Solar-Aerodynamic Formation Flight for 5G Experiments

by J. Thoemel, J. Querol, Z. Bokal, J. Duncan, M. Gholamian, O. Kodheli, S. Kumar, C. Martinez, N. Maturo, L. Rana, S. Chatzinotas, M. Olivares, T. Van Dam, A. Abdalla, J. Doche, H. Atrache, R. Palisetty, S. Chacon, B. Ottersten

November 24th, 2021

12th European CubeSat Symposium

Paris-Palaiseau, France

UNIVERSITY OF LUXEMBOURG

University of Luxembourg
Interdisciplinary Centre for Security, Reliability and Trust

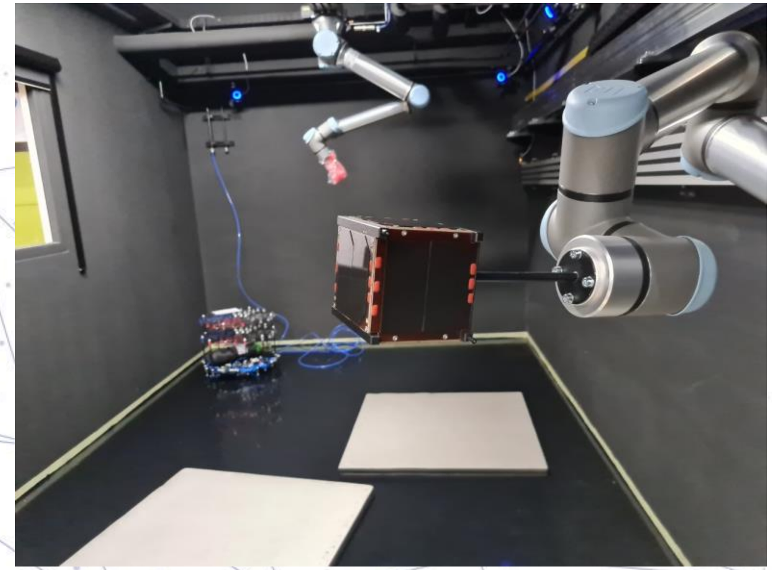
- Space Research & Space Labs
    1. LunaLab – analogue facility
    2. Concurrent Design Facility
    3. ZeroG Lab
    4. CubeSatLab – CubeSat integration facility
    5. SatComLab – testbed for satellite communication
    6. 5G Space Lab project

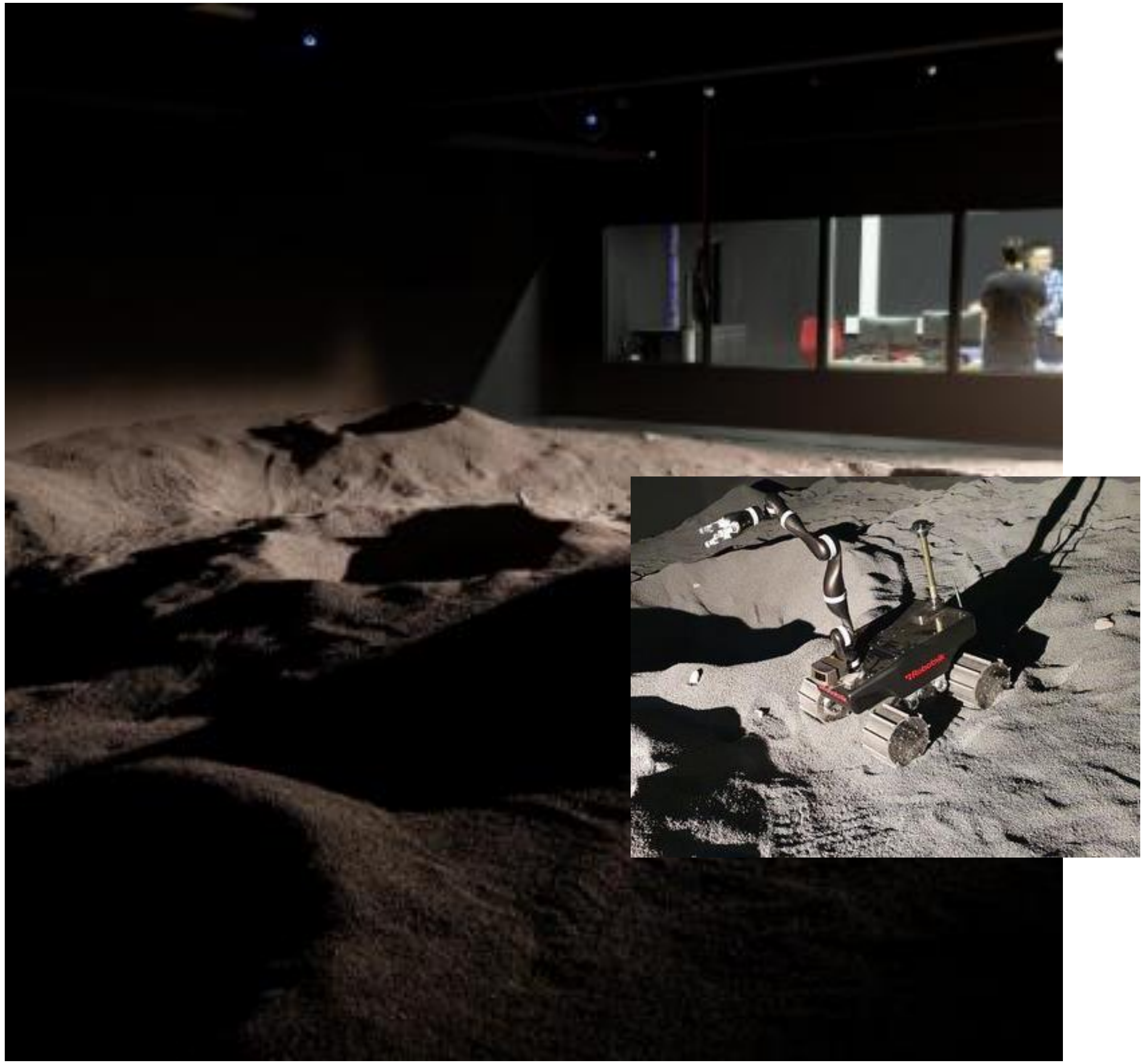
- Interdisciplinary Space Master, courses on
    - technical competences:
        - mission design
        - system engineering
        - satellite communication
        - robotics
        - navigation
    - business competences:
        - entrepreneurship
        - space project management
        - legal aspects

LunaLab & ZeroG Lab

- simulates surface of the Moon:
  - material: regolith/basalt
  - topology: craters
  - lighting: sun, crater shadows

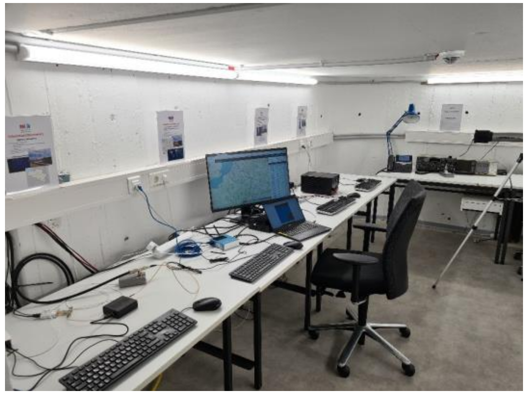
- interaction of two objects in orbit
  - rendezvous
  - space debris grabbing
  - computer vision

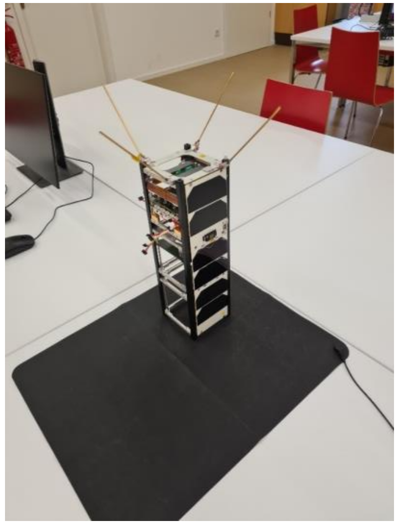




CubeSatLab

- course:
  - basics of low earth orbit space flight and CubeSats
  - design of a CubeSat mission
  - experimenting with the EduSat
- facility:
  - satellite integration room
  - observatory



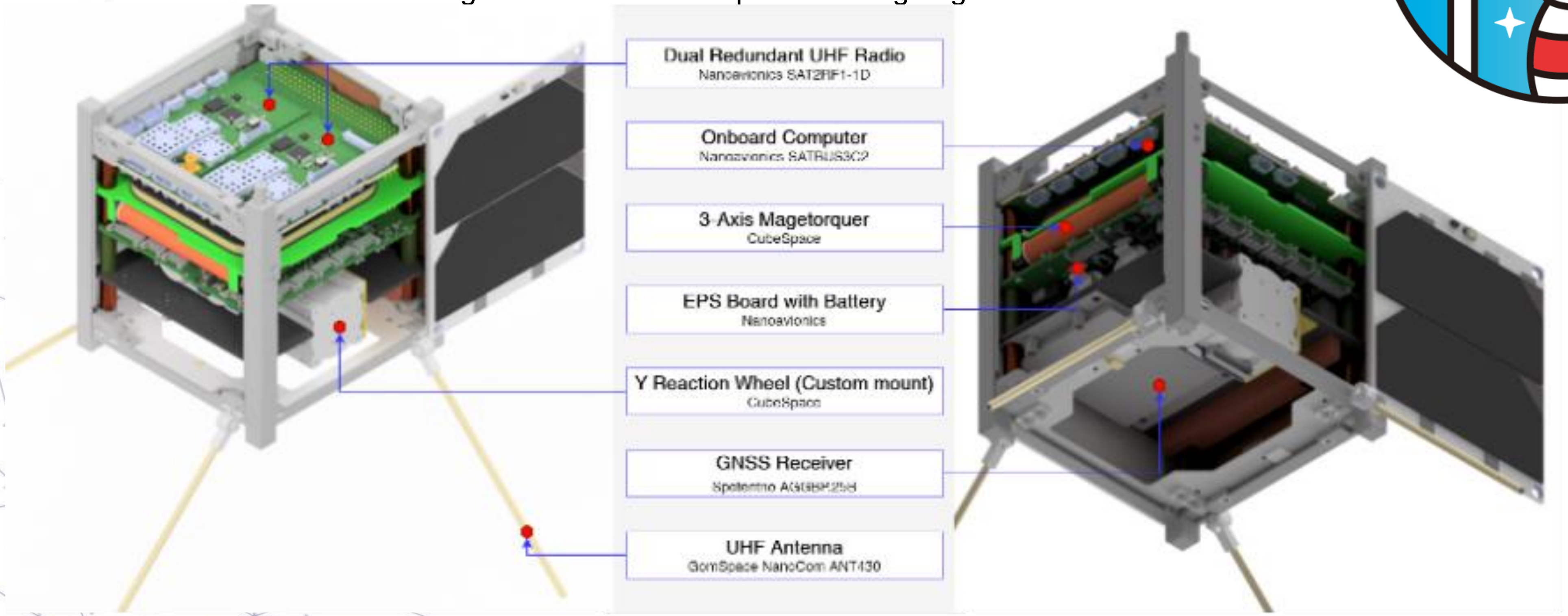


Students designed CubeSat Mission: GoldCrest

determination of soil moisture with:

- 1U CubeSat mission featuring 1 solar panel
- orbit: 6 am SSO
- on-board processing for data reduction
- measurement method GNSS-reflectometry

investigation into business potential ongoing



Friday 26 November 2021, 14:15 – 14:30, Session 10: Cubesat Missions

Global land dampness characterization using reflectometry by students (GOLDCREST): mission and CubeSat design (ID 70)

5G-SpaceLab (Earth-orbiting Scenario)
Objectives and Challenges

Objective:

- **Emulation of LEO CubeSat-based Over-The-Air (OTA) 5G Non-Terrestrial Network (NTN) communication**

To address the challenges:

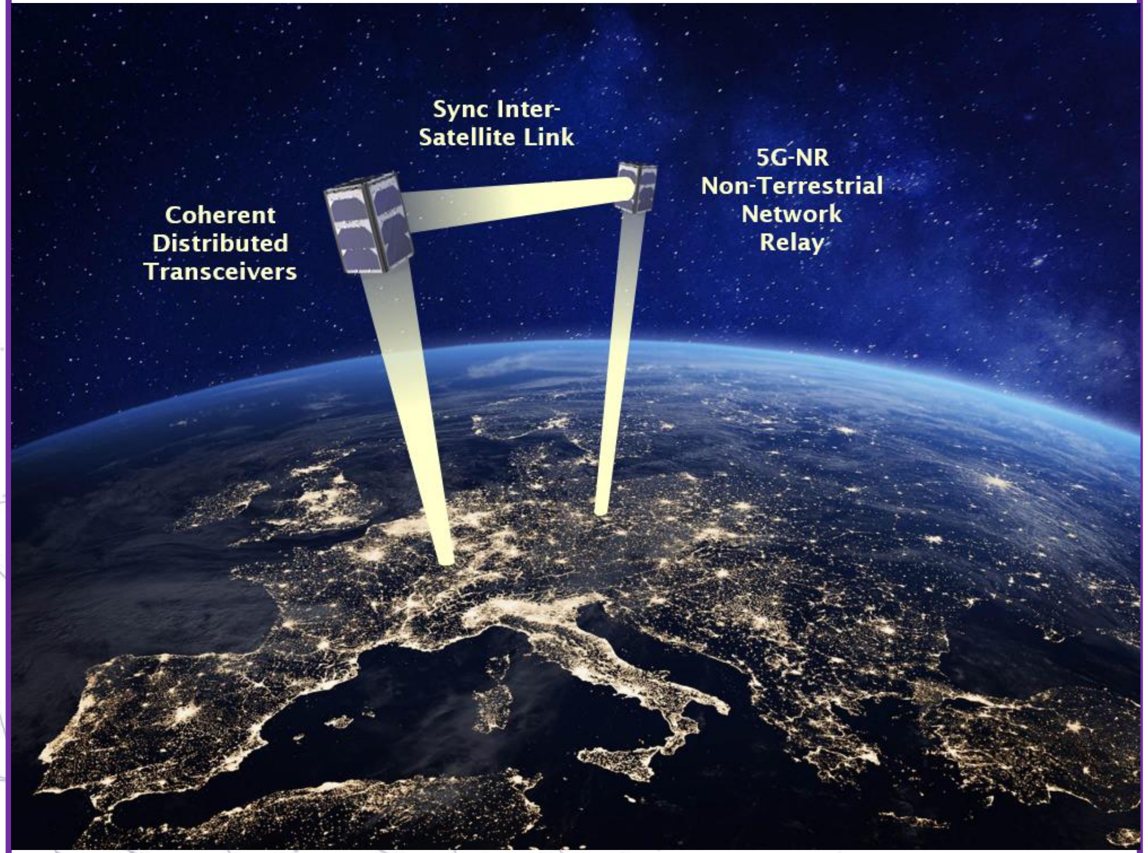
1. **Doppler Shift**
2. **Latency**
3. **Seamless hand-over**

Through the following test scenarios

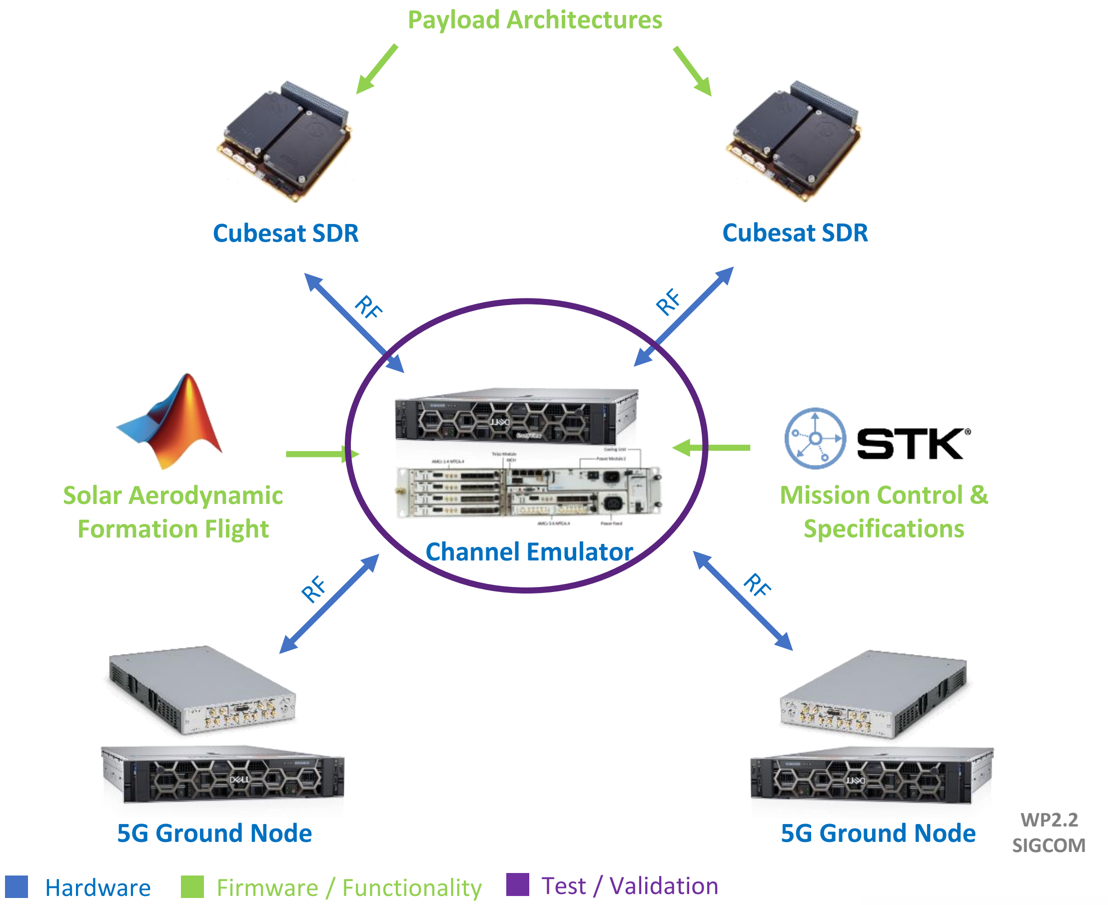
1. **bent-pipe**
2. **node-relaying**
3. **coherent distributed communications**

5G-SpaceLab (Earth-orbiting Scenario)

Conceptual Diagram



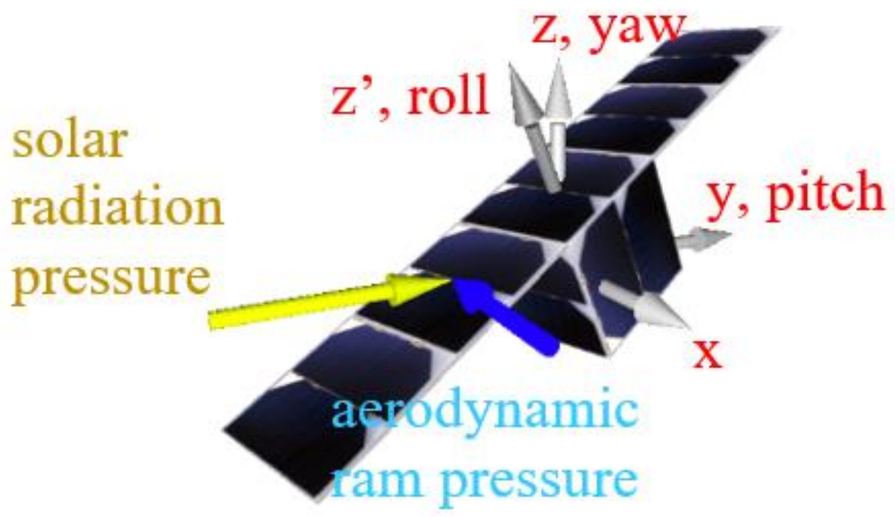
Laboratory Implementation



Challenge: Satellite Flight

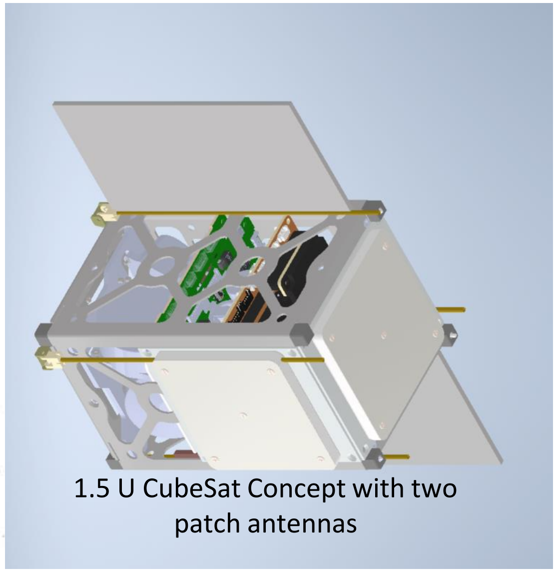
- Problem 1:
  Requirement on a defined distance between the satellites
- Solution:
  Formation Flight, i.e. Multiple satellites with closed-loop control on-board provide a coordinated motion control on basis of relative positions to preserve an appropriate topology for observations[1].

- Problem 2:
  Control and Control Forces
- Solution:
  Aerodynamic and solar-radiation forces combined with an control algorithm

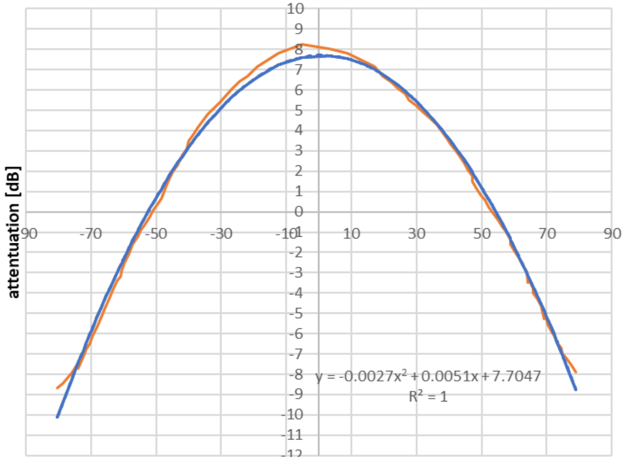


[1]adapted from: K. Schilling, "Mission Analysis for Low-Earth-Observation Missions with Spacecraft Formations," *RTO-EN SCI-231 - Small Satell. Form. Distrib. Surveill. Syst. Des. Optim. Control Considerations*, pp. 1–24, 2011.

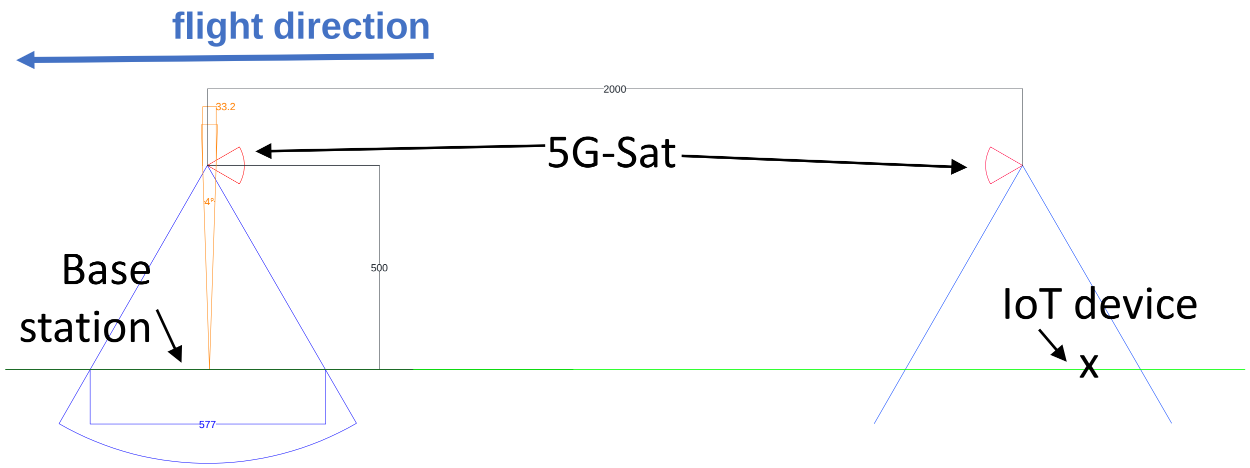
Challenges: communication



1.5 U CubeSat Concept with two patch antennas



antenna pattern GomSpace ANT2000-> 30deg half-cone width

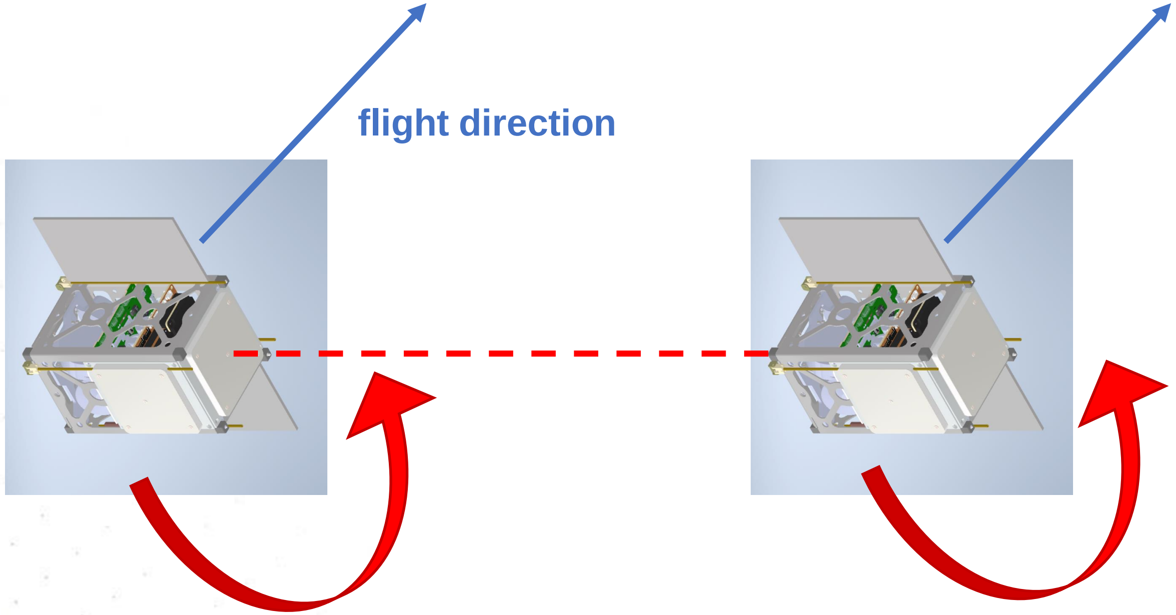


dimensions in km and deg

-> In trailing formation: experiment duration is ~90 s/day

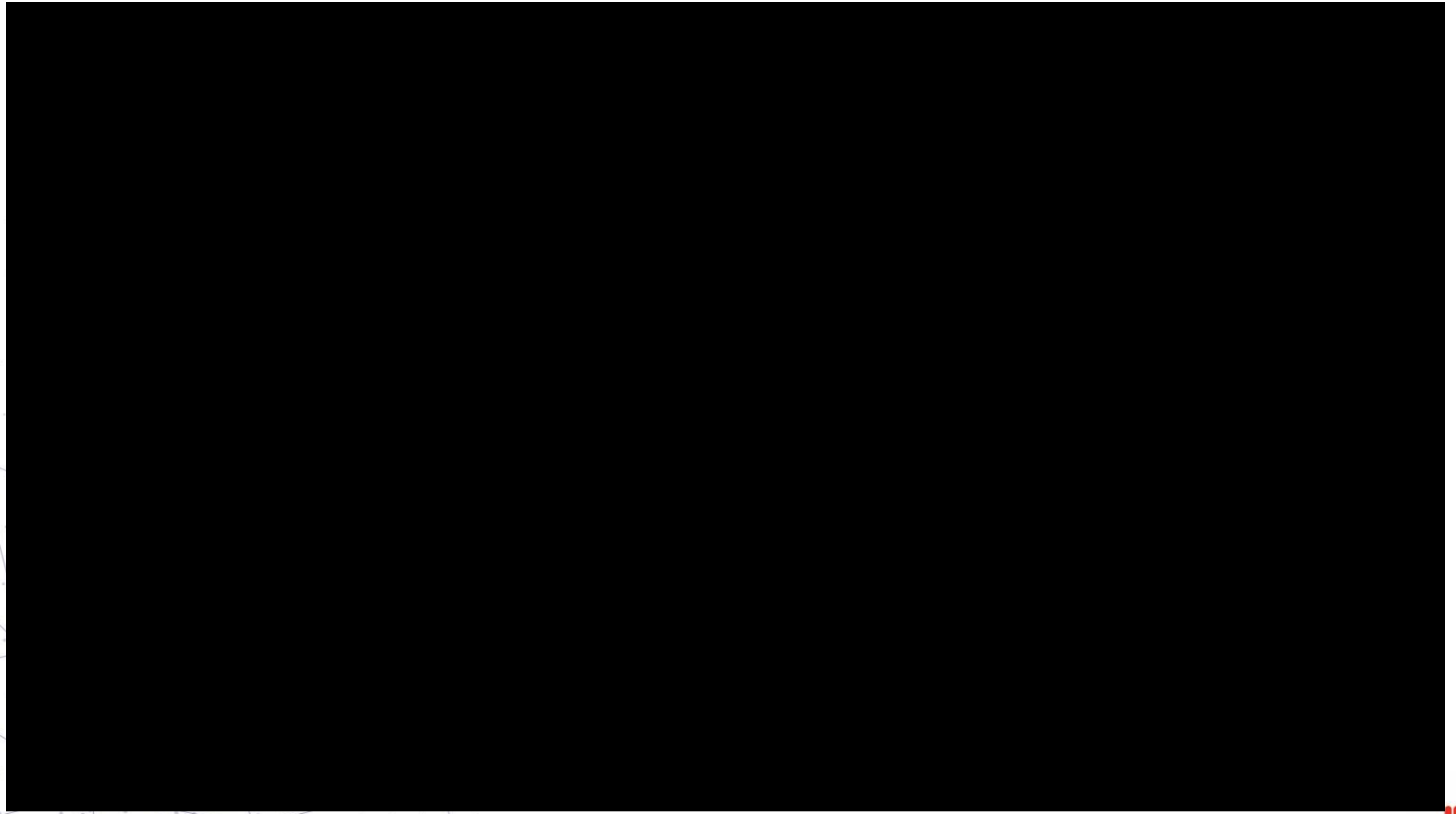
Formation Flight Experimentation Solution

- **Side by Side flight with roll/one-axis target pointing**

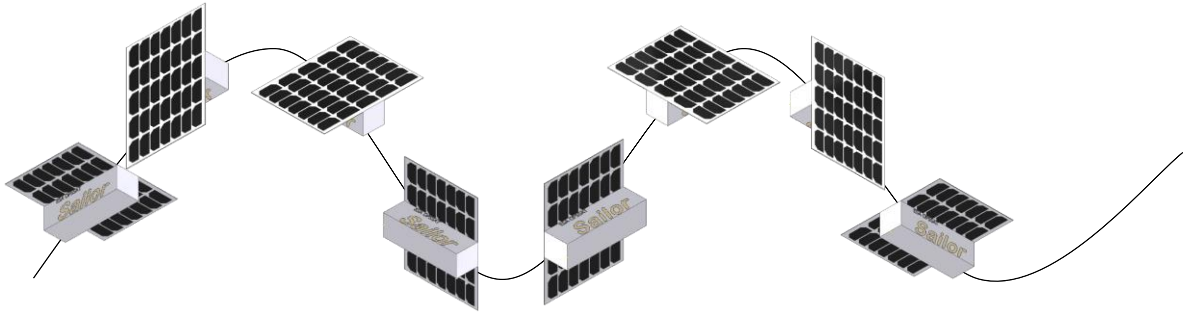


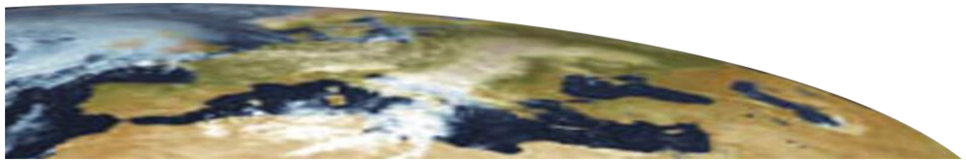
-> experiment duration ~15 min/day

Simulation Results

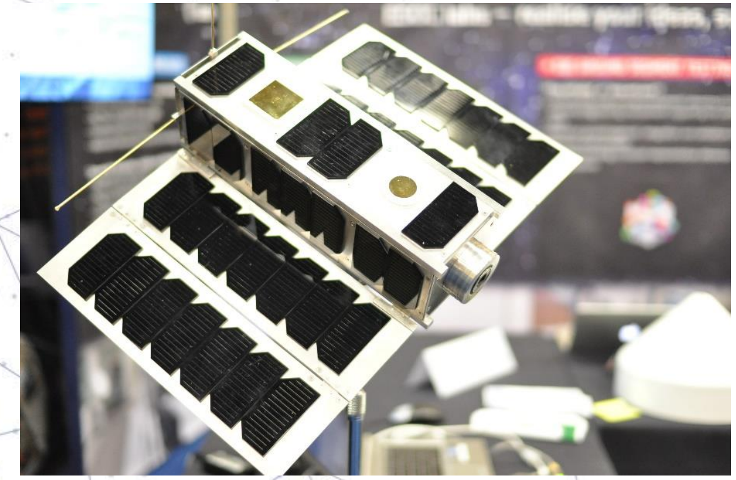


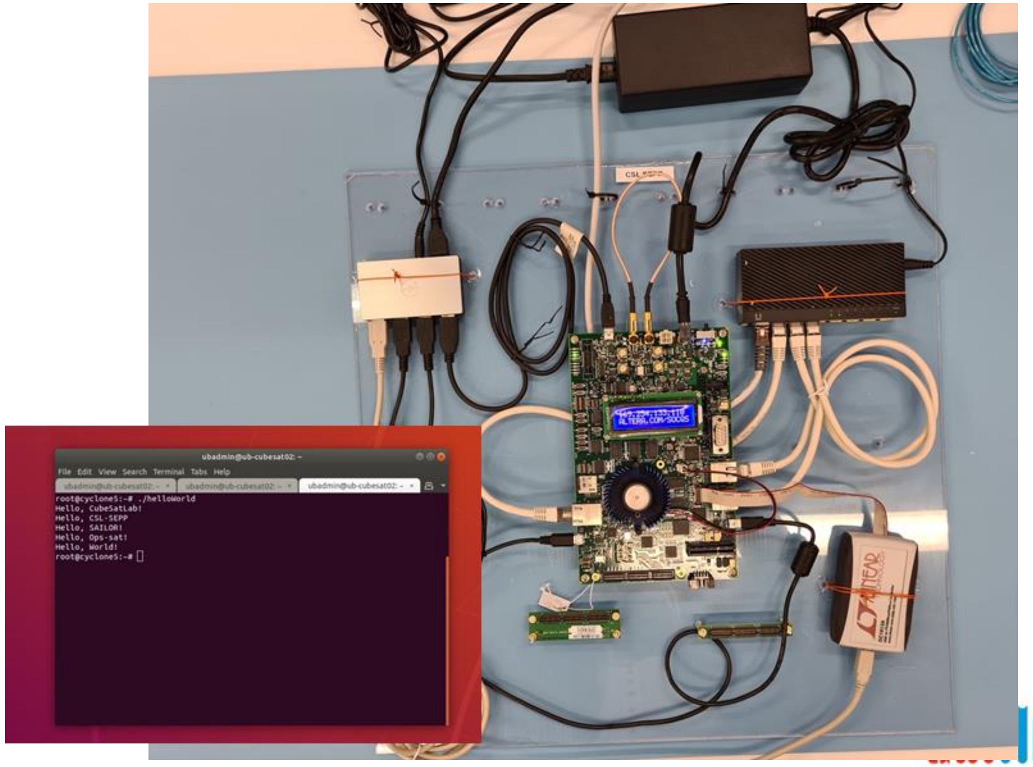
Next: Project Sailor





- **Objective:**
  - prove formation flight algorithm in-situ
  - 5G use case as reference
- **Means:**
  - ESA Opssat
  - combination real satellite-virtual satellite
- **Status:**
  - Experiment approved
  - ESA OSIP Idea accepted
  - cosmos code in upgrading
  - Opssat payload computer engineering model established





Concluding Remarks

1. **Uni.lu researches formation flight**

Thank you!
Do you have any questions?

Speaker: Jan Thoemel

University of Luxembourg
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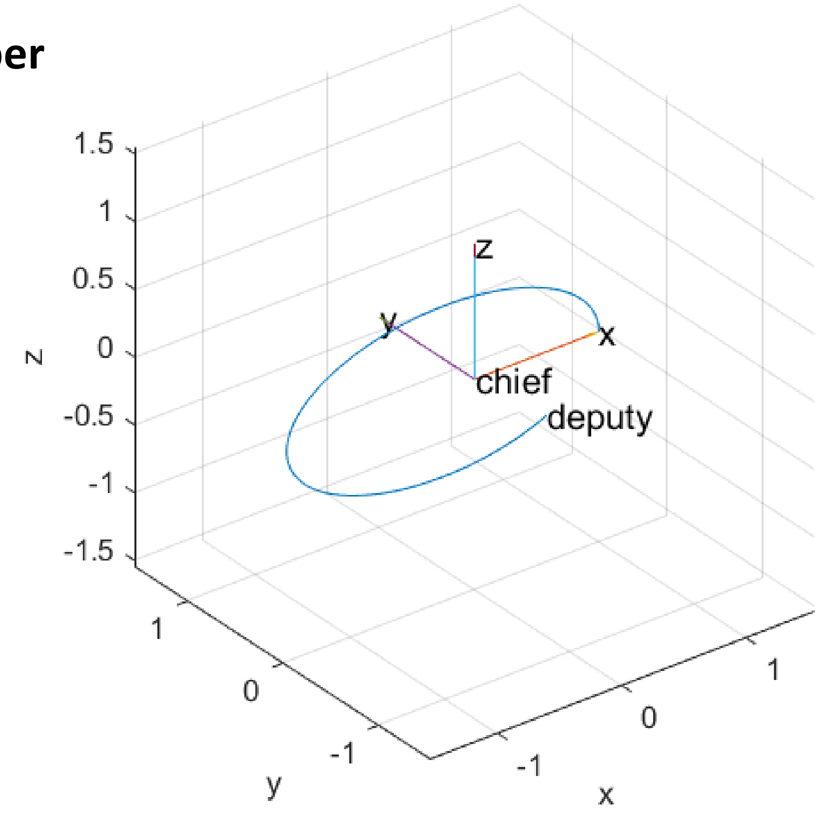
Derivation Formation Flight Physics I

- from Kepler body problem
- given a local coordinate system (figure)
- the following equations can be derived for each formation member



$$\ddot{x} - 2\omega\dot{z} = 0$$
$$\ddot{y} + \omega^2 y = 0$$
$$\ddot{z} - 2\omega\dot{x} - 3\omega^2 z = 0$$

- Hill-Clohessy-Wiltshire equation
- set of ordinary differential equation for
  - three spatial coordinates: x,y,z
  - each formation flight member satellite
- right-hand-side is zero -> no forces/propulsion applied

Derivation Formation Flight Physics II

analytical solution for Hill-Clohessy-Wiltshire equation, deputy satellite:

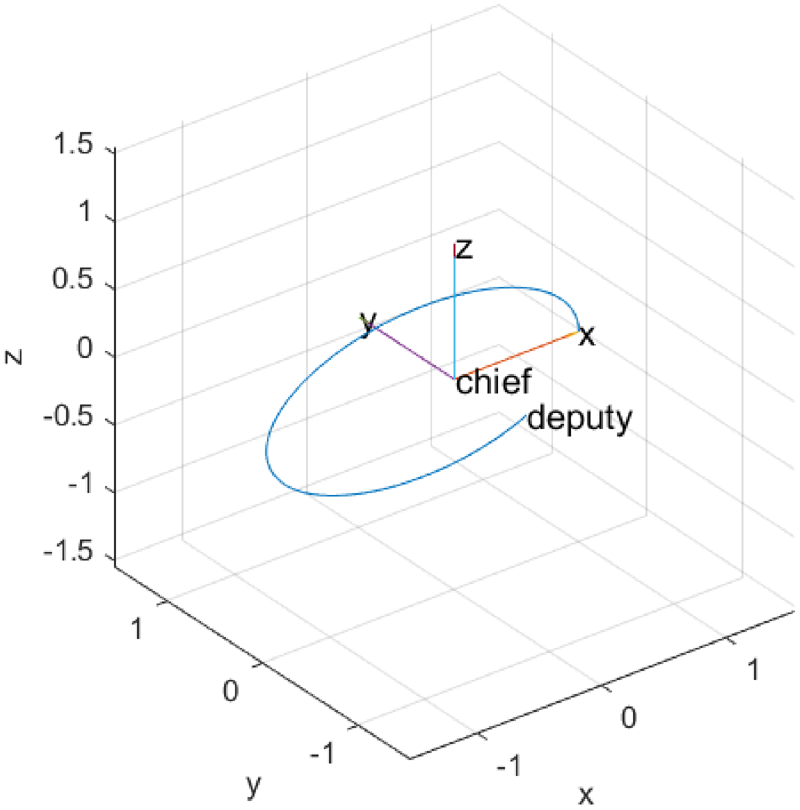
$$x(t) = -3C_1\omega t + C_2\cos(\omega t) + C_3\sin(\omega t) + C_4$$
$$y(t) = C_5 sin(\omega t) + C_6 cos(\omega t)$$
$$z(t) = 2C_1 + C_2 sin(\omega t) + C_3 cos(\omega t)$$

constants:

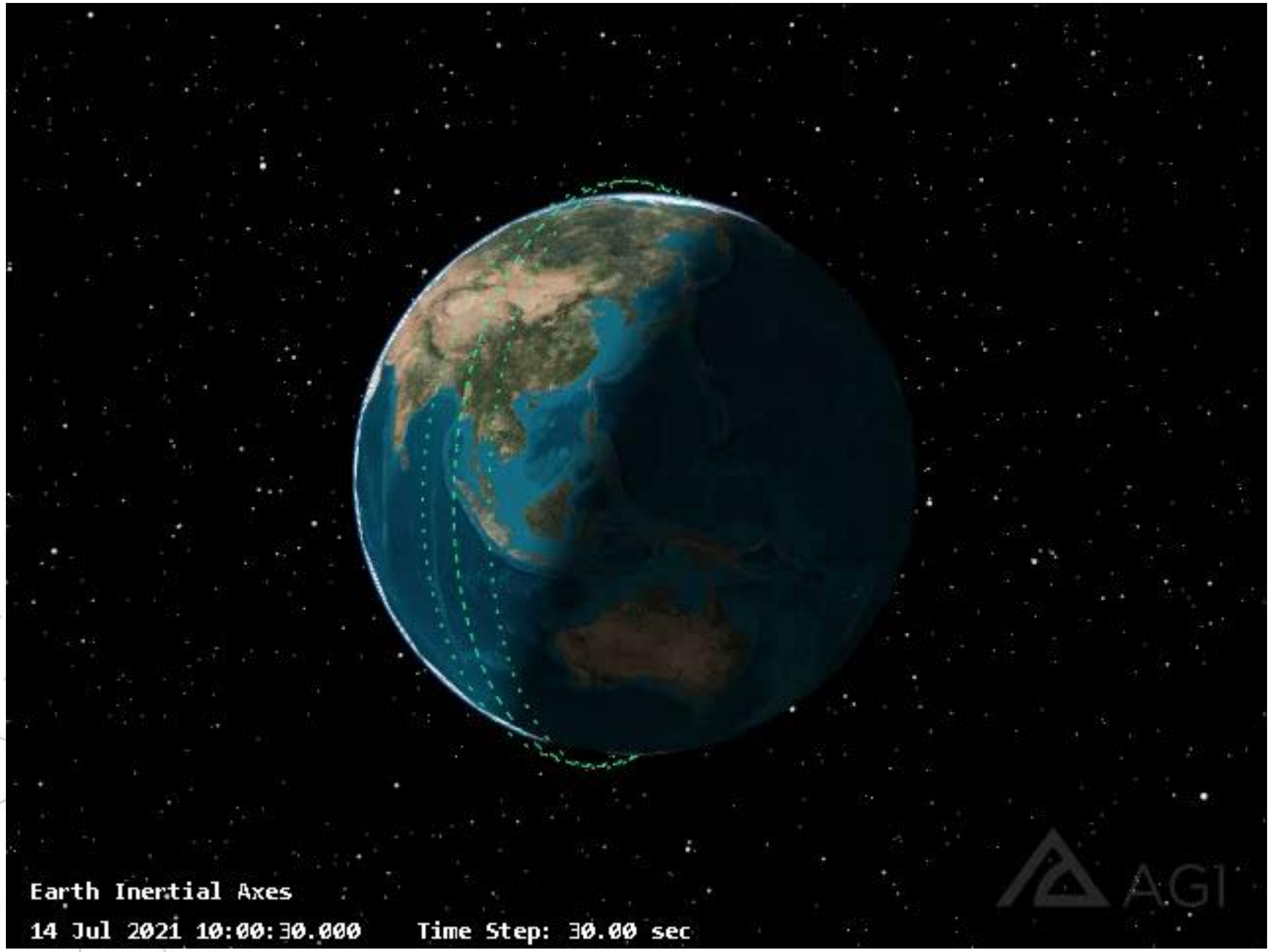
$$C_1 = \frac{u(0)}{\omega} + 2z(0)$$
$$C_2 = \frac{w(0)}{\omega}$$
$$C_3 = -3z(0) - \frac{2v(0)}{\omega}$$
$$C_4 = x(0) - \frac{2w(0)}{\omega}$$
$$C_5 = \frac{v(0)}{\omega}$$
$$C_6 = y(0)$$

initial conditions:

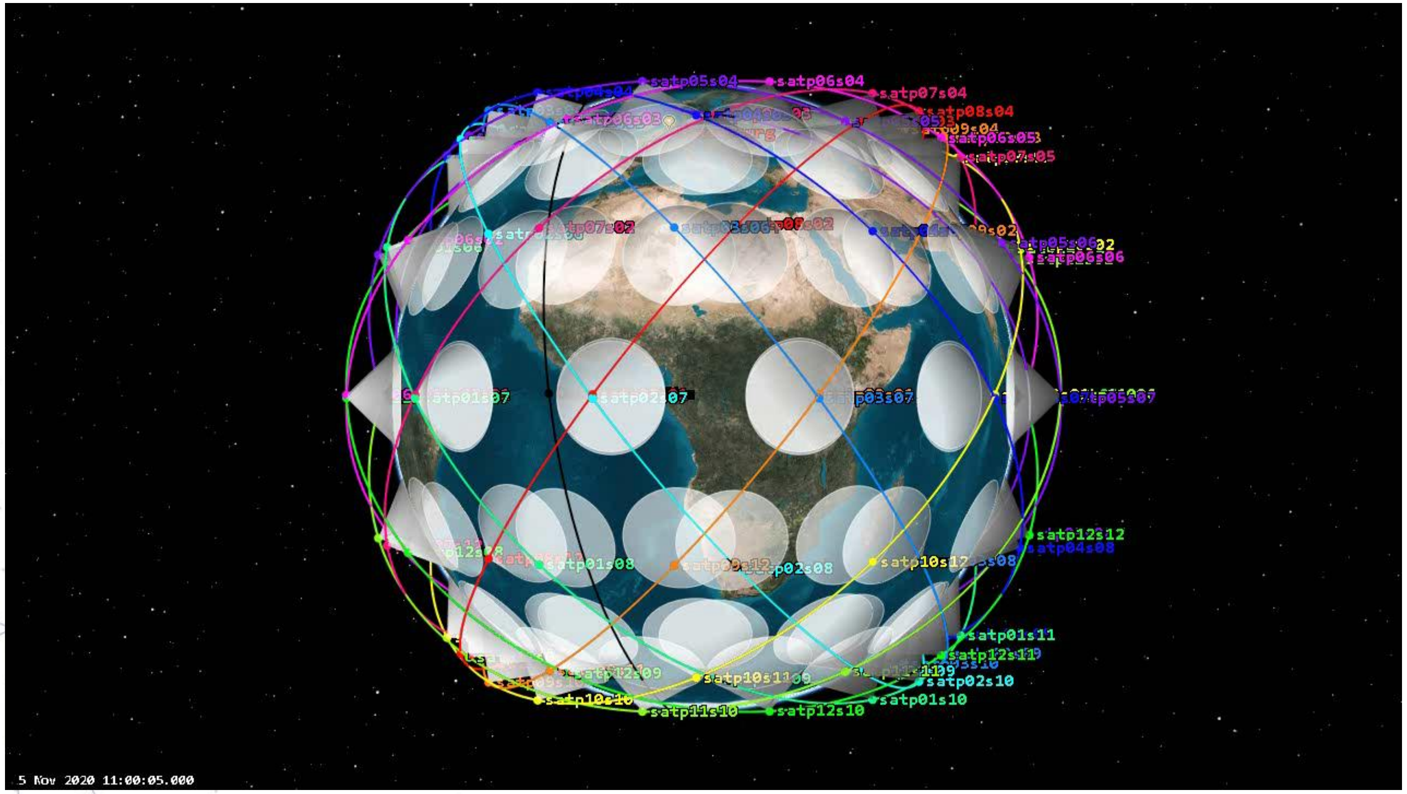
$$x(0) = 1$$
$$y(0) = 0$$
$$z(0) = 0$$
$$u(0) = 0$$
$$v(0) = 0$$
$$w(0) = \omega/2$$



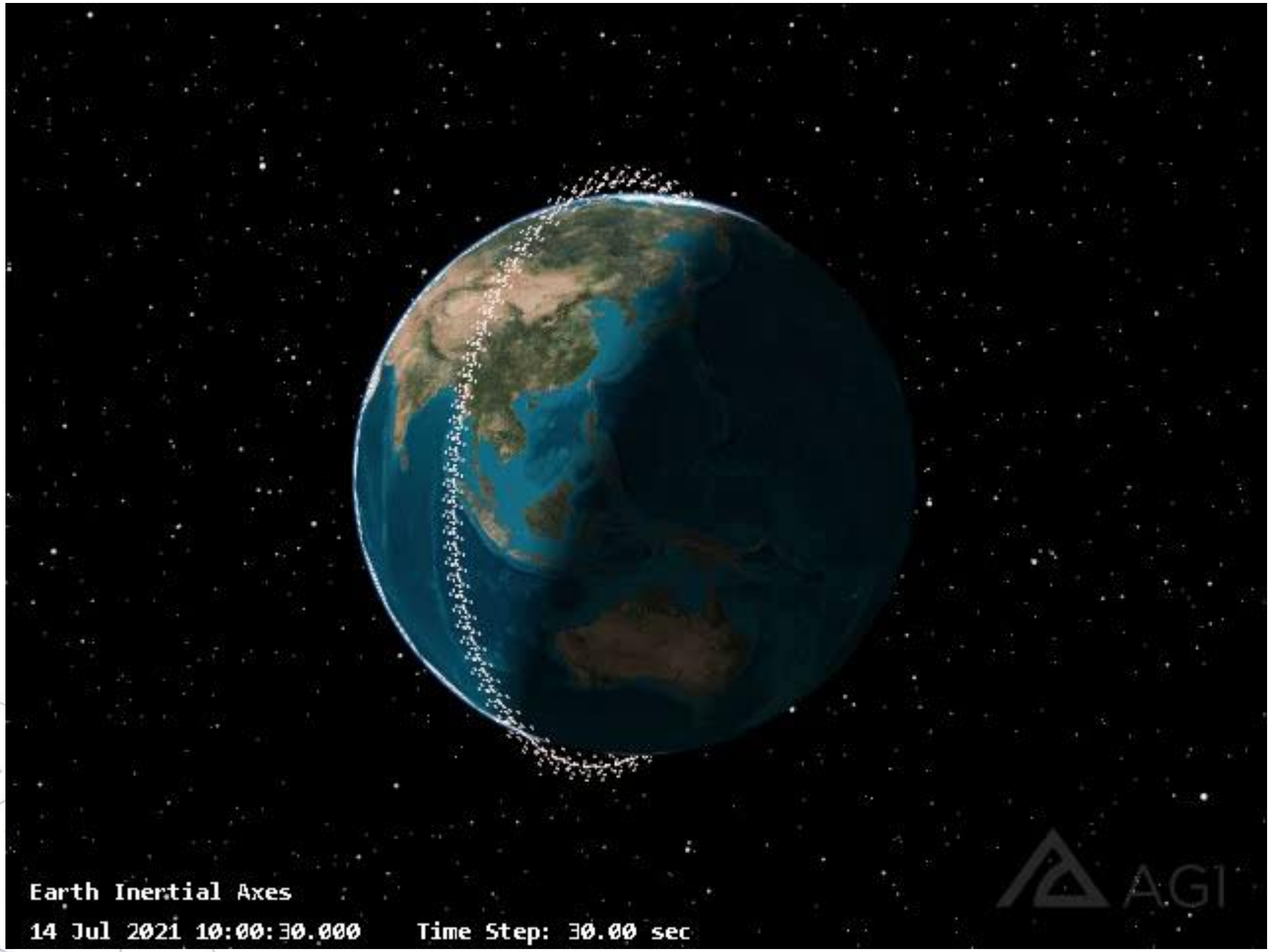
Formation


Earth Inertial Axes
14 Jul 2021 10:00:30.000 Time Step: 30.00 sec
AGI

Mega-Constellation: Definition

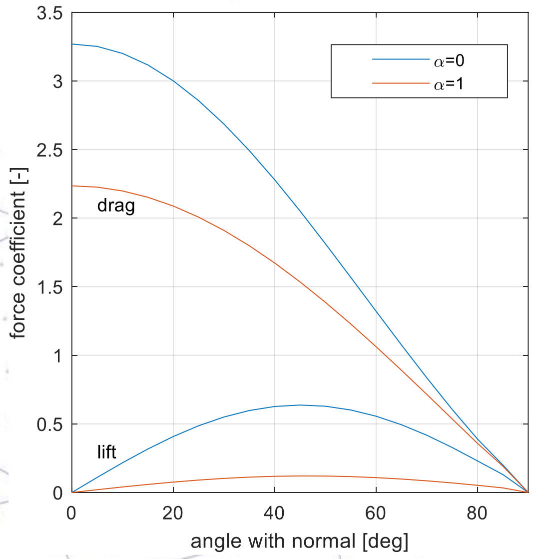


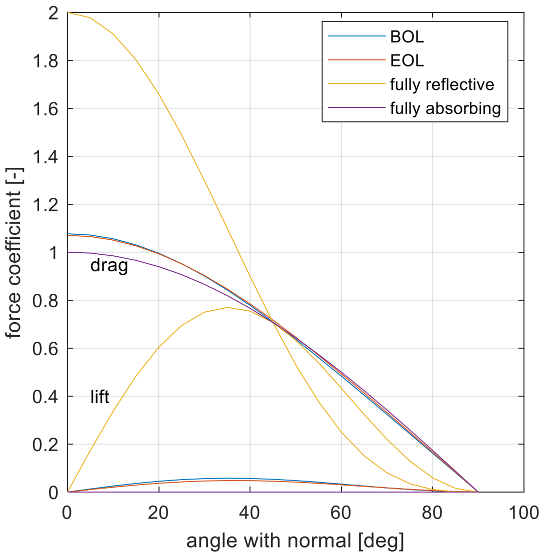
Flock/Swarm/Cluster



State-of-the-Art

1. **aerodynamics are only rudimentarily used for orbit control, e.g. for Mars Express' aero-breaking and Planet Inc.'s constellation maintenance**
2. **full 3-axes aerodynamic control is investigated only theoretically by Leonard[2], Sedwick[3], Ivanov[4], Traub[5], and others**
3. **solar radiation pressure, known to be of similar magnitude as aerodynamic forces, is only considered as disturbance not as control force**





Definitions[1]

- Distributed system of similar spacecraft cooperating to achieve a joint goal without fixed absolute or relative positions**: Flock, e.g. QB50**
- Several satellites flying in similar orbits without control of relative position organized in time and space to coordinate ground coverage: **Constellation, e.g. PlanetLabs**
- Multiple satellites with closed-loop control on-board provide a coordinated motion control on basis of relative positions to preserve an appropriate topology for observations: **Formation/Swarm/Cluster, e.g. NetSat**

- **Autonomy:** a technical system reacts to disturbances without human intervention
- **Solar-Aerodynamic Flight:** the use solar radiation pressure and ram pressure of the residual atmosphere to control the orbit

[1]adapted from: K. Schilling, “Mission Analysis for Low-Earth-Observation Missions with Spacecraft Formations,” *RTO-EN SCI-231 - Small Satell. Form. Distrib. Surveill. Syst. Des. Optim. Control Considerations*, pp. 1–24, 2011.

Governing Equations

- from Kepler body problem
- given a local coordinate system (figure)
- the following equations can be derived for each formation member

$$\ddot{x} - 2\omega\dot{z} = 0$$
$$\ddot{y} + \omega^2 y = 0$$
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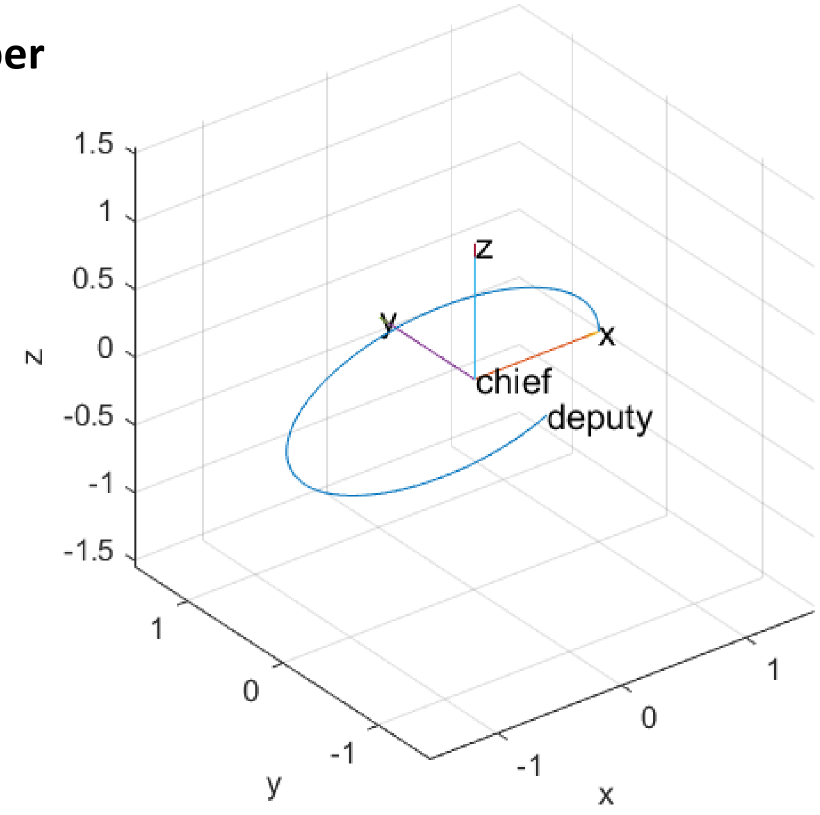
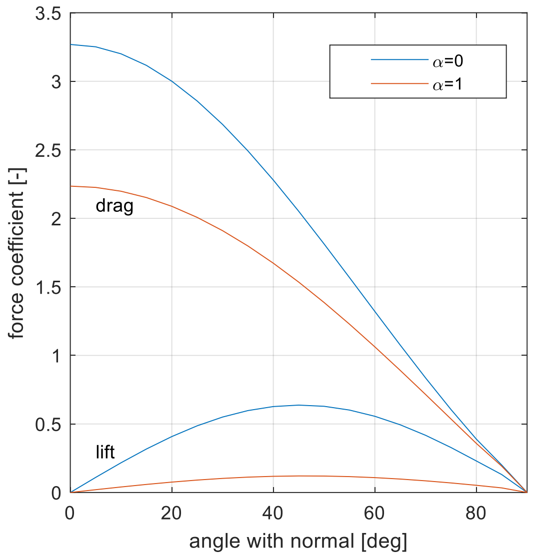
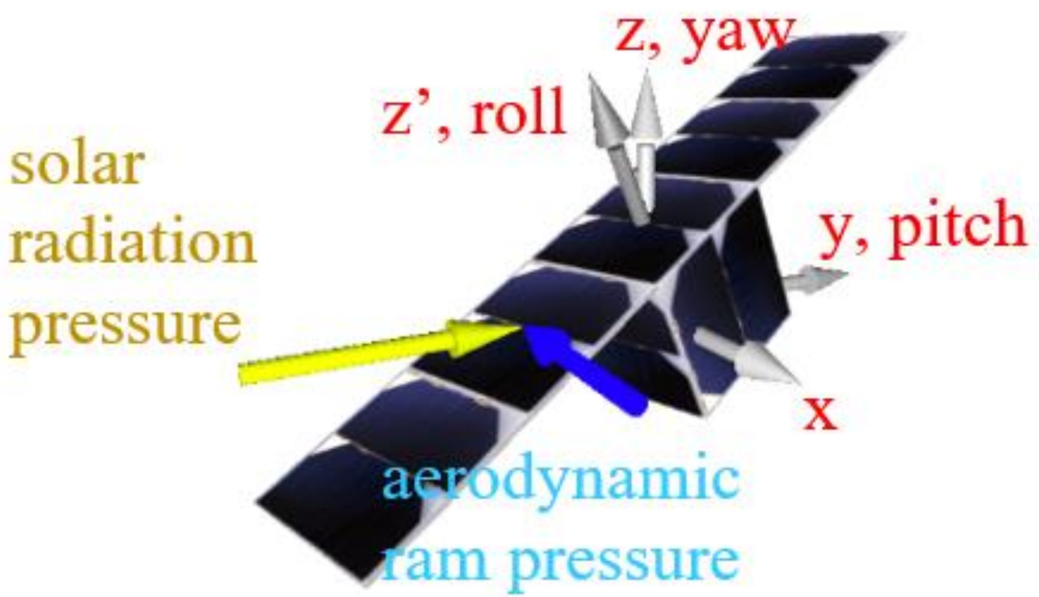


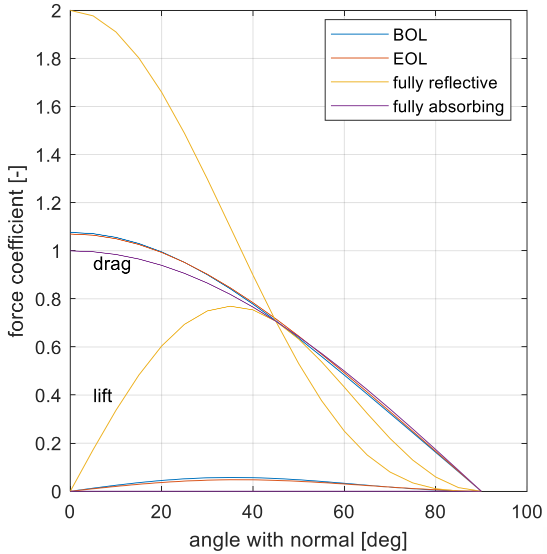
- Hill-Clohessy-Wiltshire equation
- set of ordinary differential equation for
  - three spatial coordinates: x, y, z
  - each formation flight member satellite
- right-hand-side is zero -> no forces/propulsion applied

Solar-aerodynamic Forces

- from Kepler body problem
- given a local coordinate system (figure)
- the following equations can be derived for each formation member







Formation Flight Modes

- **Deployment**
  - **satellites are co-located after launch and move to their formation location**
  - **addressed in:** J. Thoemel and T. van Dam, “Autonomous formation flight using solar radiation pressure,” *CEAS Sp. J.*, 2021.

- **Maintenance**
  - **maintain location in formation under influence of disturbances**
  - **subject of this research**

- **Reconfiguration**
  - **formation geometry changes for instance to change observation characteristics**
  - **coming soon**