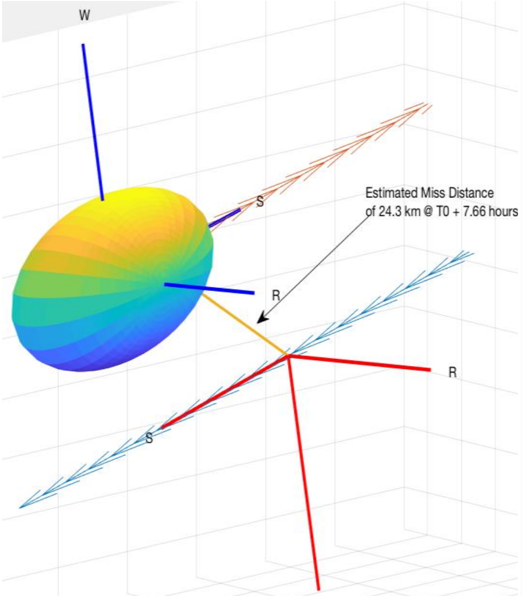
Navigation and Tracking Data Collection and Sharing (Cooperative scenario)



Quantify and Predict Tracked Space Object Uncertainty



Conjunction Analysis and Collision Avoidance

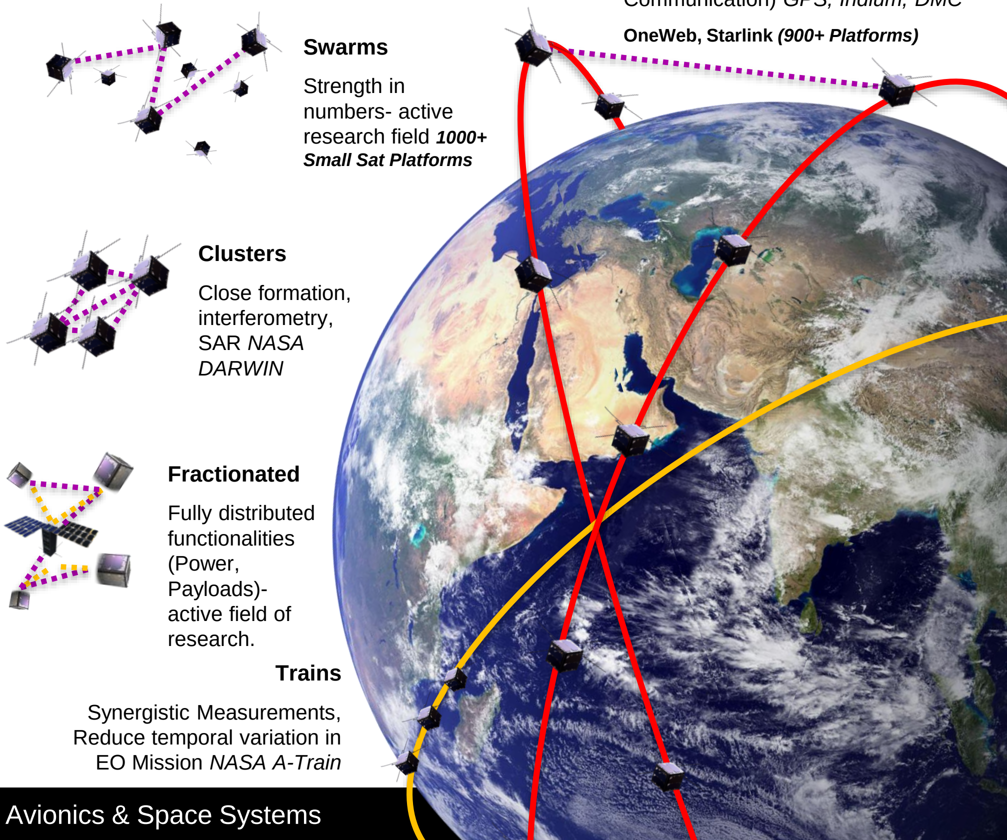


Ref.: - S. Hilton, R. Sabatini, A. Gardi, et al., "Space traffic management: towards safe and unsegregated space transport operations", Progress in Aerospace Sciences, 105, pp. 98-125, 2019.
- S. Hilton, F. Cairola, A. Gardi, R. Sabatini, N. Pongsakornsathien, and N. Ezer, "Uncertainty quantification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



Constellations

Focus on Coverage (EO & Communication) *GPS, Iridium, DMC*

OneWeb, Starlink *(900+ Platforms)*

Swarms

Strength in numbers- active research field ***1000+ Small Sat Platforms***

Clusters

Close formation, interferometry, SAR *NASA DARWIN*

Fractionated

Fully distributed functionalities (Power, Payloads)- active field of research.

Trains

Synergistic Measurements, Reduce temporal variation in EO Mission *NASA A-Train*

AI4SPACE Research Context

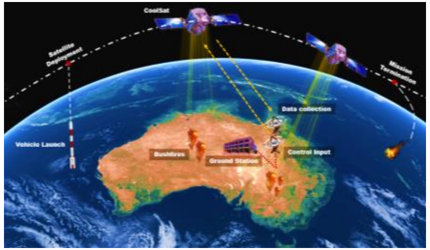
Advanced Satellite Systems, Sensors and Intelligence. Communications, connectivity and IoT technologies. Next Generation Earth Observation Services. Trusted Autonomy and Evolutionary Mission Control Centres

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

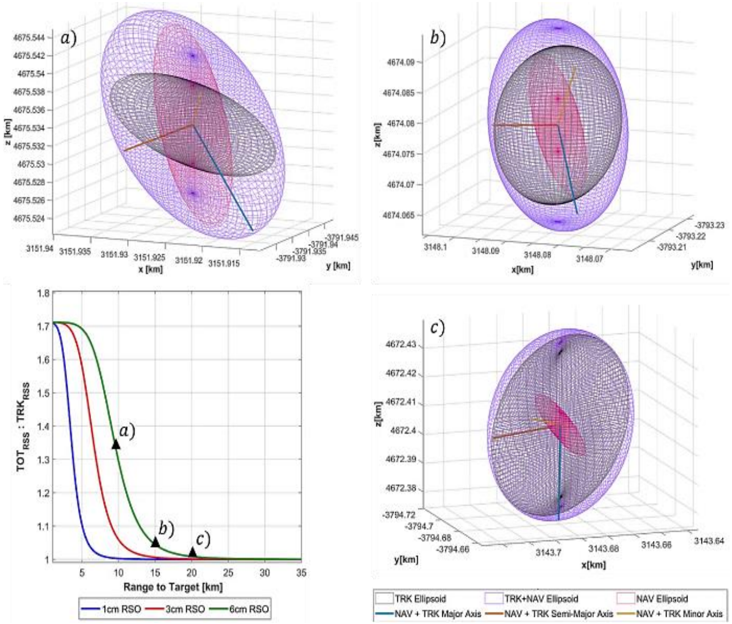
- Artificial Intelligence and Machine Learning (AI/ML) software for trusted autonomous operation
- Fault-tolerant avionics/spaceflight systems research
- Intelligent satellite health management systems
- Passive and active EO/IR sensors and systems

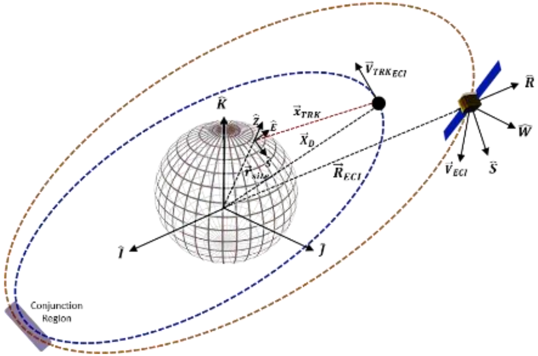


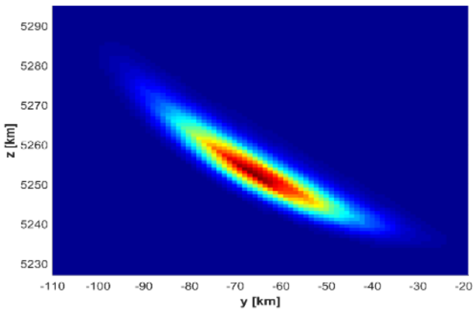
Space Domain Awareness and Traffic Management

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

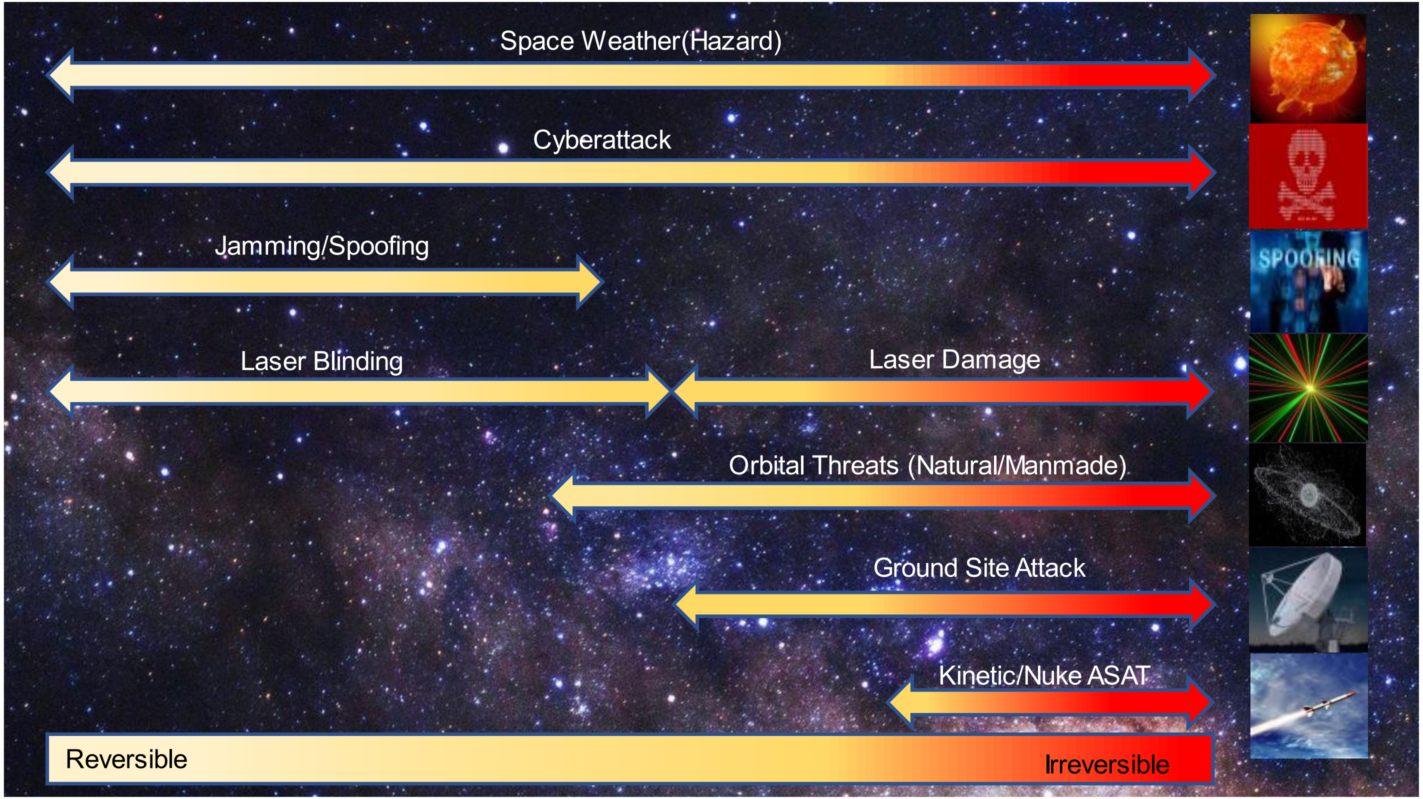






Ref.: - S. Hilton, R. Sabatini, A. Gardi, et al., "Space traffic management: towards safe and unsegregated space transport operations", Progress in Aerospace Sciences, 105, pp. 98-125, 2019.
- S. Hilton, F. Cairola, A. Gardi, R. Sabatini, N. Pongsakornsathien, and N. Ezer, "Uncertainty quantification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

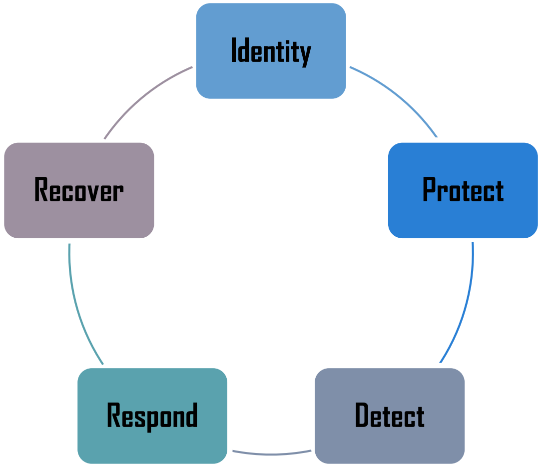
Space Cyber-Physical Threats



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

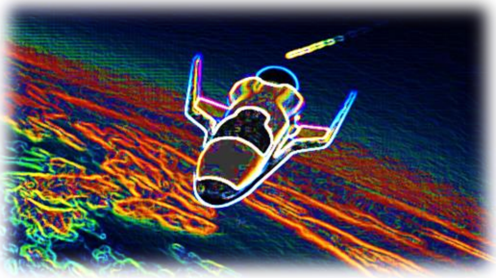
Segment	Vulnerability	Threats
Space Segment	**Payload Vulnerabilities**	Denial of Service, Hardware Backdoor, Bespoke Malware, Privilege Escalation, Hijacking, Sensor Injection.
Link Segment	**Signal Vulnerabilities**	Jamming, Eavesdropping, Spoofing, Metadata-Analysis, Command Injection, Replay Attacks,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

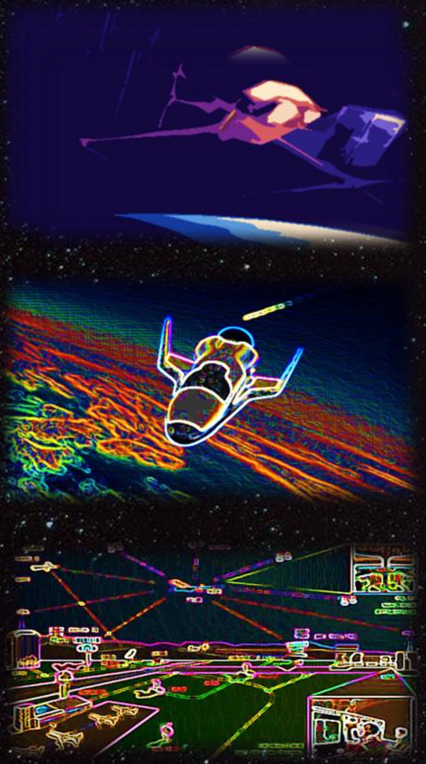


K. Thangavel, J.J. Plotnek, A. Gardi, R. Sabatini, “Understanding and Investigating Adversary Threats and Countermeasures in the Context of Space Cybersecurity”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.

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





Thank you!

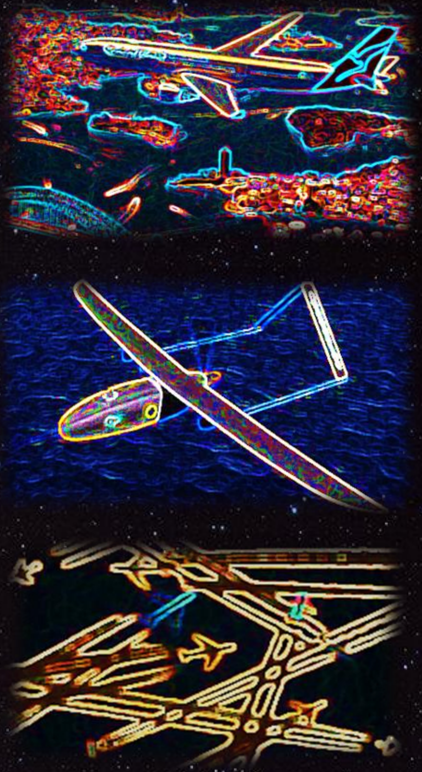
If you wish to discuss how you can contribute to the ASP activities please send me an email at: roberto.sabatini@ku.ac.ae

You can find additional information about the ASP at: https://ieee-aess.org/tech-ops/avionics-systems-panel-asp

IEEE/AIAA Digital Avionics Systems Conference: https://2022.dasconline.org/

IEEE/AIAA Integrated Communication, Navigation and Surveillance Conference: https://i-cns.org/about/

IEEE/AIAA Aerospace Conference: https://www.aeroconf.org/



References

[1] R. Sabatini, A. Roy, E. Blasch, K. A. Kramer, G. Fasano, I. Majid, O. G. Crespillo, D. A. Brown and R. Ogan, “IEEE Avionics Systems Panel Research and Innovation Perspectives.” IEEE Aerospace and Electronic Systems Magazine, Vol. 35, Issue 12, December 2020 (in press).

[2] FAA, "NextGen Implementation Plan." Federal Aviation Administration (FAA), Washington DC, USA, 2013. Available online at: https://www.faa.gov/sites/faa.gov/files/2022-06/NextGen_Implementation_Plan_2018-19%20%281%29.pdf

[3] FAA, “NAC NextGen Priorities Joint Implementation Plan CY2019–2022: 2021 Update.” Federal Aviation Administration (FAA), Washington DC, USA, 2013. Available online at: https://www.faa.gov/headquartersoffices/ang/nac-nextgen-priorities-joint-implementation-plan-cy2019-2022-2021-update

[4] 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, Issue 4, October 2018.

[5] SESAR, "European ATM Master Plan - The Roadmap for Delivering High Performing Aviation for Europe." Single European Sky ATM Research (SESAR) Joint Undertaking, Belgium, 2015.

[6] ICAO , “Improving the Performance of the Air Navigation System through the Aviation System Block Upgrades.” AN-Conf/13-WP/11. Proceeding of the 13th Air Navigation Conference. Montreal, Canada, June 2018.

[7] ICAO, “Annual Report of the Council to the Assembly.” Available online at: https://www.icao.int/annual-report-2019/Pages/the- world-of-air-transport-in-2019.aspx

[8] G. Bisignani, “Vision 2050 Report.” IATA: Singapore, 2011. Available online at: https://www.iata.org/contentassets/ bccae1c5a24e43759607a5fd8f44770b/vision-2050.pdf

[9] Royal Commission on Environmental Pollution, “The Environmental Effects of Civil Aircraft in Flight.” Royal Commission on Environmental Pollution: London, UK, 2002. Available online at: https://www.aef.org.uk/uploads/RCEP_Env__Effects_of_Aircraft__in__Flight_1.pdf

[10] IATA., “20 Year Passenger Forecast—Global Report.” IATA: Geneva, Switzerland, 2008.

[11] ICAO, “Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis.”, March 2022. Available online at: https://www.icao.int/sustainability/Documents/Covid-19/ICAO_coronavirus_Econ_Impact.pdf

[12] B. Graver, “Polishing my crystal ball: Airline traffic in 2050.” International Council on Clean Transportation (ICCT), January 2022. Available online at: https://theicct.org/global-aviation-airline-traffic-jan22/

References

[13] BryceTech, “2019 Global Space Economy at a Glance.” A BryceTech publication, 5 October 2020. Available online at: https://brycetech.com/reports

[14] F. Dolce, F. Monaci and E. Del Grande, "ItAF simulation tools in support of a suborbital flight risk assessment." ICAO/UNOOSA Space Symposium. Abu Dhabi (UAE), 15 March 2016. Available online at: https://www.icao.int/Meetings/SPACE2016/Presentations/6%20-%20F.%20Dolce%20-%20Italian%20Air%20Force.pdf

[15] IPCC, “Aviation and the Global Atmosphere.” Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.) Prepared in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer. Cambridge University Press, UK. 1999. Available online at: https://www.ipcc.ch/report/aviation-and-the-global-atmosphere-2/

[16] M. Janic. “The Sustainability of Air Transportation: a Quantitative Analysis and Assessment.” Farnham (UK): Ashgate Publishing Limited. 2007

[17] JJEI , “UAV TASK-FORCE Final Report - A Concept for European Regulations for Civil Unmanned Aerial Vehicles (UAVs).” The Joint JAA/Eurocontrol Initiative (JJEI) on UAVs. 2005. Available online at: http://easa.europa.eu/system/files/dfu/NPA_16_2005_Appendix.pdf

[18] L. Delgado, G. Gurtner, T. Bolić, and L. Castelli, "Estimating economic severity of Air Traffic Flow Management regulations," Transportation Research Part C: Emerging Technologies, vol. 125, p. 103054, 2021.

[19] C. Mannino, A. Nakkerud, and G. Sartor, "Air traffic flow management with layered workload constraints," Computers & Operations Research, vol. 127, p. 105159, 2021.

[20] A. Tabassum, R. Sabatini and A. Gardi, “Probabilistic Safety Assessment for UAS Separation Assurance and Collision Avoidance Systems.” Aerospace – Special Issue on Civil and Military Airworthiness, Vol. 6(2). February 2019.

[21] A. Gardi, S. Ramasamy, R. Sabatini and T.Kistan, “CNS+A Capabilities for the Integration of Unmanned Aircraft in Controlled Airspace.” Proceedings of IEEE International Conference on Unmanned Aircraft Systems (ICUAS 2016). Arlington, VA (USA), June 2016.

[22] O. Brown and P. Eremenko, "The Value Proposition for Fractionated Space Architectures.“ In proceedings of 2006 AIAA Space, San Jose, CA (USA), 2006.

[23] A. Golkar and I. L. I. Cruz, "The Federated Satellite Systems paradigm: Concept and business case evaluation." Acta Astronautica, vol. 111, pp. 230- 248, 2015.

[24] M. T. Burston, R. Sabatini, R. Clothier, A. Gardi and S. Ramasamy, “Reverse Engineering of a Fixed Wing Unmanned Aircraft 6-DoF Model for Navigation and Guidance Applications.” Applied Mechanics and Materials, Vol. 629, pp. 164-169, October 2014.

[25] S. Ramasamy, R. Sabatini, and A. Gardi, "A Novel Approach to Cooperative and Non-Cooperative RPAS Detect-and-Avoid.“ SAE Technical Paper 2015-01-2470, September, 2015.

References

[26] S. Ramasamy and R. Sabatini, "A Unified Approach to Cooperative and Non-Cooperative Sense-and-Avoid.“ In proceedings of 2015 International Conference on Unmanned Aircraft Systems (ICUAS '15), Denver, CO (USA), June 2015.

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

[28] M. Marino, J. Ambani, R. Watkins, and R. Sabatini, "StopRotor - A New VTOL Aircraft Configuration." In proceedings of the 17th Australian International Aerospace Congress: AIAC 2017, pp. 157-168, February 2017.

[29] Lim, Y., Gardi, A., Sabatini, R., Ramasamy, S., Kistan, T., Ezer, N., Vince, J., Bolia, R., “Avionics Human-Machine Interfaces and Interactions for Manned and Unmanned Aircraft.” Progress in Aerospace Sciences, vol. 102, pp. 1-46, 2018.

[30] Manchester Z.R., "Centimeter-Scale Spacecraft: Design, Fabrication, and Deployment." PhD Dissertation, Cornell University, 2015.

[31] Liu, J., Gardi, A., Ramasamy, S., Lim, Y., and Sabatini, R., “Cognitive Pilot-Aircraft Interface for Single-Pilot Operations.” Knowledge-Based Systems, 112, pp. 37-53, 2016.

[32] M. Marino, R. Sabatini, “Advanced Lightweight Aircraft Design Configurations for Green Operations.” Practical Responses to Climate Change (PRCC) 2014. Engineers Australia Convention 2014. Melbourne (Australia), November 2014. DOI: 10.13140/2.1.4231.8405

[33] N. Pongsakornsathien, Y. Lim, A. Gardi, S. Hilton, L. Planke, R. Sabatini, T. Kistan and N. Ezer, “Sensor Networks for Aerospace Human-Machine Systems.” Sensors, vol. 19, no. 16, 3465, 2019.

[34] N. Pongsakornsathien, A. Gardi, Y.Lim, R. Sabatini, T. Kistan, and N. Ezer, "Performance Characterisation of Wearable Cardiac Monitoring Devices for Aerospace Applications.“ In proceedings of the 2019 IEEE International Workshop on Metrology for Aerospace (MetroAeroSpace), Torino, Italy, 2019.

[35] Y. Lim, A. Gardi, N. Pongsakornsathien, R. Sabatini, N. Ezer, and T. Kistan, "Experimental Characterisation of Eye-Tracking Sensors for Adaptive Human-Machine Systems." Measurement, vol. 140, pp. 151-160, 2019.

[36] Y. Lim, T. Samreeloy, C. Chantaraviwat, N. Ezer, A. Gardi, and R. Sabatini, "Cognitive Human-Machine Interfaces and Interactions for Multi-UAV Operations.“ In proceedings of the 18th Australian International Aerospace Congress, AIAC18, Melbourne, Australia, 2019.

[37] A. Gardi, R. Sabatini and T. Kistan, "Multi-Objective 4D Trajectory Optimization for Integrated Avionics and Air Traffic Management Systems.” IEEE Transactions on Aerospace and Electronic Systems, Vol. 55, Issue 1, pp. 170-181. February 2019.

References

[38] A. Gardi, R. Sabatini and S. Ramasamy, "Real-time UAS Guidance for Continuous Curved GNSS Approaches." Journal of Intelligent and Robotic Systems. Vol. 93, Issue 1, pp. 151-162. February 2019.

[39] E. Batuwangala, T. Kistan, A. Gardi and R. Sabatini, "Certification Challenges for Next Generation Avionics and Air Traffic Management Systems." IEEE Aerospace and Electronic Systems Magazine, Vol. 33, Issue 9, pp. 44-53, September 2018.

[40] A. C. Kelly and E. J. Macie, "The A-Train: NASA's Earth Observing System (EOS) Satellites and other Earth Observation Satellites." In proceesings of the 4th IAA Symposium on Small Satellites for Earth Observation, vol. IAA-B4-1507P, 2003.

[41] ICAO, "Global Navigation Satellite System (GNSS) Manual", Doc. 9849 AN/457 – 5th Edition. The International Civil Aviation Organization (ICAO), Montreal, Canada, 2005.

[42] R. Sabatini, T. Moore, C. Hill and S. Ramasamy, "Evaluating GNSS Integrity Augmentation Techniques for UAS Sense-and-Avoid." In proceedings of 2015 International Workshop on Metrology for Aerospace (MetroAeroSpace 2015), Benevento (Italy), June 2015.

[43] L. J. Planke, A. Gardi, R. Sabatini and T. Kistan, "Online Multimodal Inference of Mental Workload for Cognitive Human Machine Systems." Computers, Vol. 10, Issue 6, No. 81, June 2022. DOI: 10.3390/computers10060081

[44] F. Cappello, S. Bijjahalli, S. Ramasamy and R. Sabatini, "Aircraft Dynamics Model Augmentation for RPAS Navigation and Guidance." Journal of Intelligent and Robotic Systems, Vol. 91, Issue 3–4, pp 709–723. September 2018.

[45] R. Kapoor, S. Ramasamy, A. Gardi, R. Van Schyndel and R. Sabatini, "Acoustic Sensors for Air and Surface Navigation Applications." Sensors, Vol. 18, Issue 2. February 2018.

[46] C. Keryk, R. Sabatini, K. Kourousis, A. Gardi and J. M. Silva, "An Innovative Structural Fatigue Monitoring Solution for General Aviation Aircraft." Journal of Aerospace Technology and Management, Vol. 10, e0518, February 2018.

[47] J. Sliwinski, A. Gardi, M. Marino and R. Sabatini, "Hybrid-Electric Propulsion Integration in Unmanned Aircraft." Energy, Vol. 140, pp. 1407–1416. December 2017.

[48] R. Sabatini, T. Moore and S. Ramasamy, "Global Navigation Satellite Systems Performance Analysis and Augmentation Strategies in Aviation." Progress in Aerospace Sciences, Vol. 95, pp. 45-98. November 2017.

[49] H.A. Muller, "The rise of intelligent cyber-physical systems", Computers, vol. 50, pp. 4837-4869, 2017.

[50] Y. Xie, A. Gardi, R. Sabatini, "Cybersecurity Trends in Low-Altitude Air Traffic Management", IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, 2022

References

[51] S. Bijjahalli, S. Ramasamy and R. Sabatini, “A Novel Vehicle-Based GNSS Integrity Augmentation System for Autonomous Airport Surface Operations.” Journal of Intelligent and Robotic Systems, Vol. 87, Issue 2, pp. 379–403. August 2017.

[52] Y. Lim, V. Bassien-Capsa, J. Liu, S. Ramasamy and R. Sabatini, “Commercial Airline Single Pilot Operations: System Design and Pathways to Certification.” IEEE Aerospace and Electronic Systems Magazine. Vol. 32, Issue 7, pp. 4-12. July 2017.

[53] R. Sabatini, “Future Aviation Research in Australia: Addressing Air Transport Safety, Efficiency and Environmental Sustainability.” International Journal of Sustainable Aviation, Vol. 3, No. 2, pp. 87 - 99, June 2017.

[54] D. Woffinden, S. Robinson, J. Williams, and Z. R. Putnam, "Linear Covariance Analysis Techniques to Generate Navigation and Sensor Requirements for the Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) Project," in AIAA Scitech 2019 Forum, 2019, p. 0662.

[55] Y. Lim, A. Gardi and R. Sabatini, “Optimal Aircraft Trajectories to Minimize the Radiative Impact of Contrails and CO2.” Energy Procedia, Volume 110, March 2017, pp. 446–452.

[56] R. Kapoor, S. Ramasamy, A. Gardi and R. Sabatini, “UAV Navigation Using Signals of Opportunity in Urban Environments: A Review.” Energy Procedia, Volume 110, March 2017, pp. 377-383.

[57] R. Sabatini, F. Cappello, S. Ramasamy, A. Gardi and R. Clothier, “An Innovative Navigation and Guidance System for Small Unmanned Aircraft using Low-Cost Sensors.” Aircraft Engineering and Aerospace Technology, Vol. 87, Issue 6, pp. 540-545. October 2015.

[58] K. Chircop, A. Gardi, D. Zammit-Mangion and R. Sabatini, "A New Computational Technique for the Generation of Optimised Aircraft Trajectories.” Nonlinear Engineering, Vol. 6, Issue 2. June 2017.

[59] 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. January 2017.

[60] ICAO, "Global Air Navigation Plan.” Doc. 9750 – 6th Edition. International Civil Aviation Organization (ICAO), Montreal, Canada, 2019. Available online at: https://www.icao.int/airnavigation/pages/ganp-resources.aspx

[61] S. Bijjahalli and R. Sabatini, “A High-Integrity and Low-Cost Navigation System for Autonomous Vehicles." IEEE Transactions on Intelligent Transportation Systems (in press). Publication expected in 2020.

References

[62] S. Lentz, M. Hornung, and W. Staudacher, "Conceptual Design of Winged Reusable Two-Stage-To-Orbit Space Transport Systems," Basic Research and Technologies for Two-Stage-To-Orbit Vehicles, pp. 9-37, 2005.

[63] J. Liu, A. Gardi, S. Ramasamy, Y. Lim and R. Sabatini, "Cognitive Pilot-Aircraft Interface for Single-Pilot Operations." Knowledge-Based Systems, Vol. 112, pp. 37–53. R. Kapoor, S. Ramasamy 1, A. Gardi, C. Bieber, L. Silverberg and R. Sabatini, "A Novel 3D Multilateration Sensor Using Distributed Ultrasonic Beacons for Indoor Navigation." Sensors, Vol. 16, No. 10, pp. 1637-1649. October 2016.

[64] V. Sharma, R. Sabatini and S. Ramasamy, "UAVs Assisted Delay Optimization in Heterogeneous Wireless Networks." IEEE Communications Letters, Vol. 20, Issue 12, pp. 2526-2529. September 2016.

[65] S. Ramasamy, R. Sabatini, A. Gardi, J. Liu, "LIDAR Obstacle Warning and Avoidance System for Unmanned Aerial Vehicle Sense-and-Avoid." Aerospace Science and Technology, Vol. 55, pp. 344–358, August 2016.

[66] Gardi, R. Sabatini, S. Ramasamy, "Multi-Objective Optimisation of Aircraft Flight Trajectories in the ATM and Avionics Context." Progress in Aerospace Sciences, Vol. 83, pp. 1-36. May 2016.

[67] R. Sabatini, M.A. Richardson, A. Gardi and S. Ramasamy, "Airborne Laser Sensors and Integrated Systems." Progress in Aerospace Sciences, Vol. 79, pp. 15-63, November 2015.

[68] Mohamed, S. Watkins, R. Clothier, M. Abdulrahim, K. Massey and R. Sabatini, "Fixed-wing MAV attitude stability in atmospheric turbulence—Part 2: Investigating biologically-inspired sensor." Progress in Aerospace Sciences, Vol. 71, pp. 1-13, November 2014.

[69] S. Ramasamy, M. Sangam, R. Sabatini and A. Gardi, "Flight Management System for Unmanned Reusable Space Vehicle Atmospheric and Re-entry Trajectory Optimisation." Applied Mechanics and Materials, Vol. 629, pp. 304-309, October 2014.

[70] L. Planke, Y. Lim, A. Gardi, R. Sabatini, T. Kistan and N. Ezer, "A Cyber-Physical-Human System for One-to-Many UAS Operations: Cognitive Load Analysis." Sensors, Vol. 20(19), 5467, September 2020.

[71] A. Mohamed, R. Clothier, S. Watkins, R. Sabatini and M. Abdulrahim, "Fixed-Wing MAV Attitude Stability in Atmospheric Turbulence PART 1: Suitability of Conventional Sensors." Progress in Aerospace Sciences. Vol. 70, pp. 69-82. July 2014.

[72] K. Ranasinghe, S. Bijjahalli, A. Gardi, R. Sabatini, "Intelligent Health and Mission Management for Multicopter UAS Integrity Assurance", IEEE/AIAA 40th Digital Avionics Systems Conference (DASC2021), San Antonio, TX, USA, October 2021.

References

[73] N. Pongsakornsathien, A. Gardi, S. Bijjahalli, R. Sabatini, T. Kistan, "A Multi-Criteria Clustering Method for UAS Traffic Management and Urban Air Mobility", IEEE/AIAA 40th Digital Avionics Systems Conference (DASC2021), San Antonio, TX, USA, October 2021.

[74] V. Vijayakumar, V. Subramaniyaswamy, J. Abawajy, and L. Yang, "Intelligent, smart and scalable cyber-physical systems", Journal of Intelligent Fuzzy Systems, vol. 36, pp. 3935-3943, 2019.

[75] J. Zhu, A. Liapis, S. Risi, R. Bidarra, and G. M. Youngblood, "Explainable AI for Designers: A Human-Centered Perspective on Mixed-Initiative Co-Creation," 2018 IEEE Conference on Computational Intelligence and Games (CIG), 2018, pp. 1-8.

[76] DARPA, Explainable Artificial Intelligence (XAI) Program Update, DARPA/I2O. November 2017. Available online: https://www.darpa.mil/attachments/XAIProgramUpdate.pdf (accessed on 19 May 2018).

[77] B. Kirwan, A. Evans, L. Donohoe, A. Kilner, T. Lamoureux, T. Atkinson, et al., "Human factors in the ATM system design life cycle", FAA/Eurocontrol ATM R&D Seminar, 1997, pp. 16-20.

[78] T. Prevot, J. Mercer, L. Martin, J. Homola, C. Cabrall, and C. Brasil, "Evaluation of high density air traffic operations with automation for separation assurance, weather avoidance and schedule conformance", 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, including the AIAA Balloon Systems Conference and 19th AIAA Lighter-Than, 2011, p. 6890.

[79] E. Sunil, J. Hoekstra, J. Ellerbroek, F. Bussink, D. Nieuwenhuisen, A. Vidosavljevic, et al., "Metropolis: Relating airspace structure and capacity for extreme traffic densities", ATM seminar 2015, 11th USA/EUROPE Air Traffic Management R&D Seminar, 2015.

[80] T.B. Sheridan and R. Parasuraman, "Human-Automation Interaction", Reviews of Human Factors and Ergonomics, vol. 1, pp. 89-129, 06/01 2005.

[81] "CPS Principles, Foundations, System Characteristics, and Complementary Skills", in In A 21st Century Cyber-Physical Systems Education, ed. National Academies Press: National Academies of Sciences Engineering and Medicine, 2016.

[82] Y. Lim, N. Premlal, A. Gardi, and R. Sabatini, "Eulerian optimal control formulation for dynamic morphing of airspace sectors." 31st Congress of the International Council of the Aeronautical Sciences (ICAS 2018), Belo Horizonte, Brazil, 2018.

References

[83] N. Pongsakornsathien, S. Bijjahalli, A. Gardi, A. Symons, Y. Xi, R. Sabatini and T. Kistan, “A Performance-based Airspace Model for Unmanned Aircraft Systems Traffic Management.” Aerospace – Special Issue on Advances in Aerospace Sciences and Technology, Vol. 7, 154, October 2020.

[84] Y. Zhu, Z. Chen, F. Pu, and J. Wang, "Development of Digital Airspace System." Strategic Study of Chinese Academy of Engineering, vol. 23, no. 3, pp. 135-143, 2021.

[85] M. Xue and A. Ishihara, "Define Minimum Safe Operational Volume for Aerial Vehicles in Upper Class E Airspace." In AIAA Aviation 2021 Forum (virtual event), 2021. 2-6 August 2021.

[86] M. Ackermann, D. Cox, R. R. Kiziah, P. Zimmer, and J. Mcgraw, "A systematic examination of ground-based and space-based approaches to optical detection and tracking of artificial satellites," 2015.

[87] N. Cai, R. Sabatini, X. Dong, M. J. Khan and Y. Yu, “Decentralized Modeling, Analysis, Control, and Application of Distributed Dynamic Systems.” Journal of Control Science and Engineering, Vol. 2016-1. December 2016.

[88] A. Zanetti, Alessandro Gardi and R. Sabatini, “Introducing Green Life Cycle Management in the Civil Aviation Industry: the State-of-the-Art and the Future.” International Journal of Sustainable Aviation, Vol. 2, Issue 4, pp. 348-380. December 2016.

[89] F. Cappello, S. Ramasamy and R. Sabatini, “A Low-Cost and High Performance Navigation System for Small RPAS Applications.” Aerospace Science and Technology, Vol. 58, pp. 529–545. November 2016.

[90] M. Hempsell and A. Bond, "SKYLON: An example of commercial launch system development," JBIS - Journal of the British Interplanetary Society, Article vol. 67, no. 11-12, pp. 434-439, 2014. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84940654339&partnerID=40&md5= 3c4e9f3a33939a392e98afe988dcc03e.

[91] T. Masson-Zwaan and S. Freeland, "Between heaven and earth: The legal challenges of human space travel," Acta Astronautica, vol. 66, no. 11, pp. 1597-1607, 2010/06/01/ 2010, doi: https://doi.org/10.1016/j.actaastro.2009. 12.015.

[92] S. Bijjahalli, R. Sabatini and A. Gardi, “GNSS Performance Modelling and Augmentation for Urban Air Mobility.” Sensors – Special Issue on Aerospace Sensors and Multisensor Systems, Vol. 19(19), 4209. September 2019.

[93] C. Insaurralde, E. Blasch, R. Sabatini, “Ontology-Based Situation Awareness for Air and Space Traffic Management”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, 2022.

References

[94] Y. Xie, A. Gardi, R. Sabatini, M. Liang, “Hybrid AI-based Dynamic Re-routing Method for Dense Low-Altitude Air Traffic Operations”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, 2022.

[95] 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, 2022.

[96] J. Muhammad, J. Silva and R. Sabatini, “A Holistic Approach to Evaluating the Effect of Safety Barriers on the Performance of Safety Reporting Systems in Aviation Organisations.” Journal of Air Transport Management, Vol. 63, pp. 95-107. August 2017.

[97] K. Ranasinghe, R. Kapoor, A. Gardi, R. Sabatini, V. Wickramanayake, D. Ludovici, "Alternative Approaches for Health Assessment of Vehicle Subsystems", 12th International Conference on Health and Usage Monitoring (HUMS21), Melbourne, Australia, November 2021.

[98] K. Thangavel, A. Gardi, S. Hilton, A. M. Afful, R. Sabatini, "Towards Multi-Domain Traffic Management", 72nd International Astronautical Congress (IAC2021), Dubai, UAE, November 2021.

[99] S. Bijjahalli, A. Gardi, N. Pongsakornsathien, R. Sabatini, "A Unified Collision Risk Model for Unmanned Aircraft Systems", IEEE/AIAA 40th Digital Avionics Systems Conference (DASC2021), San Antonio, TX, USA, October 2021.

[100] S. Bijjahalli, A. Gardi, N. Pongsakornsathien, R. Sabatini, T. Kistan, “A Unified Airspace Risk Management Framework for UAS Operations.” Drones, Vol. 6, No. 184, July 2022. DOI: 10.3390/drones6070184

[101] Lim, Y., Ramasamy, S., Gardi, A., Kistan, T., and Sabatini, R., “Cognitive Human-Machine Interfaces and Interactions for Unmanned Aircraft.” Journal of Intelligent & Robotic Systems, 91(3-4), pp. 755-774, 2018.

[102] R. Kapoor, S. Ramasamy, A. Gardi, R. Sabatini, “UAV Navigation Using Signals of Opportunity in Urban Environments: A Review.” Energy Procedia, Volume 110, March 2017, pp. 377-383. DOI: 10.1016/j.egypro.2017.03.156

[103] N. Pongsakornsathien, A. Gardi, Y. Lim, R. Sabatini, T. Kistan, “Wearable Cardiorespiratory Sensors for Aerospace Applications.” Sensors, Vol. 22, No. 4673, June 2022.

[104] E. Lagona, A. Gardi, A. M. Afful, S. Hilton, R. Sabatini, “Autonomous Trajectory Optimisation for Intelligent Satellite Systems Operations and Space Traffic Management.” Acta Astronautica, Vol. 194, pp. 185-201, May 2022.

[105] M. Burston, K. Ranasinghe, A. Gardi, V. Parezanovic, R. Ajaj, R. Sabatini, “Design Principles and Digital Control of Advanced Distributed Propulsion Systems.” Energy, Vol. 241, No. 122788, February 2022.

References

[106] C.H. Flemming and N.G. Leveson, “Including Safety during Early Development Phases of Future Air Traffic Management Concepts.” Proceedings of the 11th USA/Europe Air Traffic Management Research and Development Seminar (2015). Available online at: http://sunnyday.mit.edu/papers/ATM-2015.pdf

[107] A. Gardi, R. Sabatini, S. Ramasamy, M. Marino, T. Kistan, "Automated ATM System Enabling 4DT-Based Operations.” SAE AeroTech Congress 2015, Seattle, WA (USA), Technical Paper 2015-01-2539, September 2015. DOI: 10.4271/2015-01-2539

[108] J. Gentry, “Introduction to Higher Airspace Operations.” MITRE Technical Papers. The MITRE Corporation - Center for Advanced Aviation System Development, 2021. Available online at: https://www.mitre.org/publications/technical-papers/introduction-to-higher-airspace-operations

[109] Y. Xie, N. Pongsakornsathien, A. Gardi and R. Sabatini, “Explanation of Machine Learning Solutions in Air Traffic Management.” Aerospace, Vol. 8, No. 224, August 2022.

[110] 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, Vol. 36, No. 4, pp. 5-6, April 2022

[111] Y. Lim, N. Ponsarkornsathien, A. Gardi, R. Sabatini, T. Kistan, N. Ezer and D. Bursch, “Adaptive Human-Robot Interactions for Multi-Unmanned Aircraft Systems Operations.” Robotics, Vol. 10(1), 12, January 2022

[112] T. C. Papavramides and P. Aupee, "Achieving sustainable performance in natural monopolies - the role of strategic planning in the European air navigation services," in 2004 IEEE International Engineering Management Conference (IEEE Cat. No.04CH37574), 18-21 October 2004.

[113] K. Ranasinghe, R. Sabatini, A. Gardi, S. Bijjahalli, R. Kapoor, T. Fahey and K. Thangavel, “Advances in Integrated System Health Management for Safety-Critical and Mission-Critical Aerospace Applications.” Progress in Aerospace Sciences, Vol. 128, No. 758, January 2022.

[114] S. Bijjahalli, A. Gardi and R. Sabatini, “Advances in Intelligent and Autonomous Navigation Systems for small UAS.” Progress in Aerospace Sciences. Vol. 115, May 2020.

[115] Y. Lim, A. Gardi, R. Sabatini, K. Ranasinghe, N. Ezer, K. Rodgers and D. Salluce, “Optimal Energy-based 4D Guidance and Control for Terminal Descent Operations.” Aerospace Science and Technology. Vol. 95, 105436, December 2019.

[116] S. Hilton, F. Cairola, A. Gardi, R. Sabatini, N. Pongsakornsathien and N. Ezer, “Uncertainty Quantification for Space Situational Awareness and Traffic Management.” Sensors, Vol. 19(20), 4361. October 2019.

References

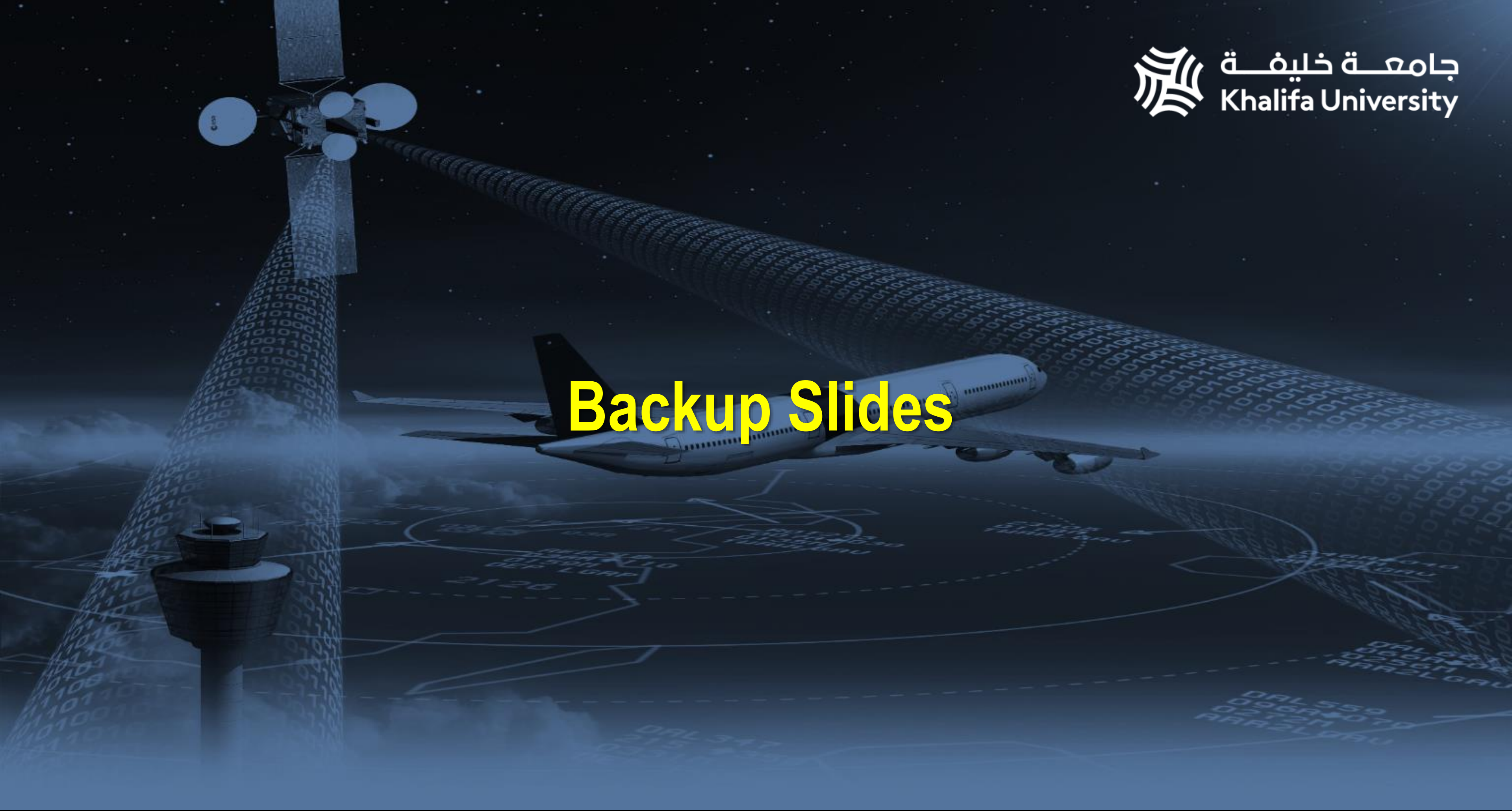
[106] C.H. Flemming and N.G. Leveson, “Including Safety during Early Development Phases of Future Air Traffic Management Concepts.” Proceedings of the 11th USA/Europe Air Traffic Management Research and Development Seminar (2015). Available online at: http://sunnyday.mit.edu/papers/ATM-2015.pdf

[107] C. Insaurralde, E. Blasch, R. Sabatini, “Ontology-Based Situation Awareness for Air and Space Traffic Management”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.

[108] Y. Xie, A. Gardi, R. Sabatini, M. Liang, “Hybrid AI-based Dynamic Re-routing Method for Dense Low-Altitude Air Traffic Operations”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.

[109] 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.

[110] Y. Xie, A. Gardi, R. Sabatini, “Cybersecurity Trends in Low-Altitude Air Traffic Management”, IEEE/AIAA 41st Digital Avionics Systems Conference, DASC 2022, Portsmouth, VA, USA, September 2022.



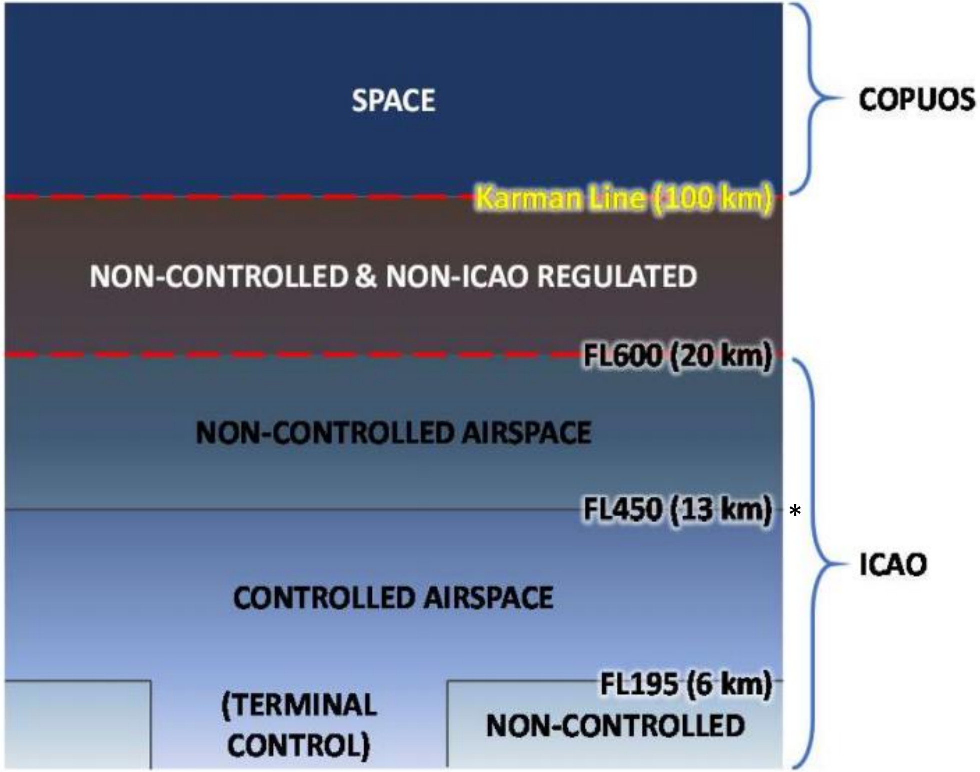
Backup Slides

Regulatory Framework Evolutions

The lack of regulatory oversight by the United Nations between FL600 (ceiling of ICAO jurisdiction) and the Karman Line (base of the COPUOS jurisdiction) is seen as a growing issue as more and more platforms operate regularly above FL600, while space launch and re-entry operations necessarily transit through this region.

An extension of the ICAO jurisdiction up to 50 km or more has been already proposed by ICCAIA.

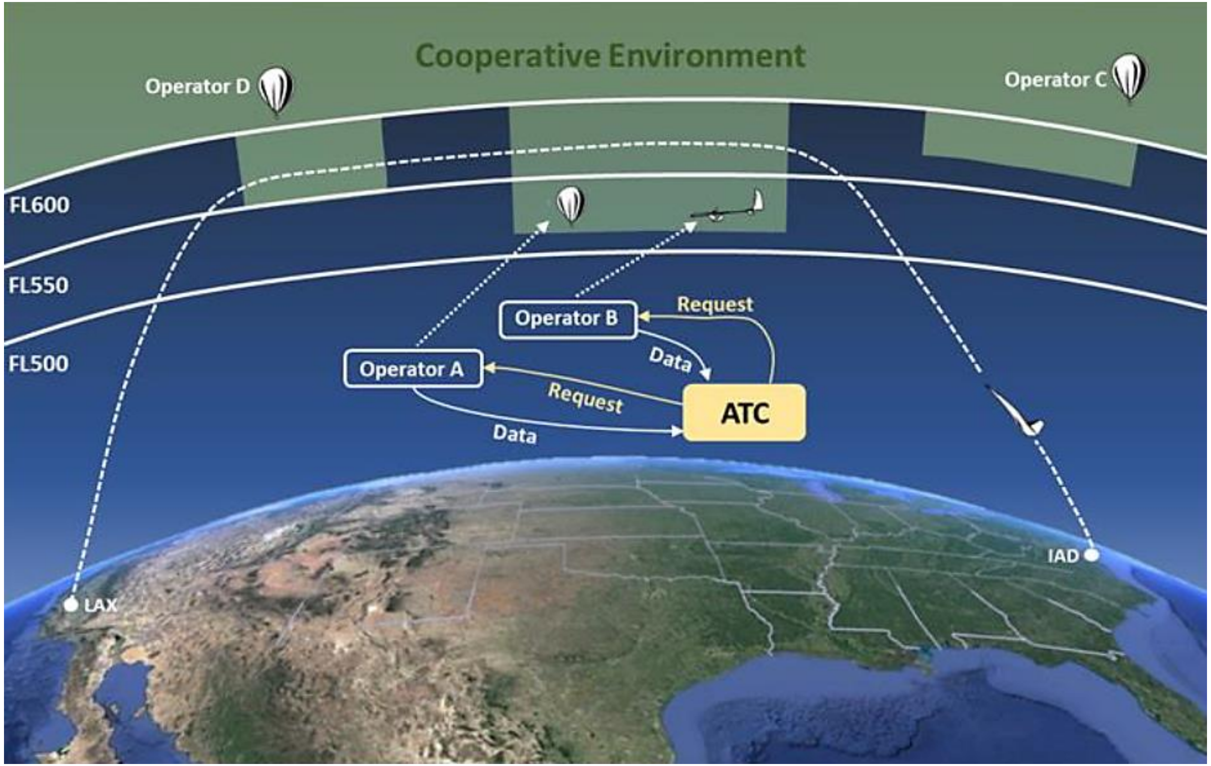
ICAO - International Civil Aviation Organization
COPUOS - Committee on the Peaceful Use of Outer Space
ICCAIA - International Coordinating Council of Aerospace Industries Associations



*Country-specific

Flight Above FL 600

- Super/Hypersonic Vehicles, VHALE UAS, Stratospheric Airships, etc.



Credit: FAA

Safety risk management for commercial space missions

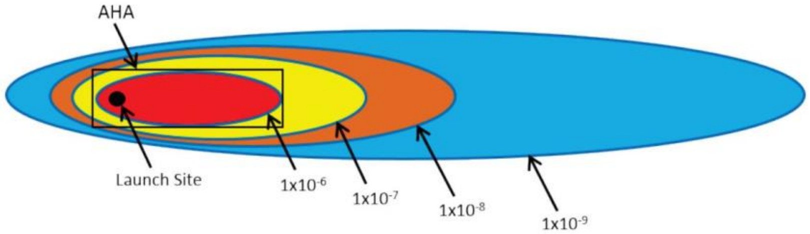
The FAA Office of Commercial Space Transportation (AST) and the Air Traffic Organization (ATO) have separately established public safety risk acceptance criteria that are expressed using different terminology and numerical values

Element	AST	ATO
Acceptable level of safety	1×10^{-6}	1×10^{-9}
Period	Per aircraft, per launch/fly-back operation	Per affected flight hour or air traffic control operation
Consequence	Casualty of an aircraft occupant	Fatality of an aircraft occupant

The ATO proposed using the ***Acceptable Level of Risk (ALR)*** approach to temporarily bridge the differences and accommodate the growth of commercial space launches in the NAS.

Aircraft Hazard Areas (AHAs)

Risk contour during launch and re-entry per-aircraft probabilities of impact with debris capable of causing a casualty

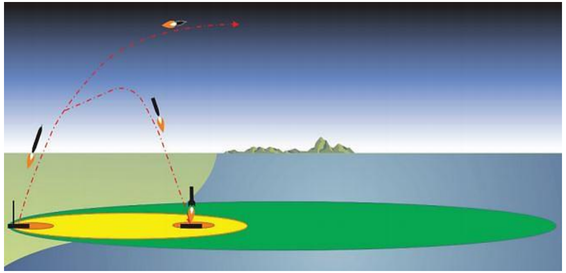


No operations are permitted in the AHA

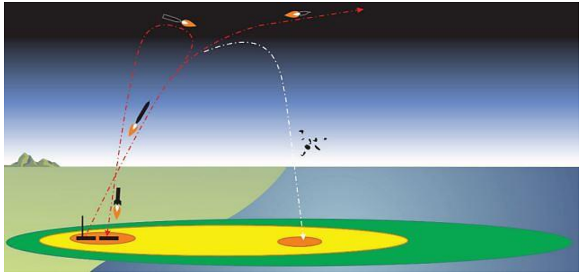
Commercial Space Mission Types

Missions using the ALR approach with the 30-Degree Angular Restriction
ALR for these missions: 1×10^{-6} and the 1×10^{-7} risk contours

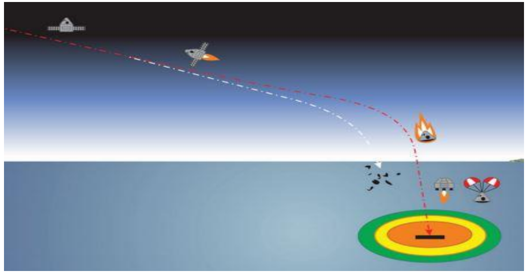
Launch Barge Fly-Back



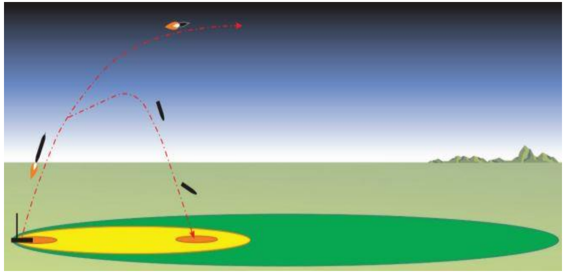
Launch Site Fly-Back



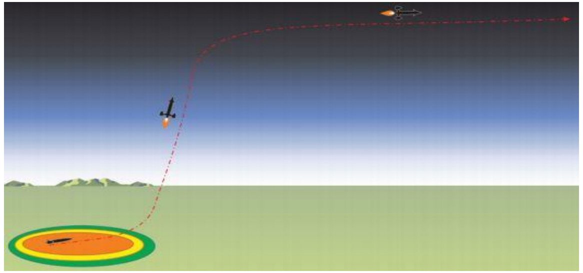
Capsule Reentry



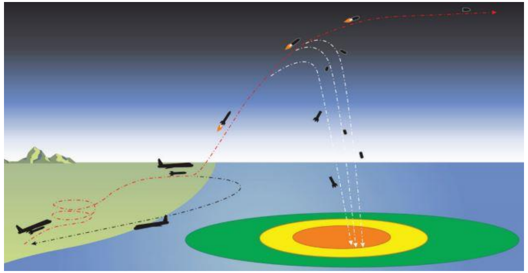
Expendable Launch Without Fly-Back



Horizontal Orbital



Captive Carry Orbital

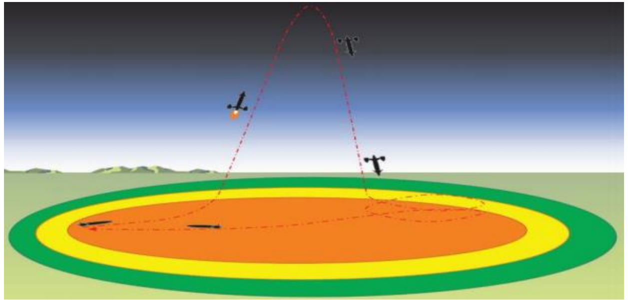


Commercial Space Mission Types

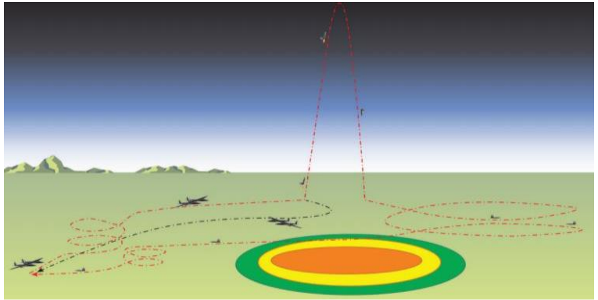
Missions using the ALR approach with a risk buffer

The appropriate risk buffer for each launch to ensure that the 1×10^{-7} individual risk limit

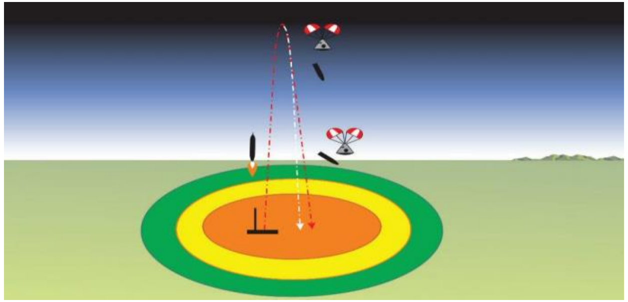
Horizontal Suborbital



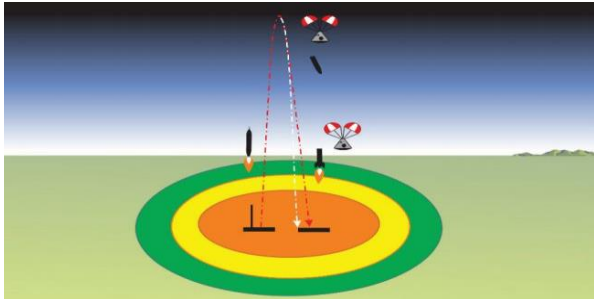
Captive Carry Suborbital



Vertical Launch Suborbital Expendable Booster



Vertical Launch Suborbital Reusable Booster

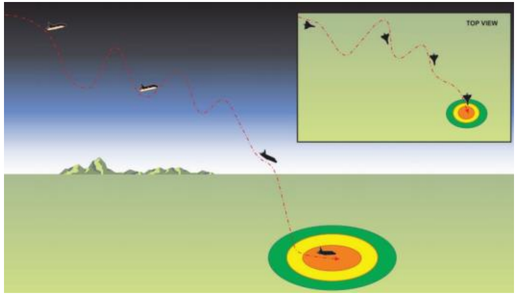


Commercial Space Mission Types

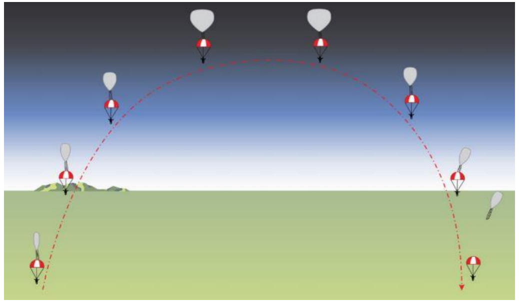
Missions to which the ALR approach cannot be applied at this time

It was not possible to identify appropriate parameters, conditions, and restrictions that would allow the application of ALR

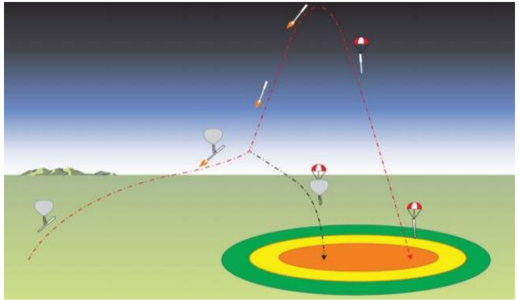
Winged Reentry



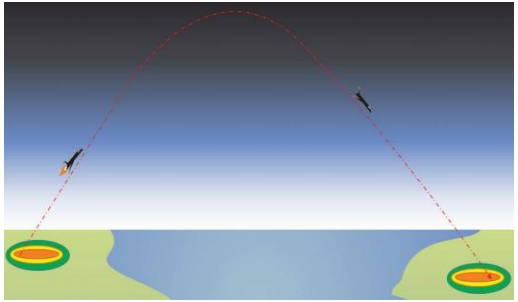
Stratospheric Manned Balloons



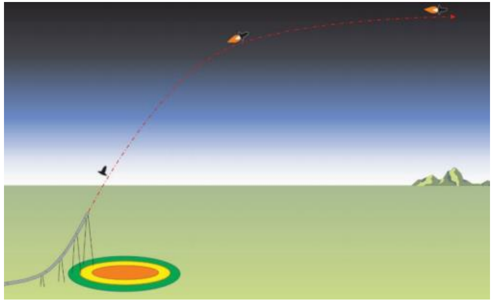
Balloon Launch



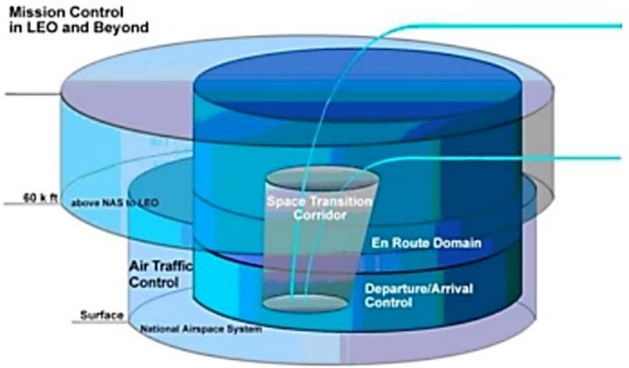
Point-to-Point



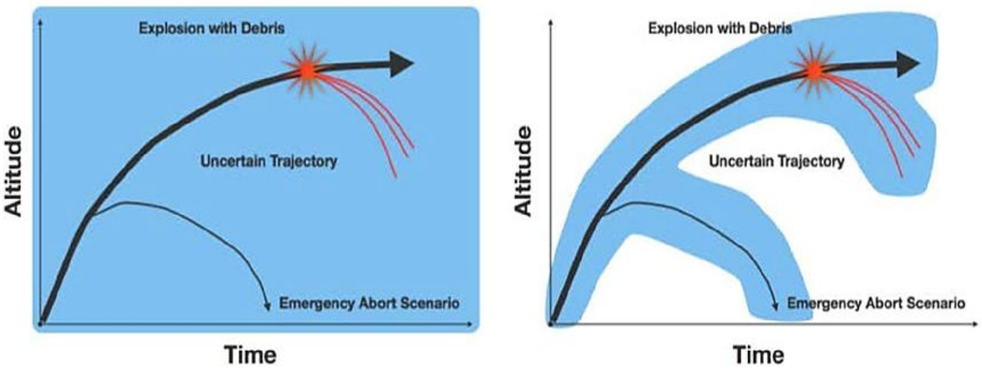
Tube and Rail Launchers



Emerging Airspace Management Concepts



Space Transition Corridor
Courtesy: NextGen US



4 Dimensional Compact Envelopes
Courtesy Stanford University Aerospace Design Lab

Space Transition Corridors

- Employing three spatial (length, width, azimuth) and two temporal parameters (duration and midpoint of corridor)
- Corridor remains static throughout its implementation

Four-Dimensional Compact Envelopes

- Based on individual probabilistic off-nominal spacecraft conditions during launch and re-entry phases
- Compact envelopes enforce only the portion of airspace that is at risk
- Elegant solution in safeguarding spacecraft operations compared to TFR (but complex practical implementation)