X THE PLACE OF USEFUL LEARNING

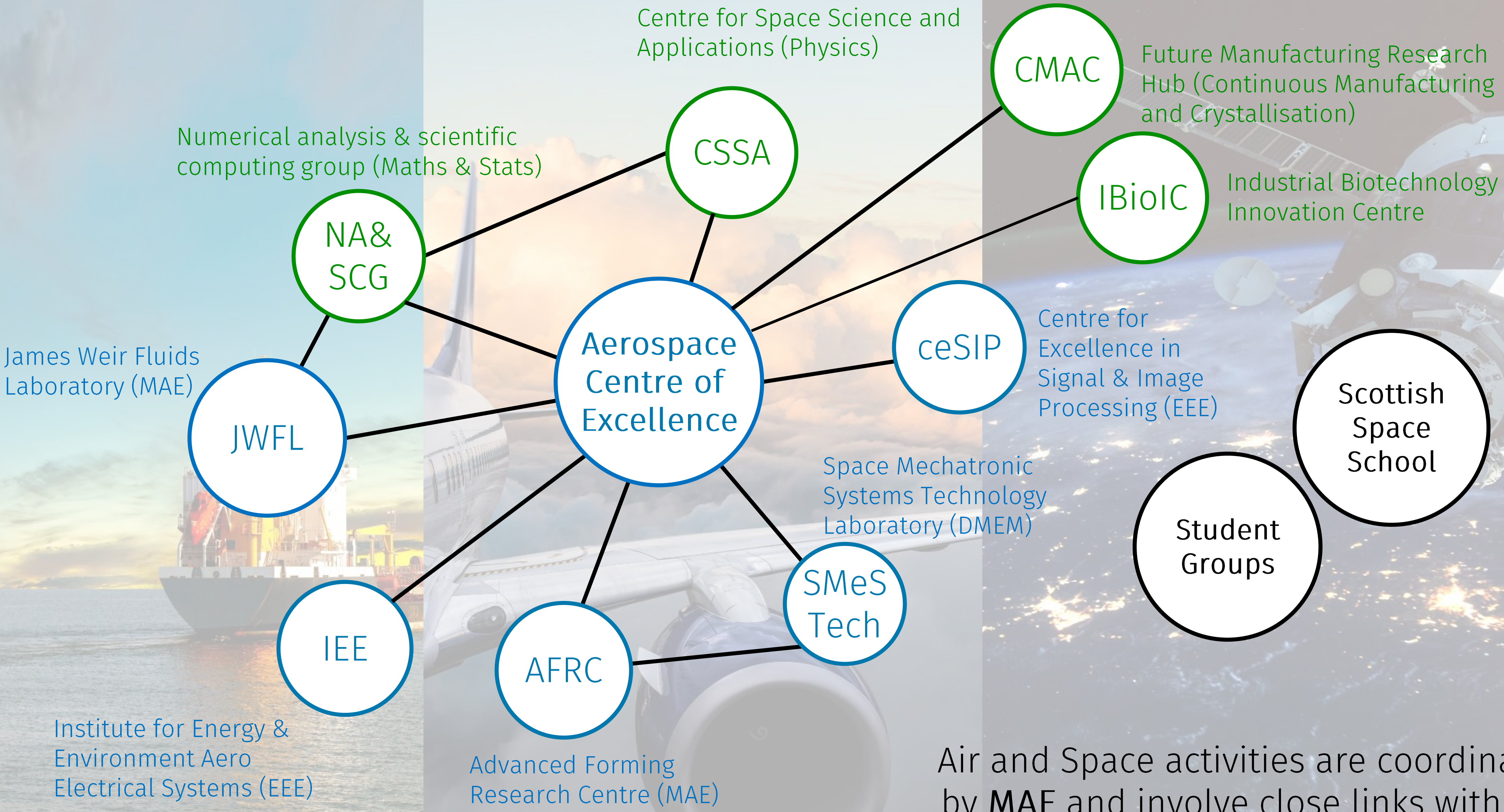
University of Strathclyde Engineering

KNOWNS AND UNKNOWNS OF SPACE ACCESS

https://www.strath.ac.uk/engineering/mechanicalaerospaceengineering/**aerospacecentreofexcellence**

Ocean – Air – Space

University Strategic Theme



Air and Space activities are coordinated by **MAE** and involve close links with **EEE** and **DMEM** (the latter through the **AFRC**)

ACE academics

AEROSPACE CENTRE of EXCELLENCE

Prof. Max Vasile
Space Systems and Resilience Engineering

Prof. Matthew Cartmell
Nonlinear dynamics and Orbital Mechanics

Dr. Christie Maddock
Transatmospheric flight dynamics and control

Dr. Marco Fossati
Multi-physics computational aerodynamics

Dr. Annalisa Riccardi
Computational Intelligence Machine Learning

Dr. Stewart Grey
Precise Orbit Determination and outreach

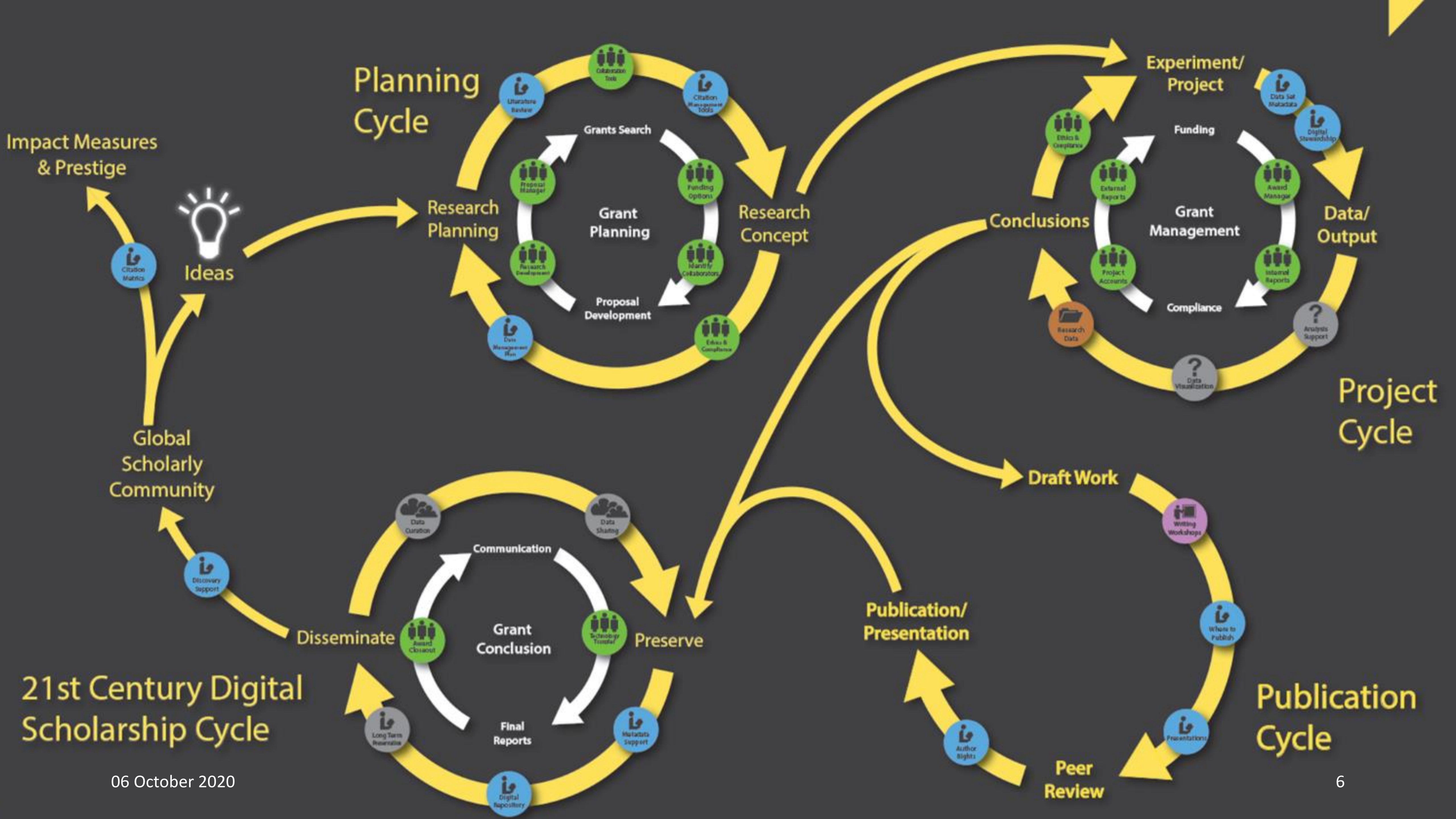
Dr. Jinglang Feng
Modeling of mechanical and dynamical system

Dr. Edmondo Minisci
Multidisciplinary Optimisation and Evidence Network Models

Dr. Mohammed Afsar
Theoretical Aerodynamics and Flow Control

Dr. Marcello Lappa
Fluid mechanics instabilities and high-temperature flows

Dr. Ioannis Kokkinakis
Turbulence and computational aeroacoustics

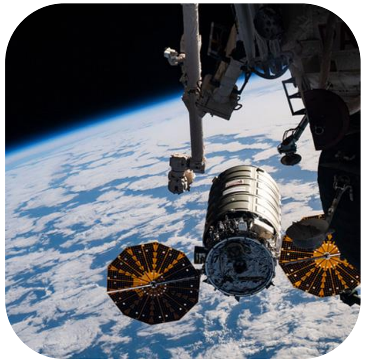


Planning Cycle
Impact Measures & Prestige
Citation Metrics
Ideas
Research Planning
Literature Review
Collaboration Tools
Citation Management Tools
Grants Search
Proposal Manager
Funding Options
Grant Planning
Research Development
Identify Collaborators
Proposal Development
Data Management Plan
Ethics & Compliance
Research Concept
Experiment/ Project
Ethics & Compliance
Funding
Data Set Metadata
Digital Stewardship
External Reports
Award Manager
Conclusions
Grant Management
Data/ Output
Project Accounts
Internal Reports
Compliance
Research Data
Analysis Support
Data Visualization
Project Cycle
Global Scholarly Community
Discovery Support
Data Curation
Data Sharing
Communication
Disseminate
Award Closeout
Grant Conclusion
Technology Transfer
Preserve
Final Reports
Long Term Preservation
Metadata Support
Digital Repository
21st Century Digital Scholarship Cycle
Draft Work
Writing Workshops
Publication/ Presentation
Where to Publish
Presentations
Author Rights
Peer Review
Publication Cycle

Aerospace Centre of Excellence

AEROSPACE CENTRE of EXCELLENCE

3 Laboratories, 11 Academics & 40+ Researchers



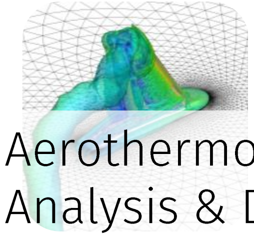
Advanced Space Concepts
ASCL

Future Air-Space Transportation
Technologies FASTT

Intelligent Computational
Engineering ICELab

Flight & Spaceflight Mechanics; Computational & Theoretical Aerodynamics;
Computational Intelligence; Robotics & Autonomy; Space Systems & Science

Aerospace Transport & Sustainability



Aerothermodynamic Analysis & Design

Resilience in Complex Systems

Small Satellite Apps. & Technology

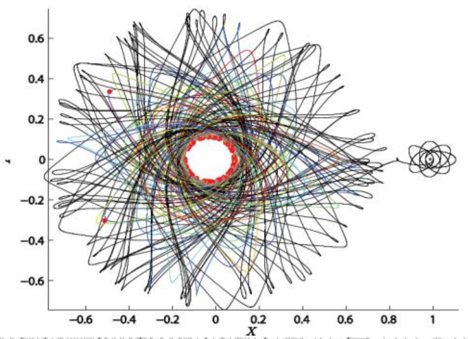
Space Exploration & Air-space Traffic

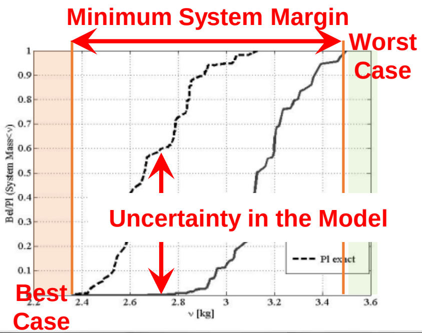
ACE expertise and applications

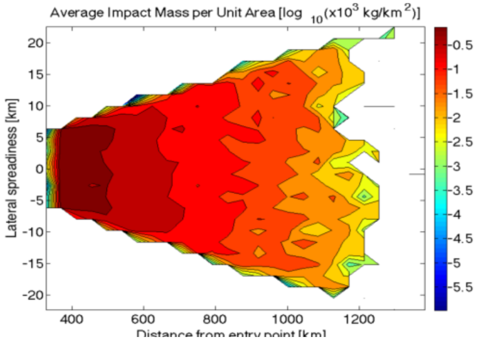
Mission analysis and design
Dynamical systems
Multi-objective optimal control
Evidence Network Models
Model predictive control
Ground impact risk analysis

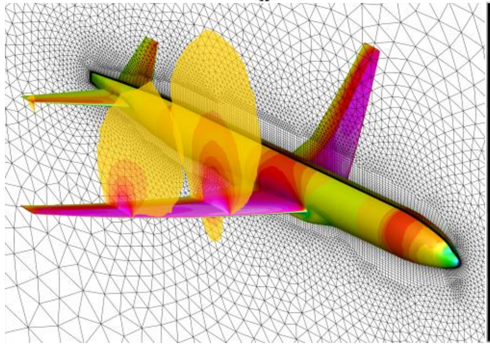
Computational Aerodynamics ([SU2](SU2))
Hypersonic and re-entry
Transition & aeroacoustics
Trajectory optimisation
GNC for ascent and re-entry
Life cycle analysis
Sustainability

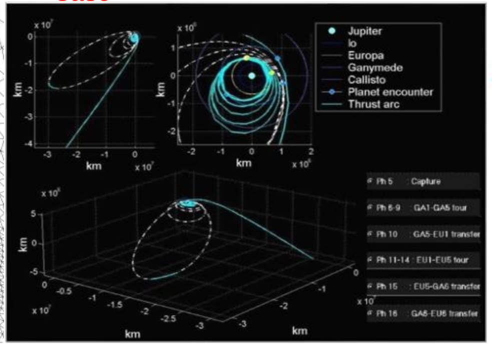
Concurrent Engineering
Multidisciplinary design
Evidence-based optimisation
Uncertainty Quantification
Machine learning
Computational intelligence

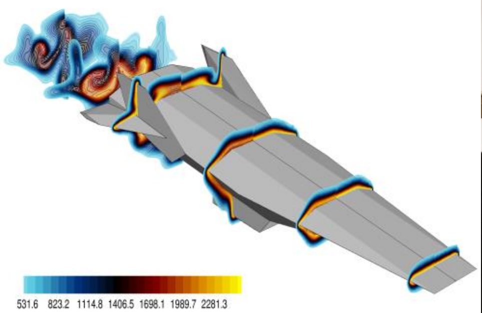












AEROSPACE CENTRE of EXCELLENCE

Some numbers and links

- £12M from the European Community (FP7, H2020)
- £400k from the UK Space Agency
- £500k from the European Space Agency
- £200k linked to the Strathclyde DTC in Space Systems with Airbus, Fraunhofer & DSTL
- £250k from KTP and EPSRC

Overall, ACE is committed to a research activity worth £15M+

SMART: Strathclyde Mechanical & Aerospace Research Toolboxes

Open source code repositories on github.com/strath-ace

smart-o2c
Optimisation and Optimal Control toolbox

smart-ml
Machine Learning toolbox

smart-astro
Astrodynamics toolbox

smart-uq
Uncertainty Quantification toolbox

smart-math
Mathematical base routines

Three github organisations

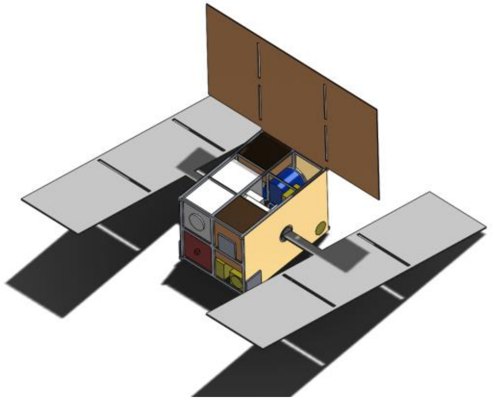
- SMART Teaching Hub
- SMART alpha on strath-ace-labs (internal testing and development)
- SMART on strath-ace (public)

AEROSPACE CENTRE of EXCELLENCE

Concurrent and Collaborative Design Studio

- Unique facility in Scotland
- End-to-end mission and system design
- Allows for remote concurrent engineering
- Advanced tools for mission and system design

NEOCORE - Nanospacecraft Exploration of Asteroids by Collision and Flyby Reconnaissance



cnes · esa · l'Observatoire de Paris · Fraunhofer IOF

Orbital500 – Horizontal Launch system

ORBITAL ACCESS · BAE SYSTEMS INSPIRED WORK

Where is space?

AEROSPACE CENTRE of EXCELLENCE

Earth diameter?

12 742 km

Low Earth orbit?

~160-2000 km

Space?

85-100 km

GPS orbit?

20 180 km

American GPS currently has 31 active satellites

Currently 6 GNSS systems operating Can you guess by whom?

EU Galileo
Russia GLONASS
China BeiDou
India NAVIC
Japan QZSS

Geostationary orbit?

35 786 km

Inmarsat-5 F4 launched on SpaceX Falcon 9 on 15 May 2017 as part of the Global Xpress network to provide high speed broadband

Satellite bus is the same height as a double decker bus

Distance to the moon?

384 400 km

How fast do satellites go?

AEROSPACE CENTRE of EXCELLENCE

Low Earth orbit

124-1243 miles

17450-14430 mph

1h29 – 2h08

You

1040 mph

23h56

GPS orbit

12 539 miles

8666 mph

11h58

Geostationary orbit

22 236 miles

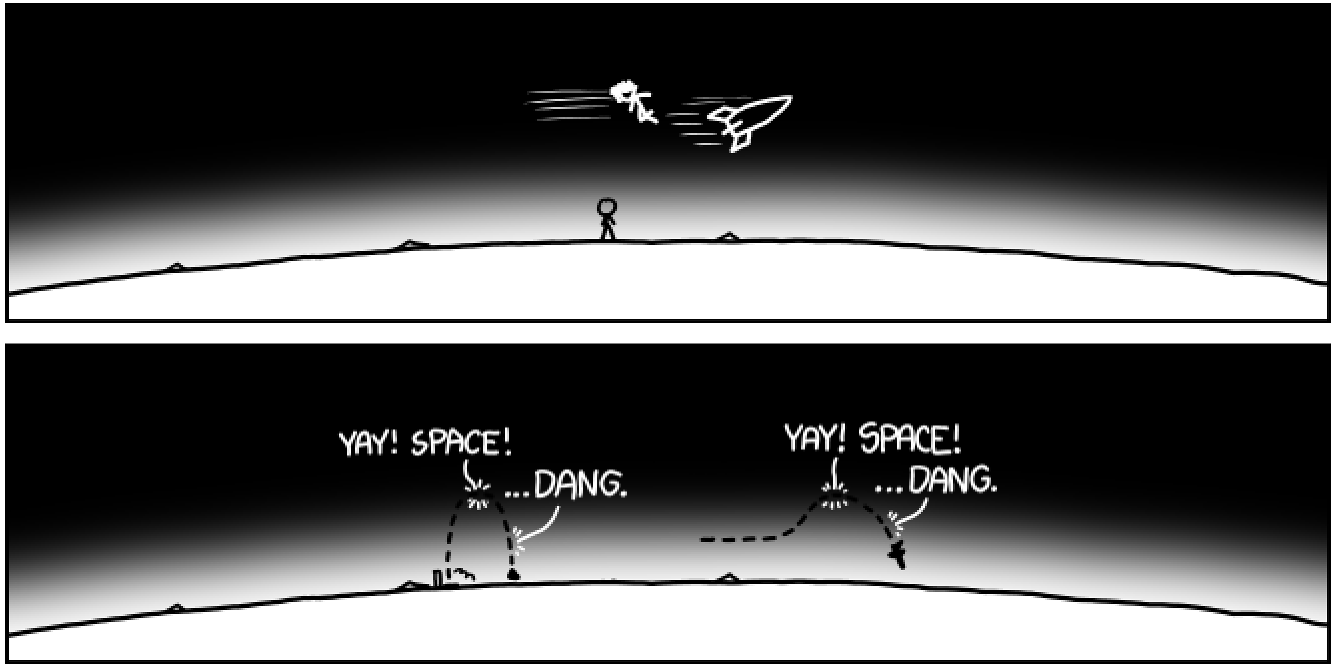
6935 mph

23h56

Why is it hard?

AEROSPACE CENTRE of EXCELLENCE

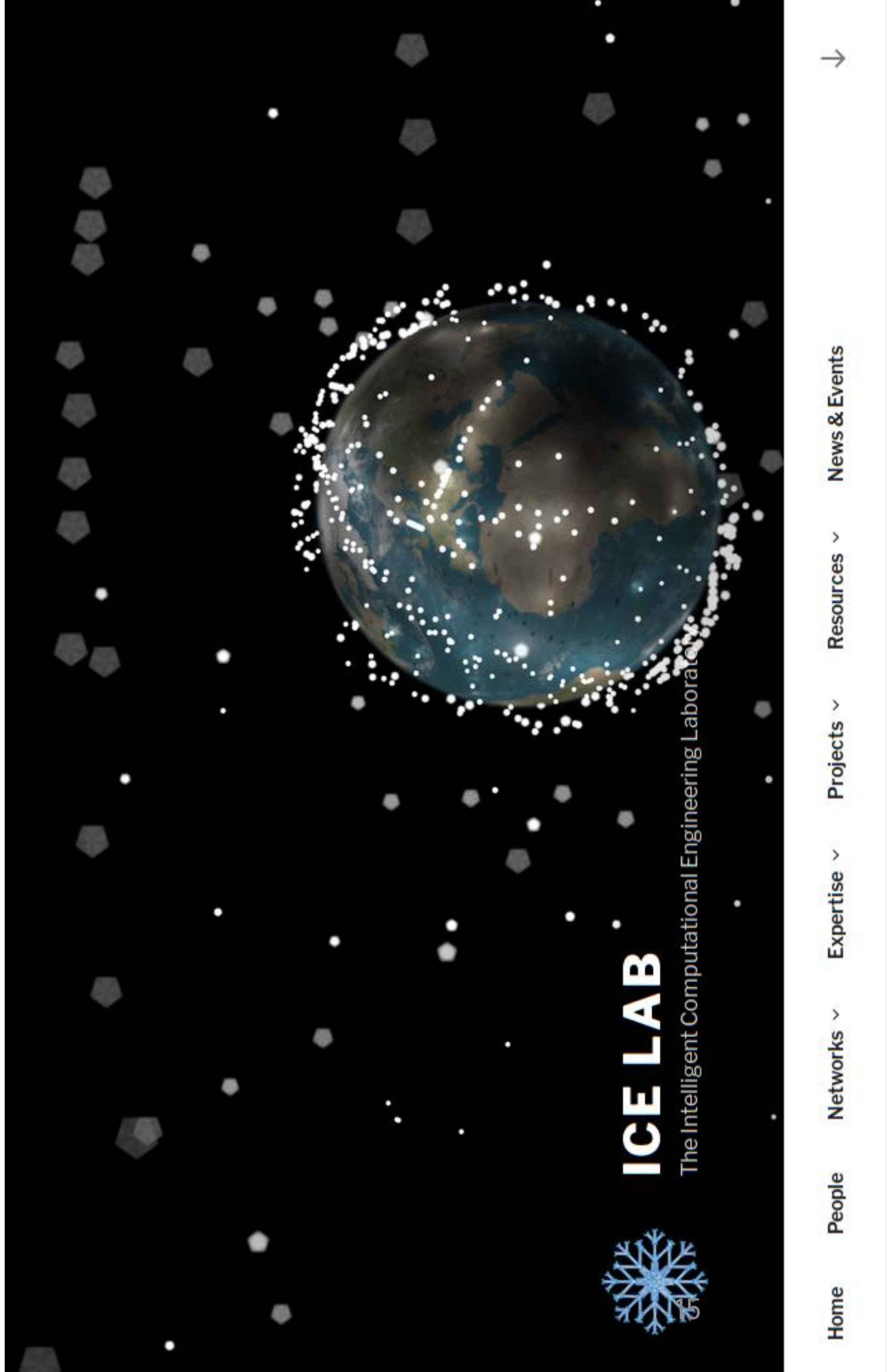
https://what-if.xkcd.com/58/



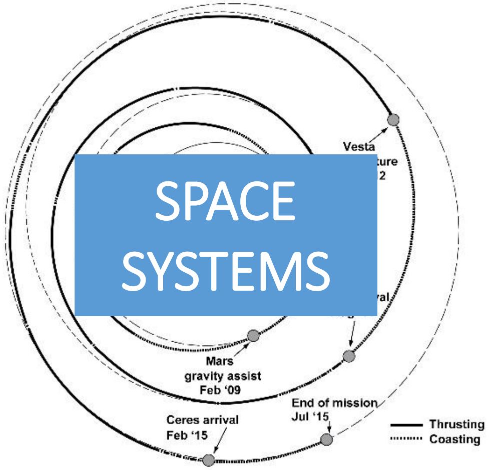
If you fired a rifle from one end of a football pitch, the International Space Station could cross the length of the field (120 yards) before the bullet has travelled 10 yards

Intelligent Computation for Engineering ICElab

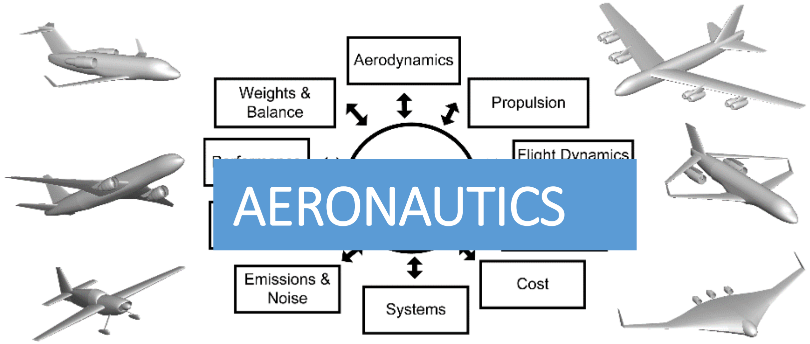
- Advanced research on Artificial and Computational Intelligence techniques, with particular focus on:
    - Optimisation, optimal control
    - Uncertainty-based multidisciplinary design optimisation, and
    - Machine learning applied to the design and control of complex engineering systems



Intelligent Computation for Engineering



Multidisciplinary Team

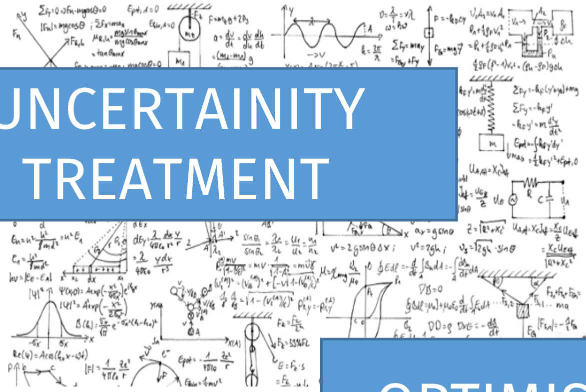


Computational methods vs applications and design

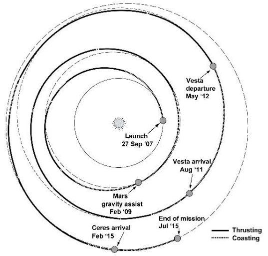
AEROSPACE CENTRE of EXCELLENCE

METHODS

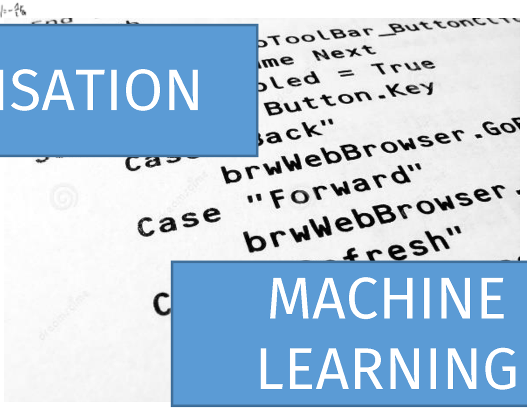
APPLICATIONS



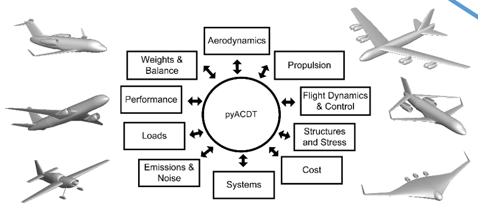
UNCERTAINITY TREATMENT



TRAJECTORY DESIGN

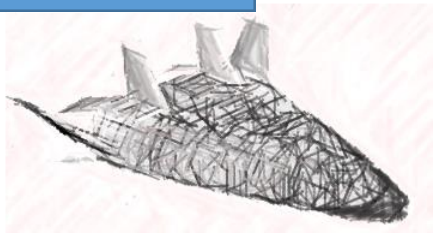


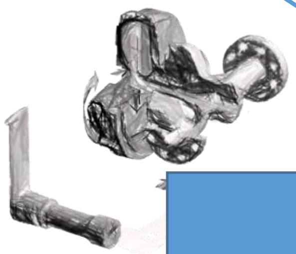
OPTIMISATION



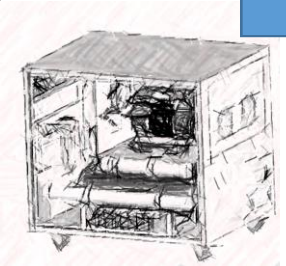
AEROSPACE SYSTEM DESIGN

MACHINE LEARNING



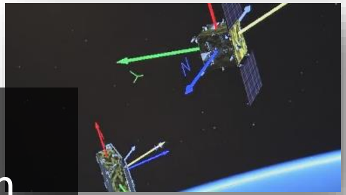


SHAPE OPTIMISATION

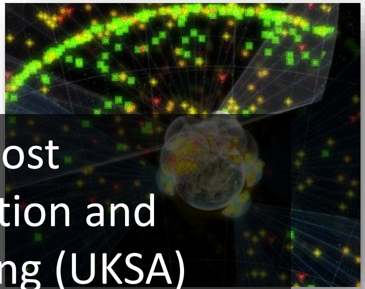


SYSTEM DESIGN

Space Environment Management



Proximity navigation



Low-cost detection and tracking (UKSA)

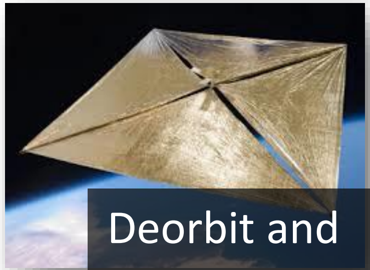
Debris de-tumbling and disposal with lasers (FP7)

Multi-target disposal exploiting natural dynamic (Airbus)

GOCE re-entry Analysis (ESA)

Multi-fidelity re-entry analysis and design for demise (FP7)

Collision avoidance manoeuvres (FP7)



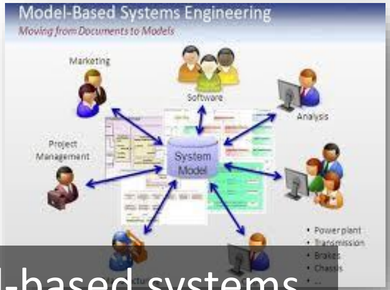
Deorbit and re-entry HAMR objects (UKSA,H2020)

On-orbit servicing (H2020)

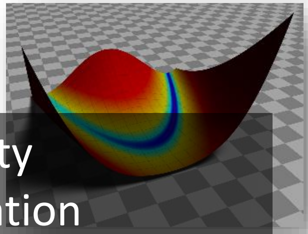
Resilience in Complex Systems

AEROSPACE CENTRE of EXCELLENCE

Uncertainty quantification in complex networks (ESA)



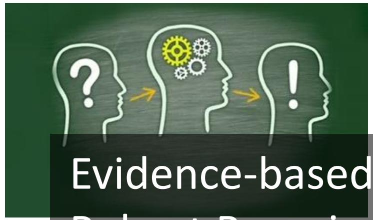
Model-based systems engineering under uncertainty (ESA)



Uncertainty Quantification

(ESA, EPSRC, H2020)

Design for reliability and for robustness (ESA, EPSRC)

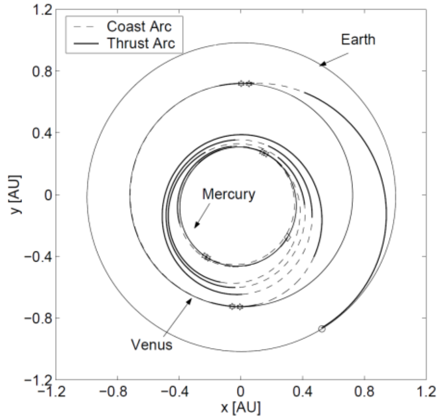


Evidence-based and Robust Bayesian reasoning (ESA, H2020)

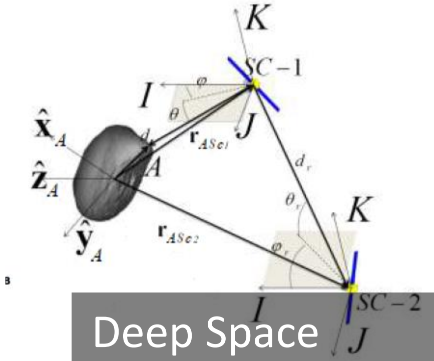
Fault tolerant networked systems (EPSRC)

Space Exploration and Advanced Concepts

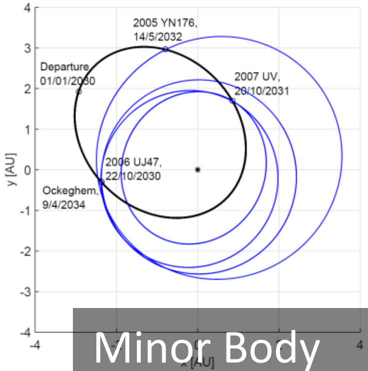
Trajectory Analysis and Design



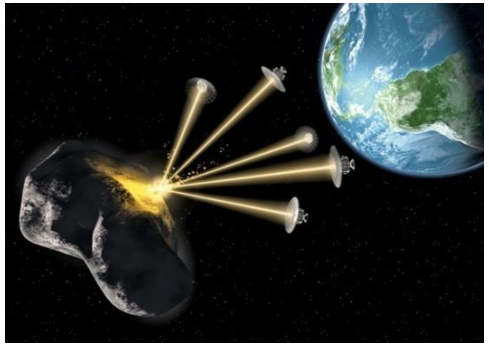
Deep Space Navigation



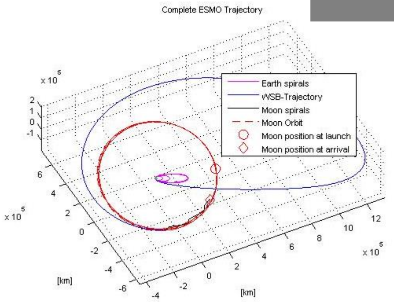
Minor Body Exploration



Planetary Defence

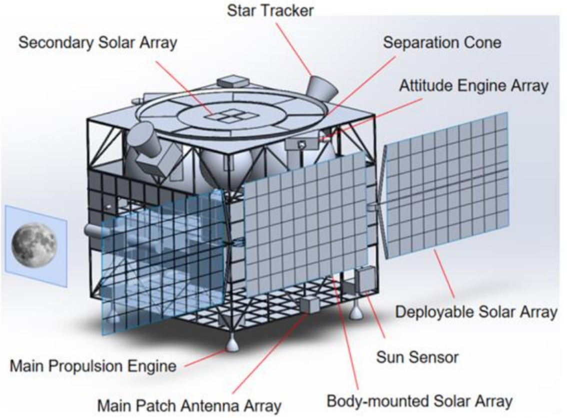


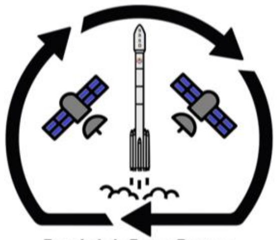
The Moon



Life cycle analysis

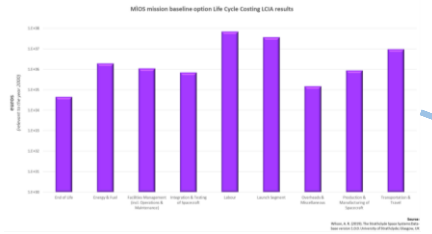
Concurrent design activities



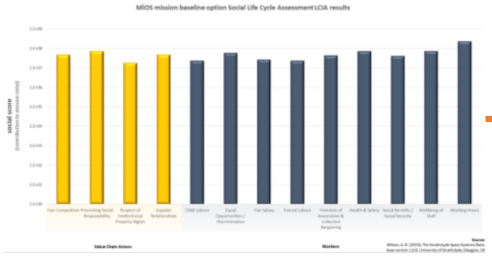


Life Cycle Sustainability Assessment

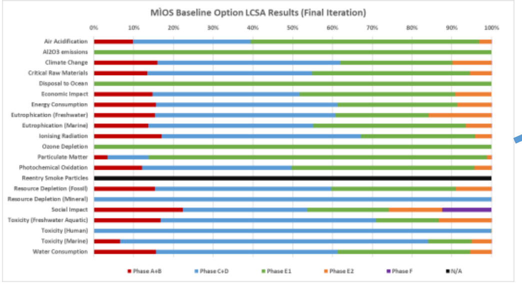
Life Cycle Costing



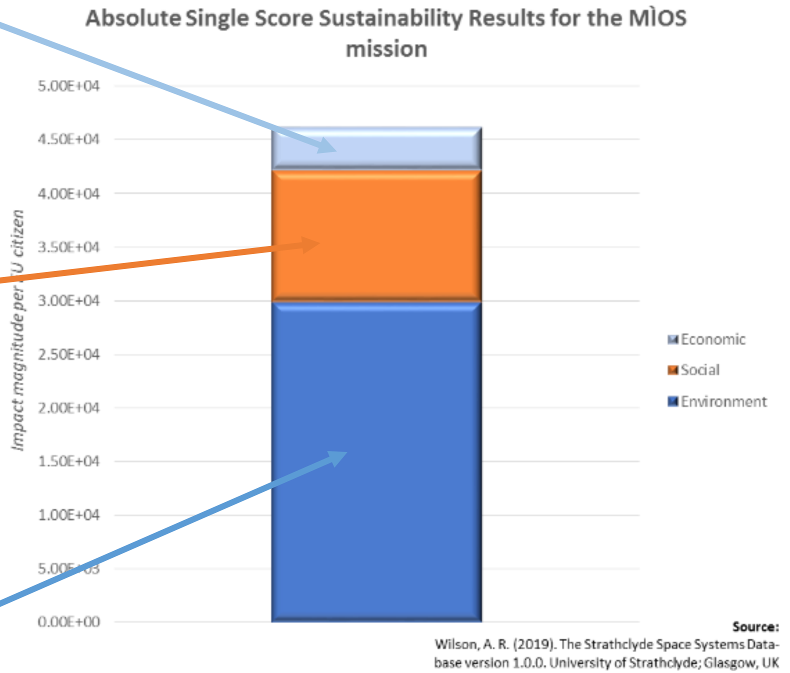
Social LCA



Environmental LCA

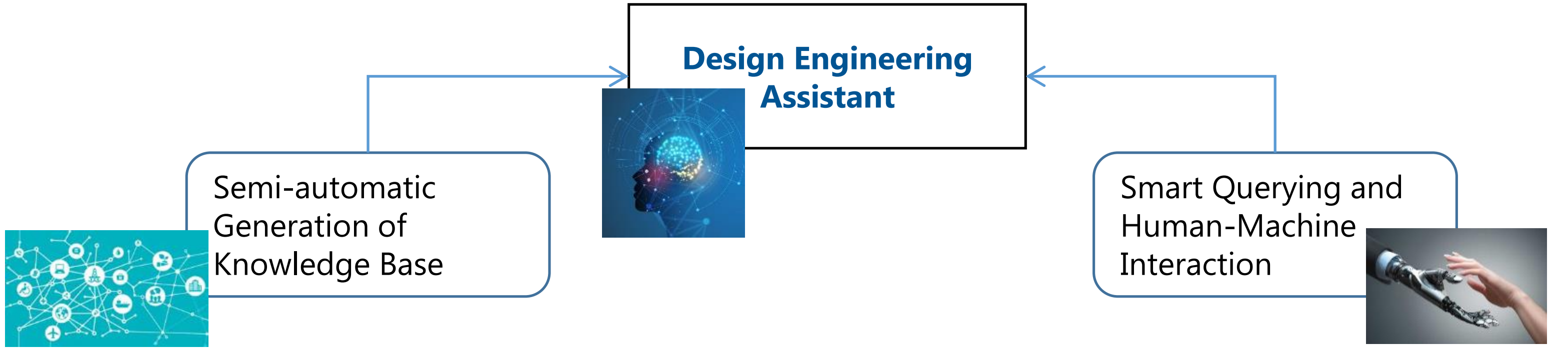


Multi-Criteria Decision Analysis (based on Multi-Attribute Value Theory)



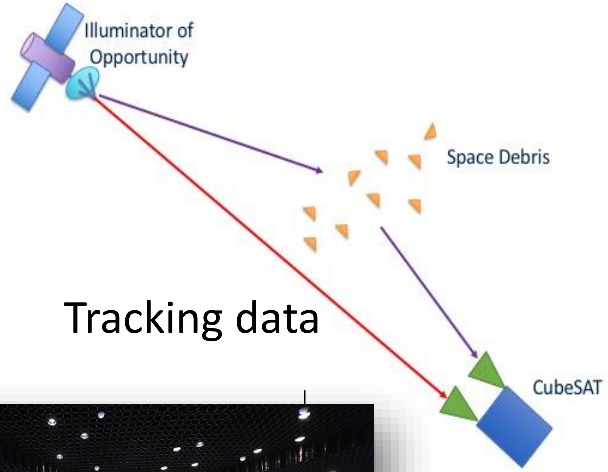
Design Engineering Assistant (DEA)

- Develop and validate a design engineering assistant for the early phases of system design, leveraging natural language processing, machine learning and knowledge management techniques.

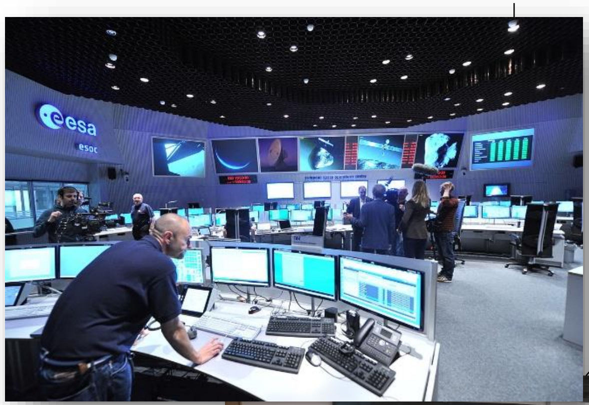


- How to automatically extract and store data collected from years of system design and make it reusable for future work?
- How to use this stored knowledge in a smart way to improve the work of the experts in the preliminary phase of the design with reliable and relevant information (e.g. browsing past lessons-learned, components list or avoiding “reinventing the wheel”)?

Space Environment Management

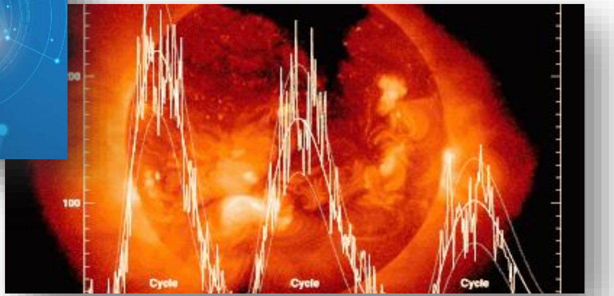


Tracking data

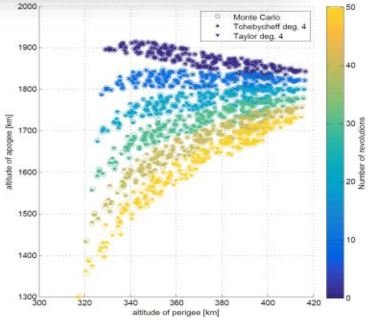


AI for STM

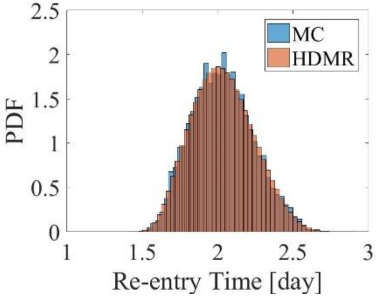
Space weather



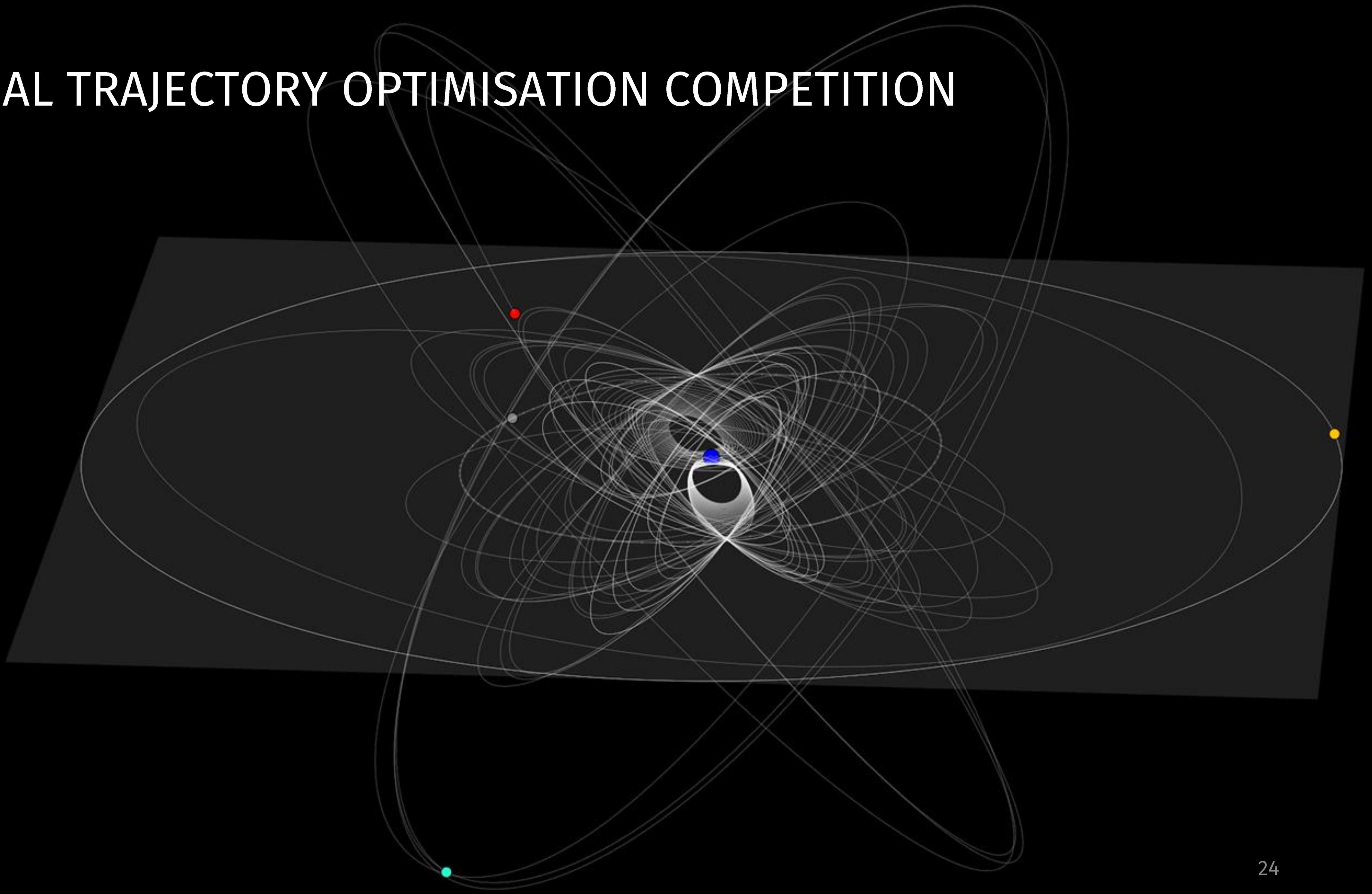
UQ in Orbital Mechanics



Re-entry and demise



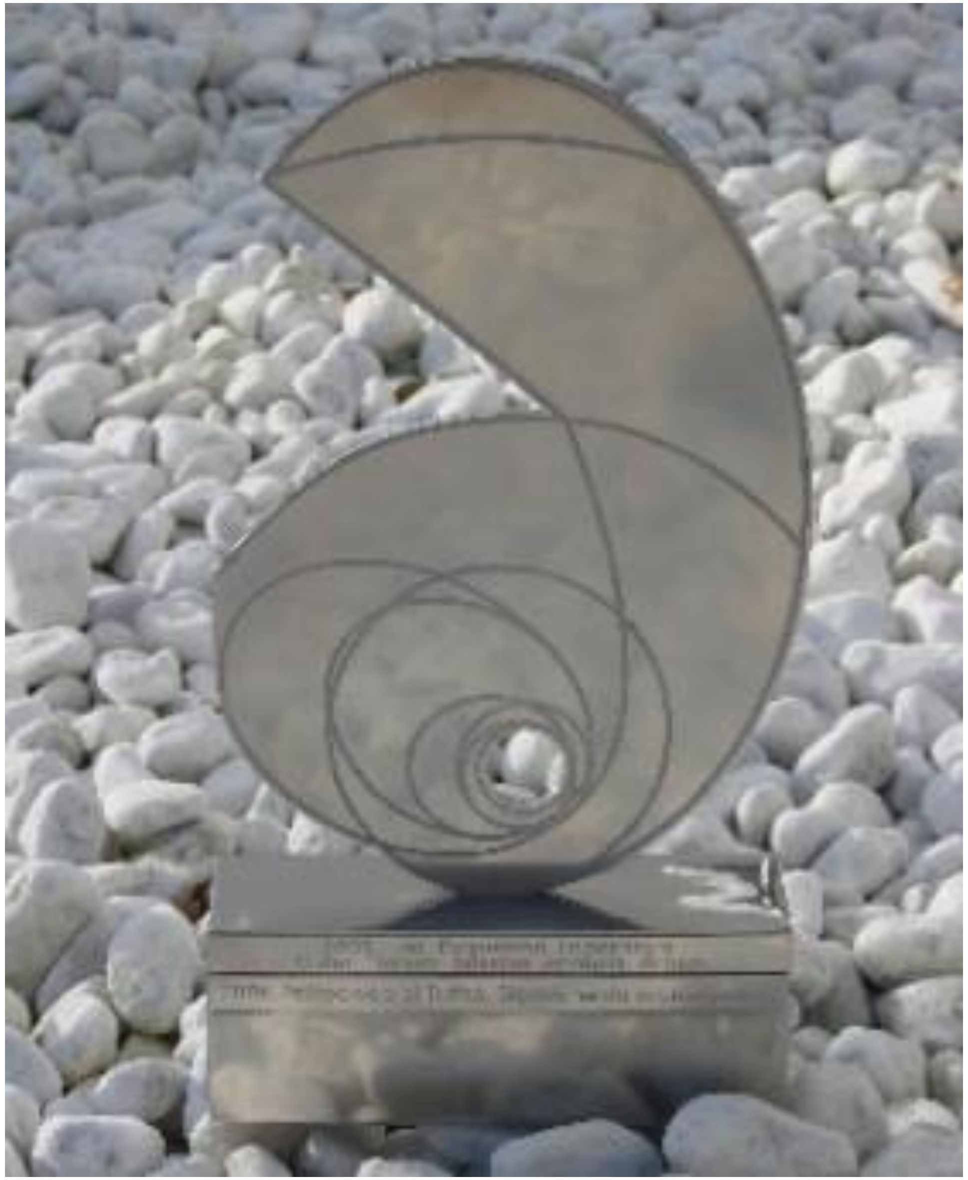
GLOBAL TRAJECTORY OPTIMISATION COMPETITION



Global trajectory optimisation competition

AEROSPACE CENTRE of EXCELLENCE

- Initiated in 2005 by the European Space Agency
- Each year is organised by the winner of the previous edition
- It has been defined as the "American Cup of Rocket Science"
- Worldwide competition
- 1 month to solve a complex trajectory optimisation problem with unlimited resources



This year problem

AEROSPACE CENTRE of EXCELLENCE

- Design an impulsive trajectory to deorbit 123 debris around Earth with multiple launches
- Deorbiting→ rendezvous with the object + waiting time of 5 days
- Objective function as the sum of the launch cost (linearly increasing with time) and a quadratic mass cost
- Constraints on maximum propellant mass, minimum pericentre, times between launches and times between rendezvous

Approach

- Combinatorial Optimisation: ad hoc beam search + deep first search for reconstruction of launch sequences
- Continuous optimisation: design of the impulses manoeuvres with MPAIDEA
- Multi-fidelity: mean dynamic with J2 + full dynamic + multiple shooting transcription

- Computational resources (desktops, CCDS computers, access to teaching cluster)

Results

Name	Submissions	Last Submission	Best Submi	
Jet Propulsion Laboratory	10	May 1, 2017, 11:08 p.m.	May 1, 2017, p.m.	745
NUDT Team	12	May 1, 2017, 8:23 p.m.	May 1, 2017, p.m.	241
XSCC-ADL	12	May 1, 2017, 9:14 p.m.	May 1, 2017, p.m.	282
Tsinghua-LAD	12	May 1, 2017, 8:45 p.m.	May 1, 2017, p.m.	784
NPU	13	April 19, 2017, 9:40 a.m.	April 19, 201 a.m.	976
Strathclyde++	14	May 1, 2017, 7:21 p.m.	May 1, 2017 p.m.	
DLR	14	April 29, 2017, 3:05 a.m.	April 29, 201 a.m.	552
Missions Learners	14	May 1, 2017, 12:16 p.m.	May 1, 2017 p.m.	585
The Aerospace Corporation	14	April 27, 2017, 3:22 a.m.	April 27, 201 a.m.	548

Name	Submissions	Last Submission	Best Submission	Debris Removed	Best Score
Jet Propulsion Laboratory	10	May 1, 2017, 11:08 p.m.	May 1, 2017, 11:08 p.m.	123	731.299366088745
NUDT Team	12	May 1, 2017, 8:23 p.m.	May 1, 2017, 8:23 p.m.	123	786.214526623241
XSCC-ADL	12	May 1, 2017, 9:14 p.m.	May 1, 2017, 9:14 p.m.	123	821.379662949282
Tsinghua-LAD	12	May 1, 2017, 8:45 p.m.	May 1, 2017, 8:45 p.m.	123	829.579877503784
NPU	13	April 19, 2017, 9:40 a.m.	April 19, 2017, 9:40 a.m.	123	878.998216662976
Strathclyde++	14	May 1, 2017, 7:21 p.m.	May 1, 2017, 7:21 p.m.	123	918.98089502739
DLR	14	April 29, 2017, 3:05 a.m.	April 29, 2017, 3:05 a.m.	123	949.853897406552
Missions Learners	14	May 1, 2017, 12:16 p.m.	May 1, 2017, 12:16 p.m.	123	964.511344175585
The Aerospace Corporation	14	April 27, 2017, 3:22 a.m.	April 27, 2017, 3:22 a.m.	123	1004.48607401648
Team Jena	15	April 27, 2017, 2:37 a.m.	April 27, 2017, 2:37 a.m.	123	1022.90631615007
UT Austin	15	May 1, 2017, 2:52 p.m.	May 1, 2017, 2:52 p.m.	122	1044.17873262314
NJU Team	16	April 28, 2017, 8:32 a.m.	April 28, 2017, 8:32 a.m.	123	1047.96850507349
ERMAN TEAM	14	April 30, 2017, 9:14 a.m.	April 30, 2017, 9:14 a.m.	119	1107.69367526485
CU Boulder	17	May 1, 2017, 10:12 p.m.	May 1, 2017, 10:12 p.m.	123	1150.84392649373
CAS-NUAA	14	April 28, 2017, 5:43 p.m.	April 28, 2017, 5:43 p.m.	123	1182.06320592623
Bruin WORHP	18	May 1, 2017, 12:05 a.m.	April 28, 2017, 7:16 p.m.	123	1229.54754156866
MTU-UoM	16	May 1, 2017, 5:37 p.m.	May 1, 2017, 5:37 p.m.	122	1251.75438475847
NebleZerolabs	16	April 12, 2017, 4:33 a.m.	April 12, 2017, 4:33 a.m.	123	1267.75016923208
NSSC-THU	13	May 1, 2017, 10:53 p.m.	May 1, 2017, 10:53 p.m.	119	1333.52081852397
TYSE	16	May 1, 2017, 10:21 p.m.	May 1, 2017, 10:21 p.m.	123	1336.85902074467
TM	18	May 1, 2017, 8:55 p.m.	May 1, 2017, 8:55 p.m.	123	1490.96595510048
Ostania	22	May 1, 2017, 10:28 p.m.	May 1, 2017, 10:28 p.m.	120	1493.85678749045
AKGaFS	20	May 1, 2017, 1:31 a.m.	May 1, 2017, 1:31 a.m.	123	1512.60176793564
Personal team	23	April 29, 2017, 3:45 a.m.	April 29, 2017, 3:45 a.m.	123	1588.57709896524
[illegible]	20	May 1, 2017, 10:29 p.m.	May 1, 2017, [illegible]	112	1819.[illegible]
UoE and Goddard	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UiPirates	20	April 21, 2017, 9:45 p.m.	April 21, 2017, 9:45 p.m.	105	2164.23216812542
Astro-ASAP-ICM	13	[illegible]	[illegible]	85	[illegible]
[illegible]	[illegible]	May 1, 2017, 10:07 p.m.	May 1, 2017, 10:07 p.m.	56	[illegible]
Cal Poly SLO	39	May 1, 2017, 10:44 p.m.	May 1, 2017, 10:44 p.m.	84	4467.87460255417
[illegible]	13	April 8, 2017, 4:24 p.m.	April 8, 2017, 4:24 p.m.	57	4481.77818625953
[illegible]	[illegible]	April 16, 2017, 11:23 p.m.	April 16, 2017, 11:23 p.m.	18	6453.02546545099
National University of Colombia	2	April 5, 2017, 9:32 p.m.	April 5, 2017, 9:32 p.m.	7	6511.54716795191
MeleeCode	1	April 30, 2017, 2:23 p.m.	April 30, 2017, 2:23 p.m.	5	6594.11056129426
AMSS_GTOC	1	April 29, 2017, 5:23 a.m.	April 29, 2017, 5:23 a.m.	4	6619.35690361113
Bremen optimizers	1	May 1, 2017, 10:13 p.m.	May 1, 2017, 10:13 p.m.	2	6760.20652880211

1st in Europe and 6th behind NASA JPL and China

Very few, if any, of humanity's inventions are designed to withstand equally extreme conditions. Rockets are subjected to awesome g-forces at lift-off, and experience extreme hot spots in places where aerodynamic friction acts most strongly, and extreme cold due to liquid hydrogen/oxygen at cryogenic temperatures. Operating a rocket is a balance act, and the line between a successful launch and catastrophic blow-out is often razor thin.

- The History of Rocket Science, Aerospace Engineering blog

HUMBLE BEGINNINGS…

Rocket propulsion started with the desire to build a pigeon

Roman writer Aulus Gellius tells a story of Archytas, who, sometime around 400 BC, built a flying pigeon out of wood. The pigeon was held aloft by a jet of steam or compressed air escaping through a nozzle.

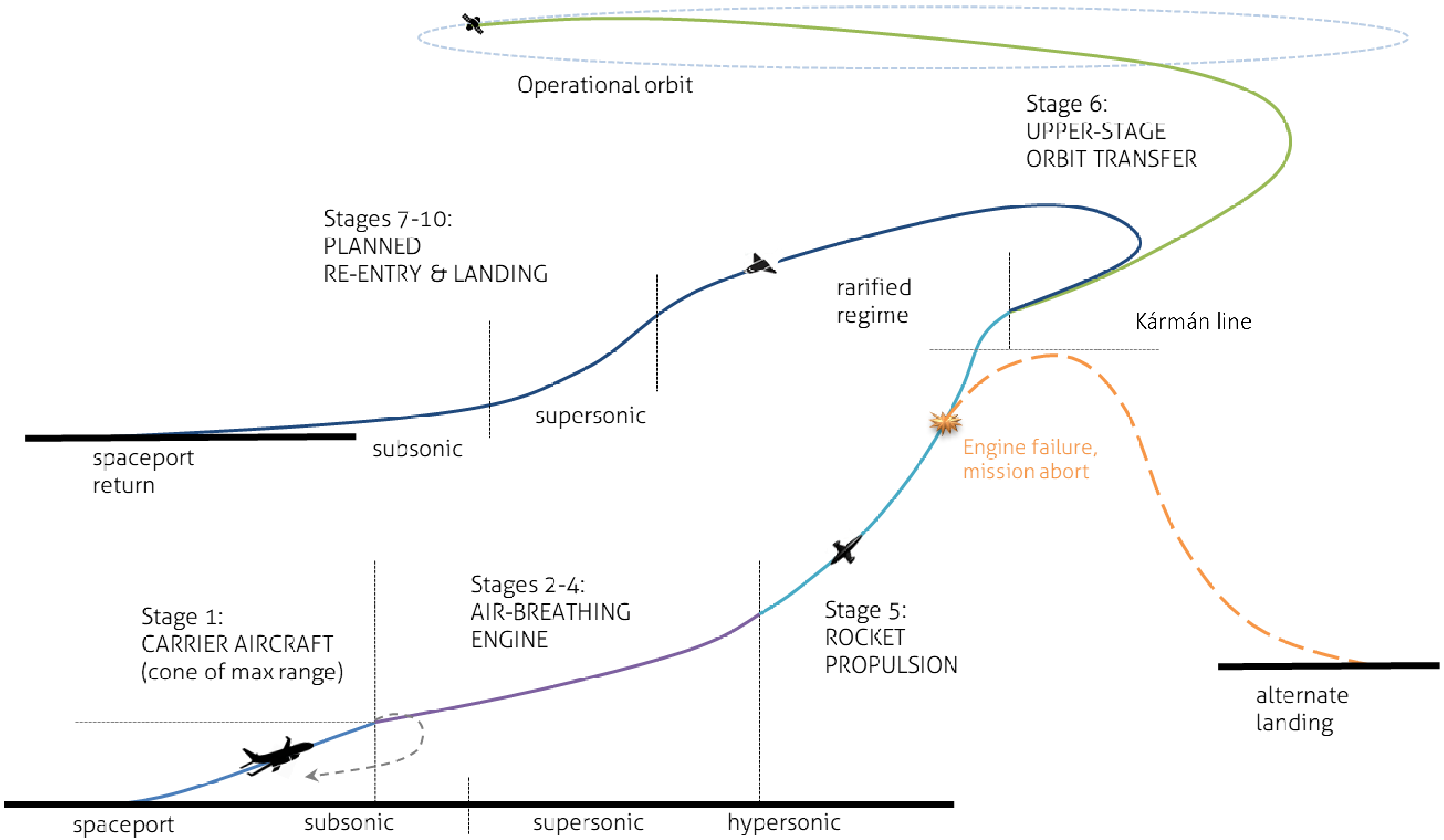
Three centuries later, Hero of Alexandria invented the aeolipile based on the same principle of using escaping steam as a propulsive fluid.

How do we access space? What are the technologies involved?

What could the future of space access systems look like?
What technologies do we need to make this happen?
What research do we need to make that happen?

What does the future of all atmospheric transportation look like?

What is state of the launch sector in the UK? What will this look like going forward?


Operational orbit
Stage 6:
UPPER-STAGE
ORBIT TRANSFER
Stages 7-10:
PLANNED
RE-ENTRY & LANDING
rarified
regime
Kármán line
supersonic
subsonic
spaceport
return
Engine failure,
mission abort
Stages 2-4:
AIR-BREATHING
ENGINE
Stage 1:
CARRIER AIRCRAFT
(cone of max range)
Stage 5:
ROCKET
PROPULSION
alternate
landing
spaceport
subsonic
supersonic
hypersonic

Defining Terms

AEROSPACE CENTRE of EXCELLENCE

Multiple objectives often defined by system/mission requirements

- Min(fuel), min(gtow), max(orbit alt), min(peak heat load, average load), max(reusable), min(variance from uncertainty)

Sets of **nonlinear constraints**: path and boundary, multi-phase trajectories

- Mass drops (stage separations), heating, dynamic pressure, loads, engine operating conditions, control saturation limits
- Geographic limits, landing sites, target orbits

Optimisable parameters: open loop control law, design parameters

- Wing reference area, nose cone radius, dry/wet masses, engine thrust
- Attitude control, thrust control

System & environment models: physics-based, **surrogate models**

- Aerodynamic databases for subsonic, transonic, supersonic in continuum regime (panel + CFD), drag in rarefied regime (gas dynamics)
- Propulsion, aerothermal, atmospheric, mass, cost

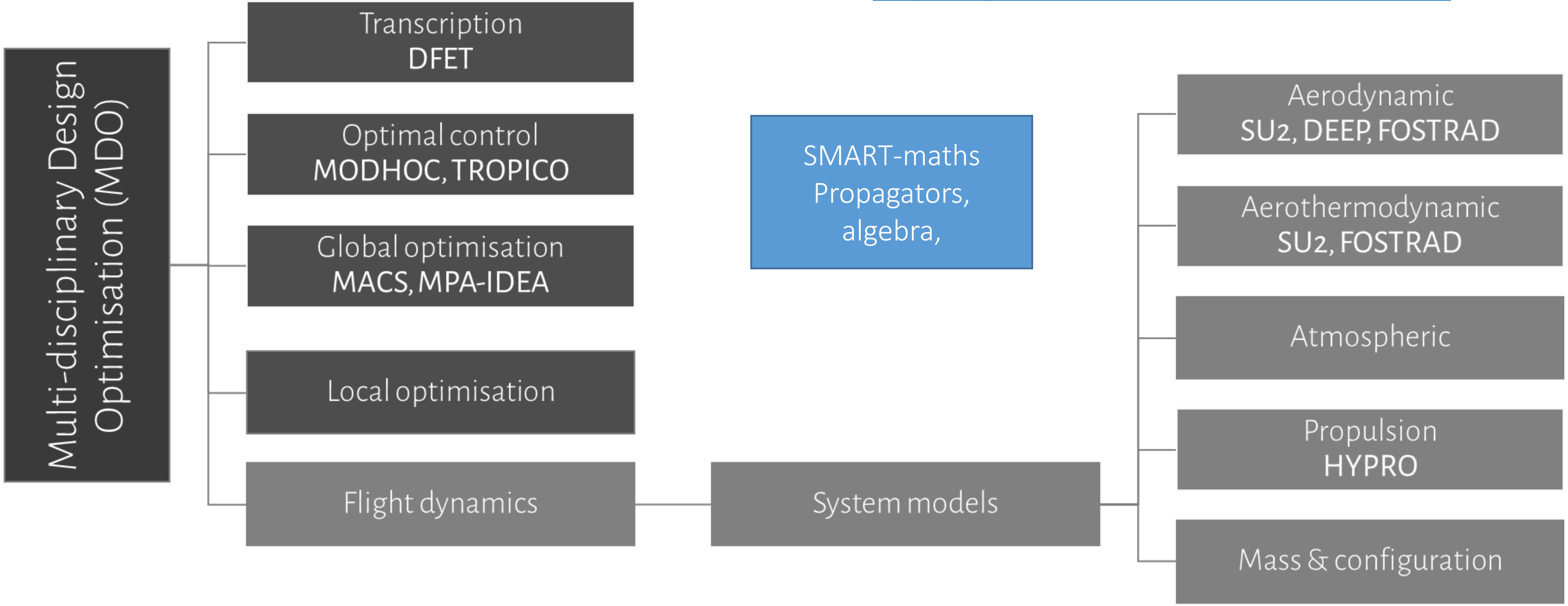
Uncertainty quantification, optimisation under uncertainty

- Epistemic (systemic) and aleatoric (statistical) uncertainty

Open Access Software

- Strathclyde Mechanical & Aerospace Research Tools (SMART) > in particular optimisation and optimal control (o2c) repo

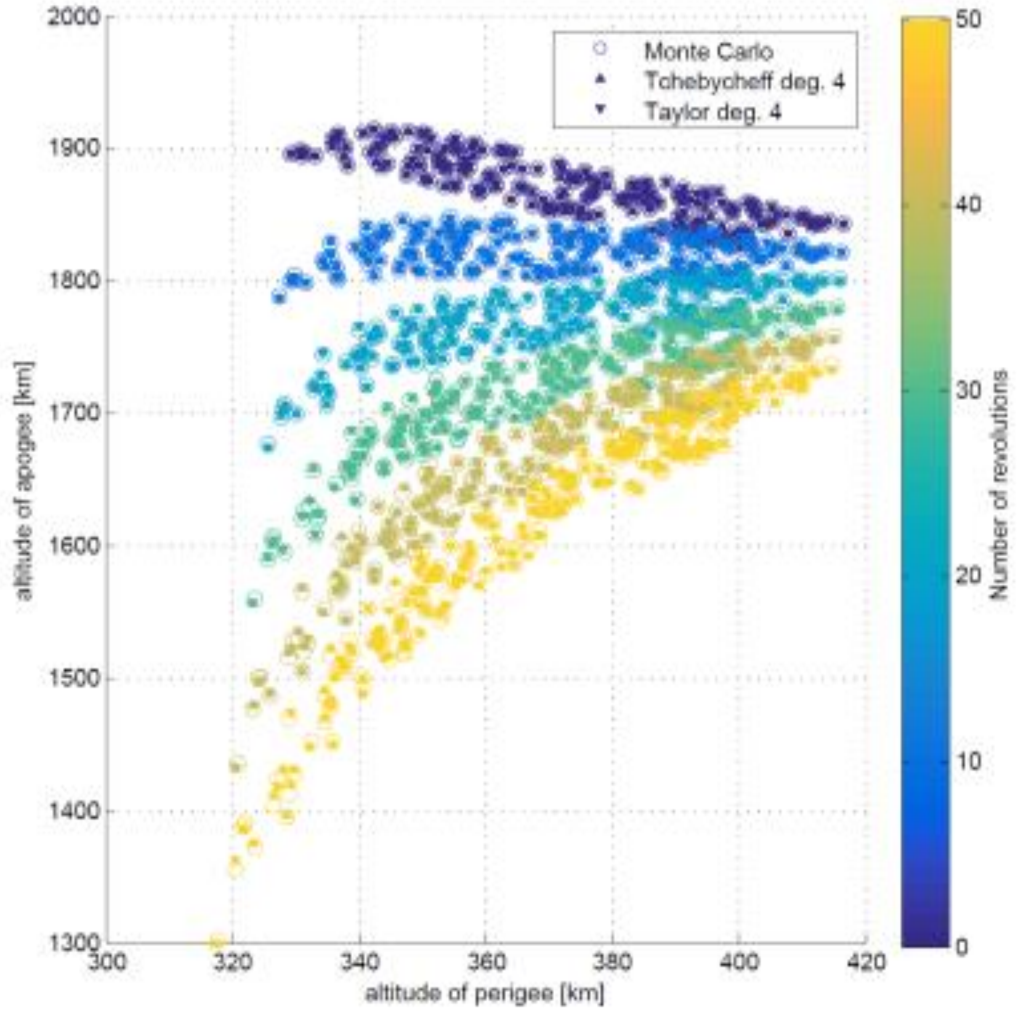
https://github.com/strath-ace/smart-o2c



Re-entry Tracking

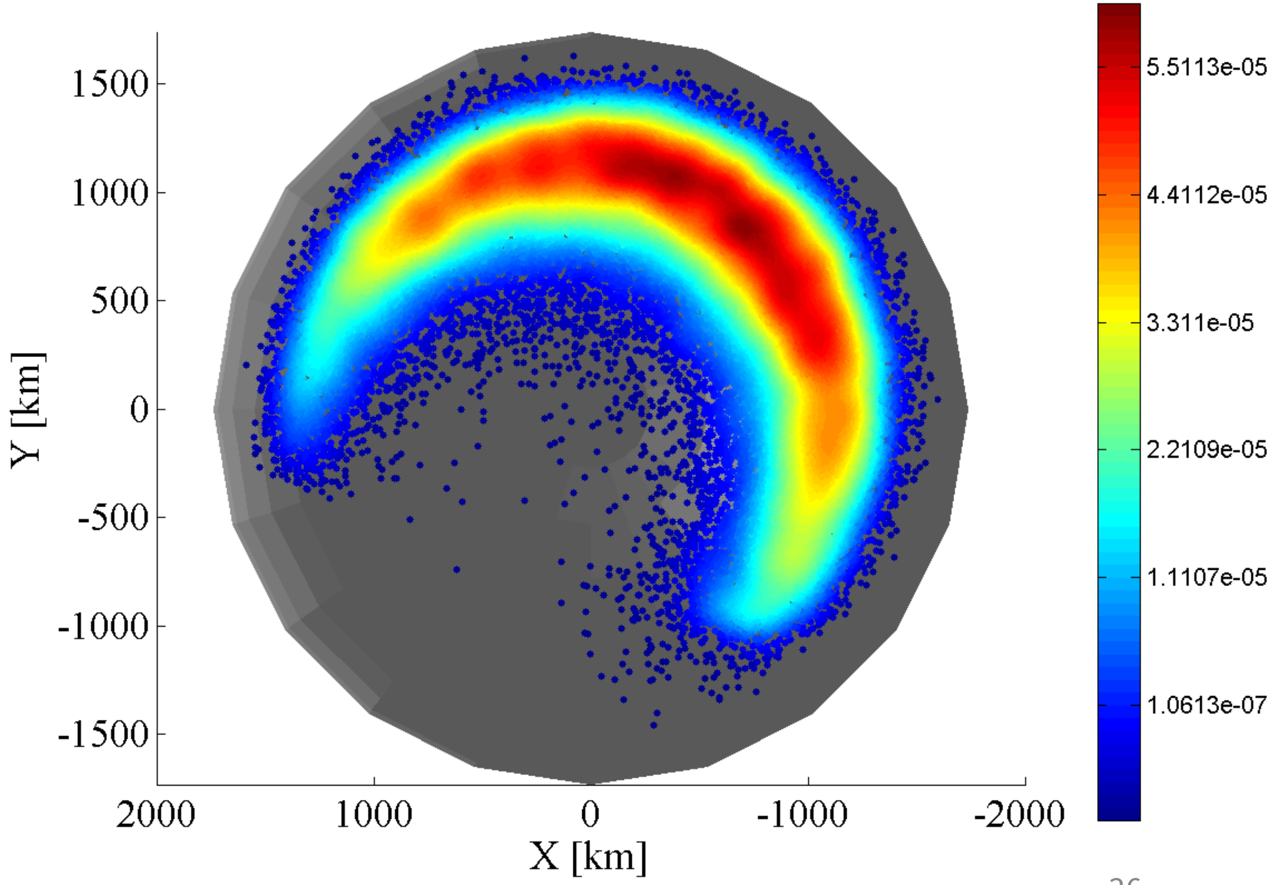
- Example of re-entry prediction
- Propagate entire regions through dynamical systems rather than single points
  - Uncertainty quantification of time varying processes, uncertainty propagation in dynamical systems
  - Stochastic optimal control
  - Filtering and state estimation in GNC
  - Propagation of level sets

RE-ENTRY ANALYSIS OF GOCE



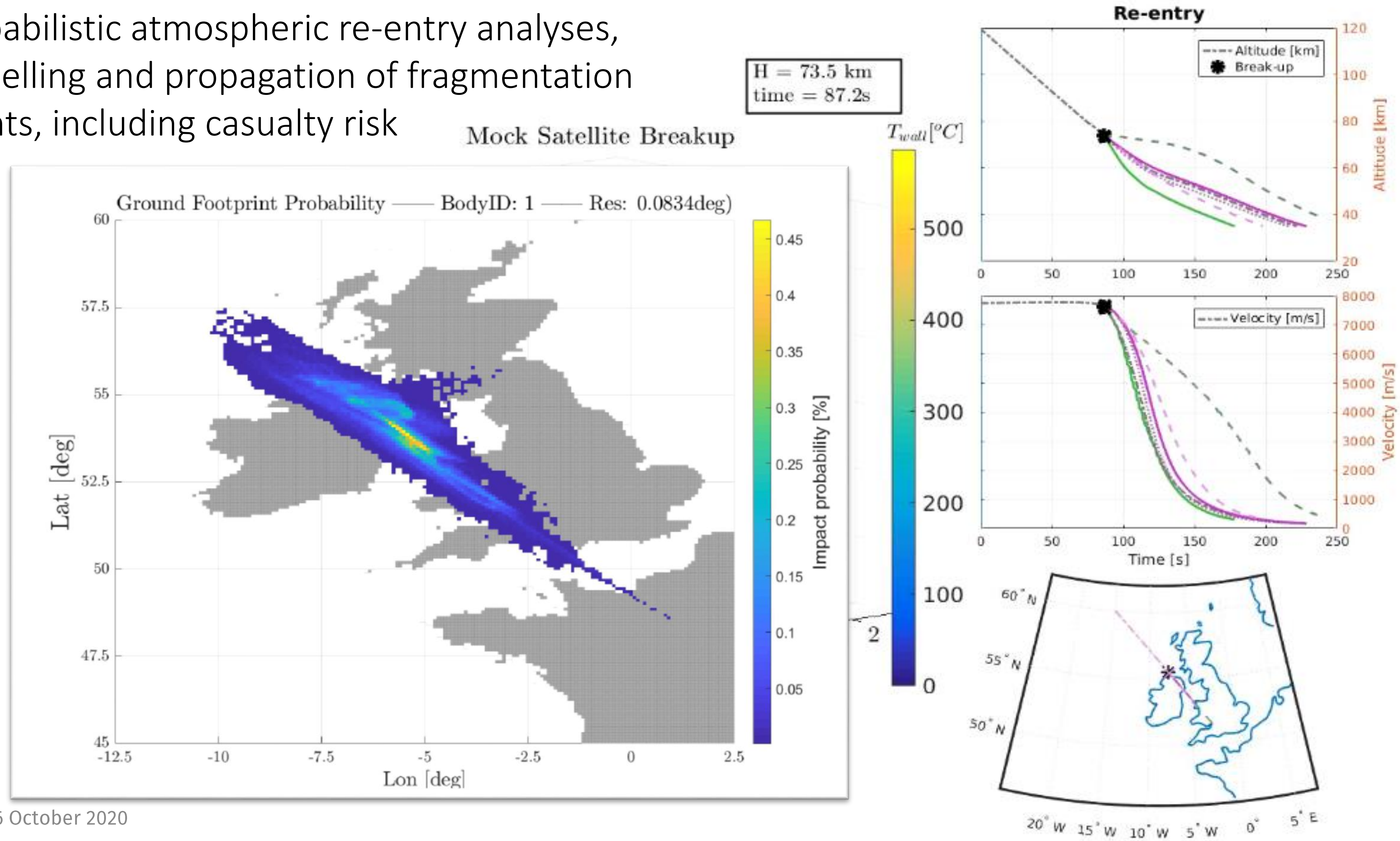
Impact Prediction

- Example of impact prediction, disposal of Gaia to the Moon, subject to uncertainty on the initial conditions
- Impact probability and full trajectory analysis from L1 and L2
- Orders of magnitude faster than Monte Carlo



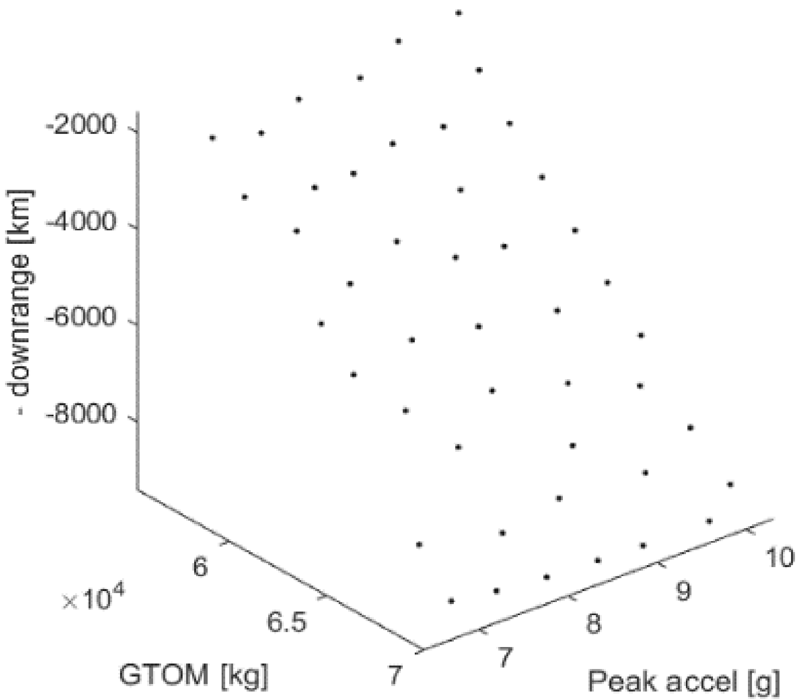
Particles dispersion and density at impact for 1% manoeuvre error and 5 km dispersion error
Colourbar represents the probability density

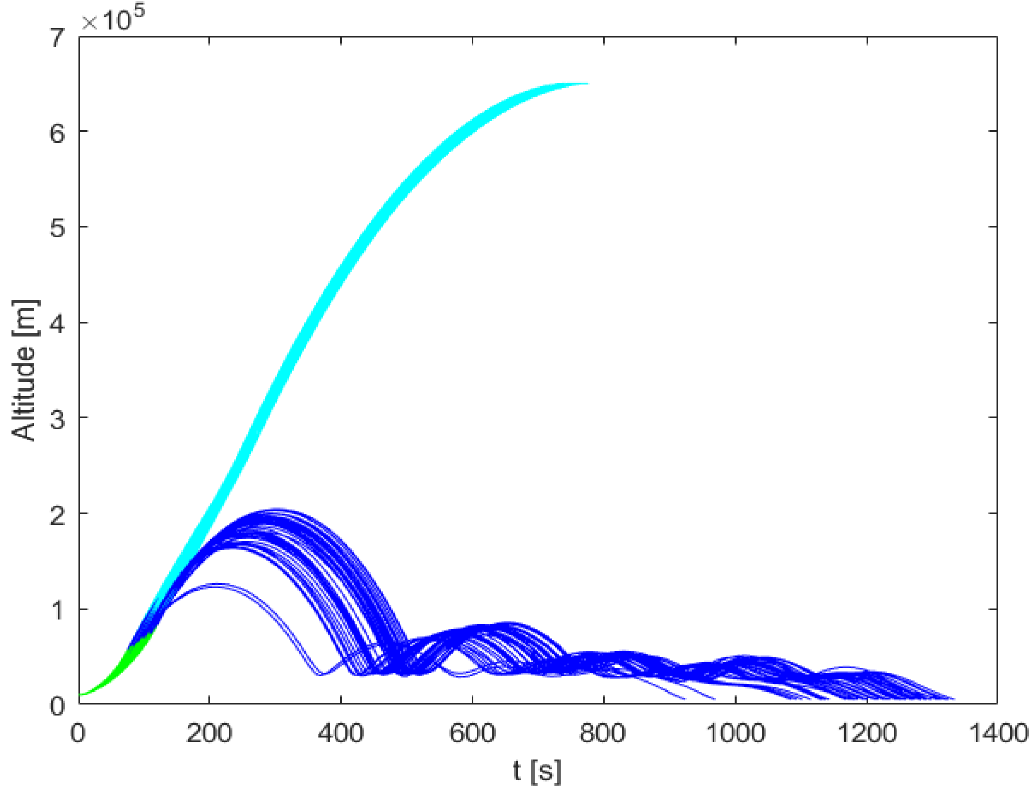
Probabilistic atmospheric re-entry analyses, modelling and propagation of fragmentation events, including casualty risk



Case Studies

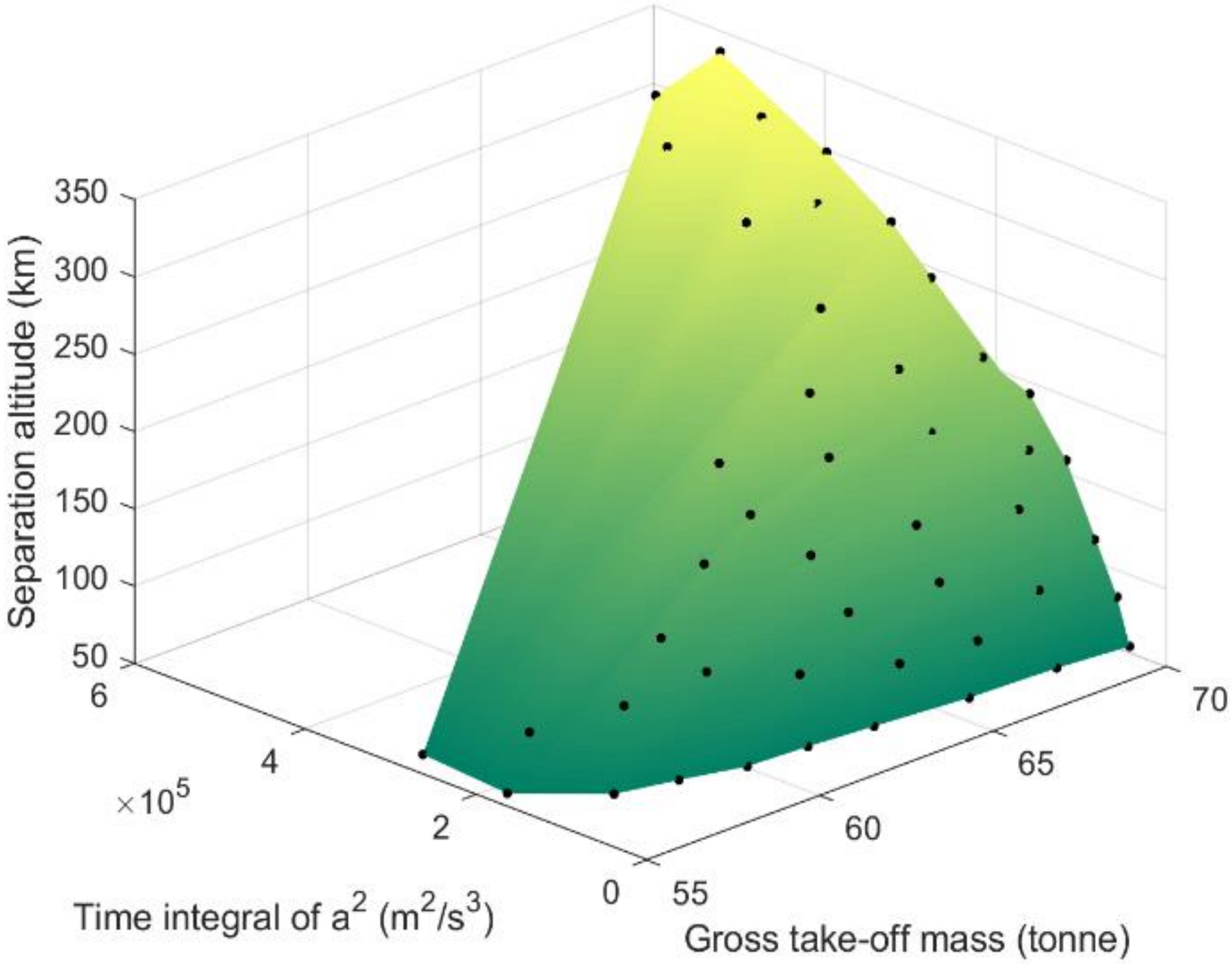
- Study examined the impact between:
  - downrange glide capability,
  - gross take-off mass (GTOM) of the vehicle, and
  - the total induced accelerations on the centre of mass during flight for two-stage spaceplane system





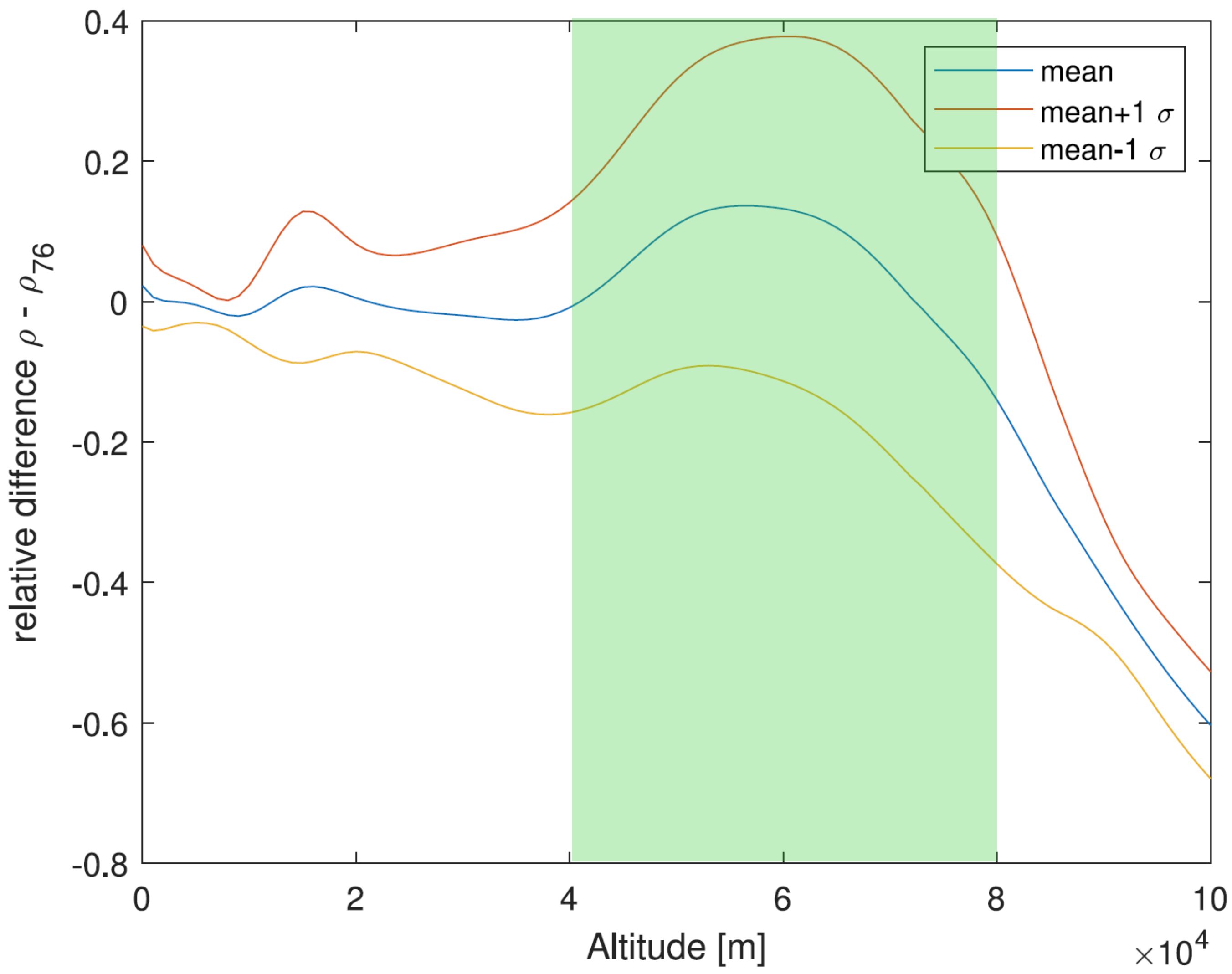
Case Studies

- Trade-off analysis for two-stage system, looking at impact of separation conditions on the vehicle design
  - Discrete control law
  - Times of flight for each stage for ascent, separation, orbital insertion and re-entry
  - Engine sizing for each stage (engine mass, propellant masses, thrust performance)
  - Gross take-off mass

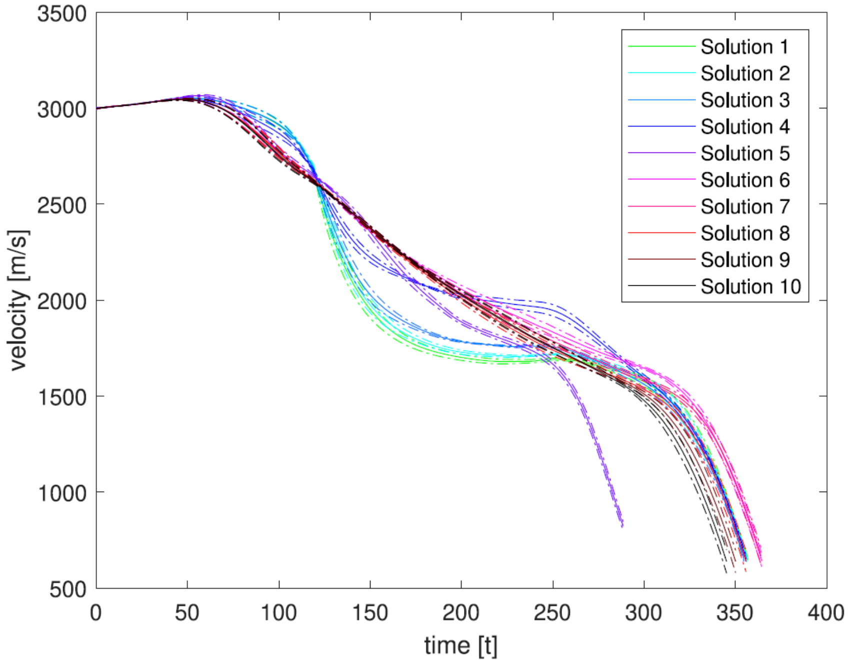


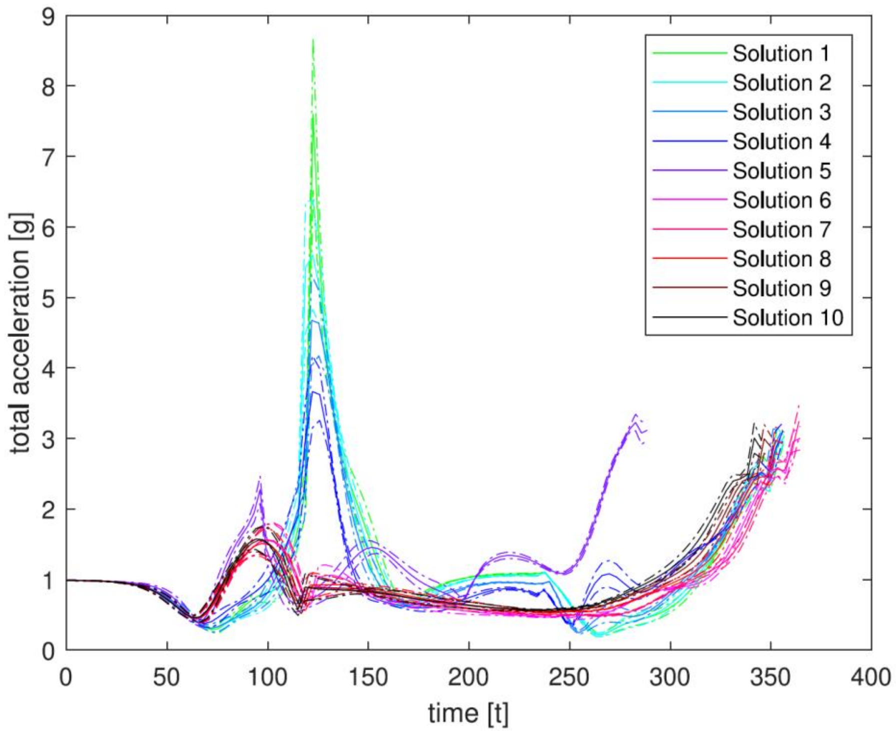
Case Studies

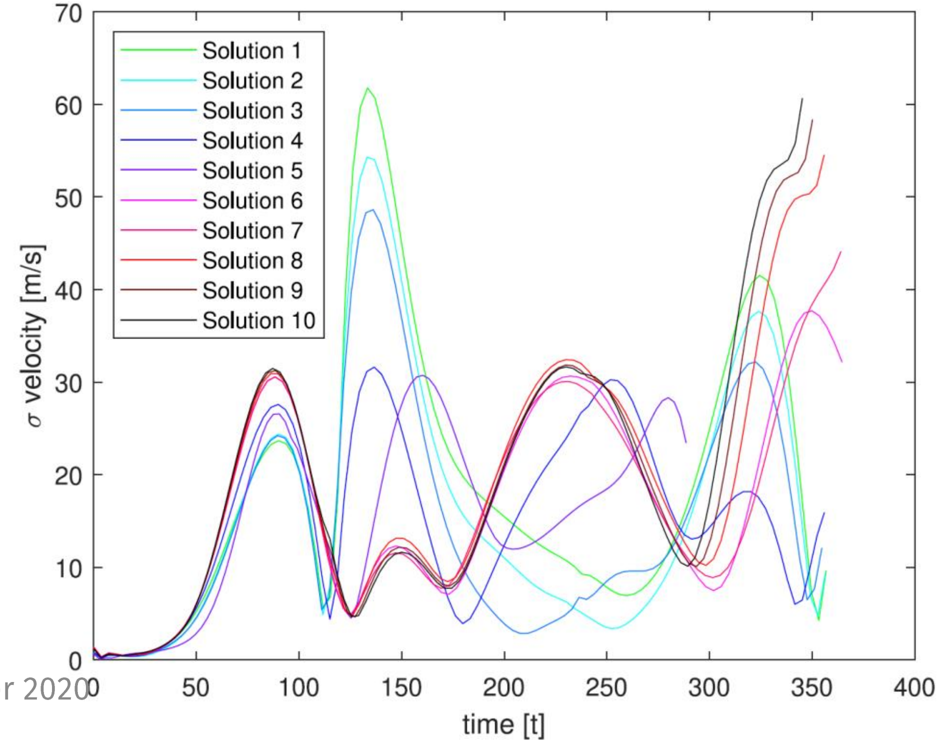
- Descent guidance strategy for TSTO spaceplane under atmospheric uncertainty
- Model of uncertainty for atmospheric density, largest difference between [40, 80] km

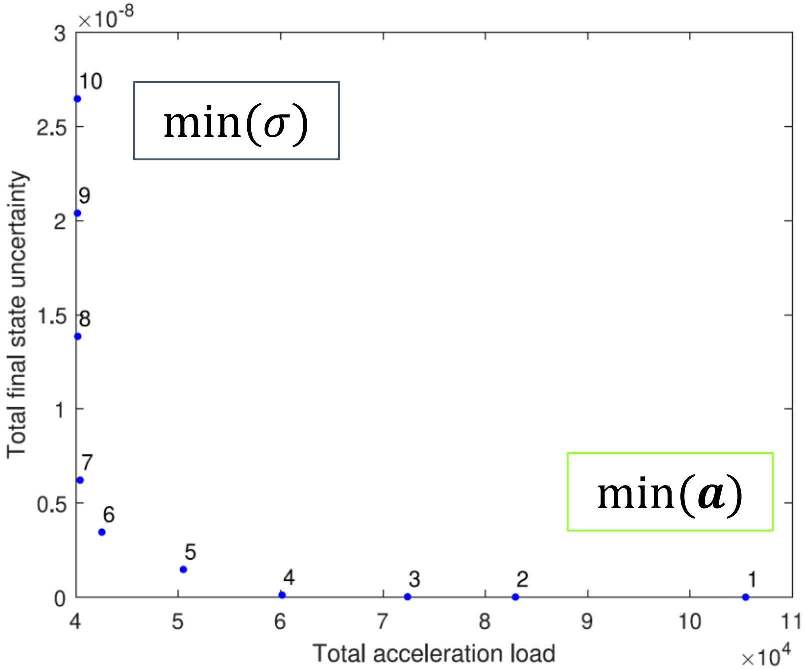


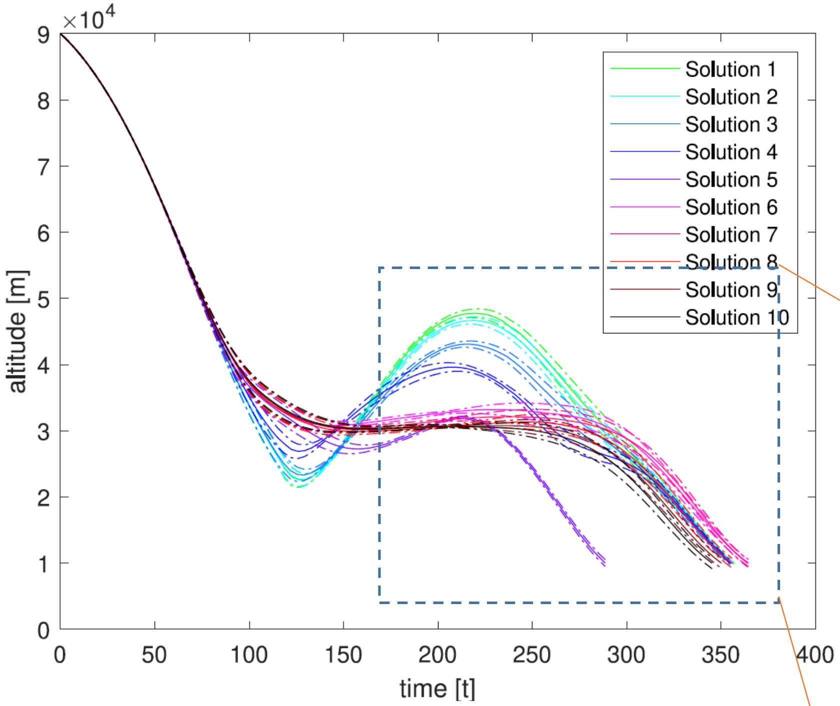
AEROSPACE CENTRE of EXCELLENCE



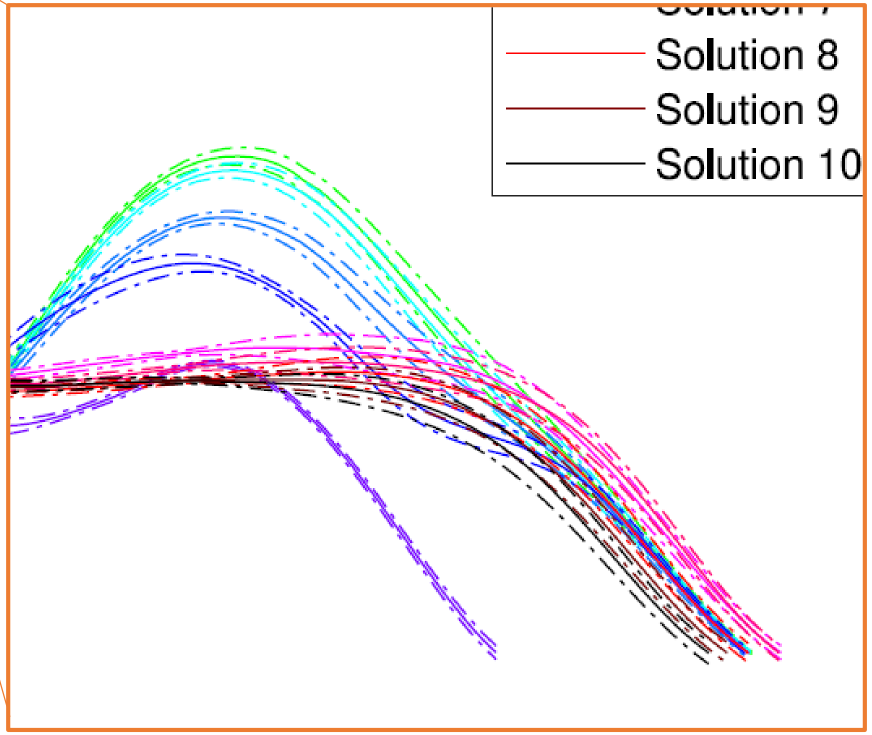


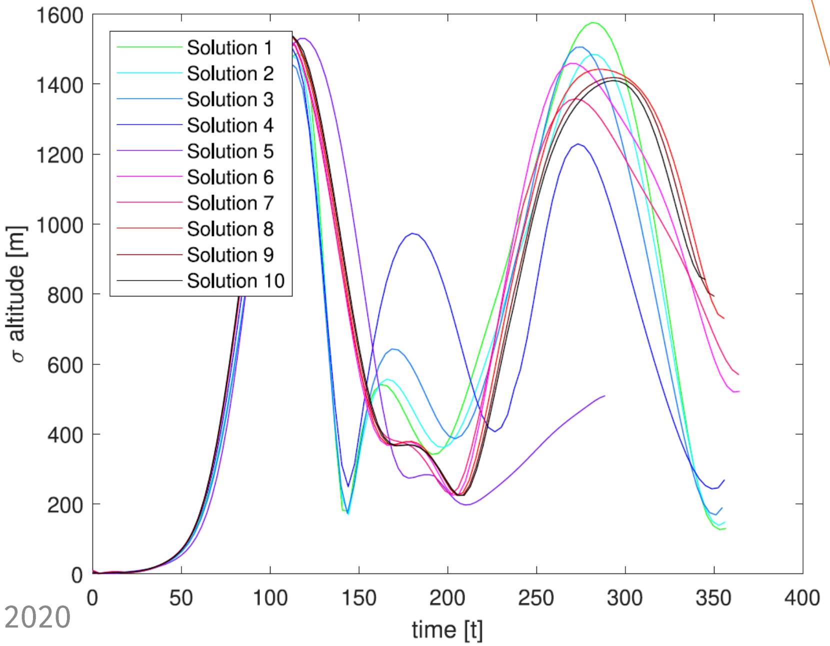






Altitude plots for nominal and OOU (dashed)





AEROSPACE CENTRE of EXCELLENCE

Summary

- Universities drive (curiosity led) research, take promising methods and analyse the application to areas of interest (industry/society driven)
- In the UK, space and space access is a critical and growing market, and includes many homegrown, and international launch vehicle developers, operators, regulators, and spaceports
- Numerical analyses, from CI/AI to mathematical theories to computational implementations/processing is crucial to any design, and in particular commercial developments
    - Allows to wider remit to explore reliability and robustness of design options at a system level
    - Not just technical objectives, but cost, development, manufacturing models directly into initial concept design

University of Strathclyde Glasgow