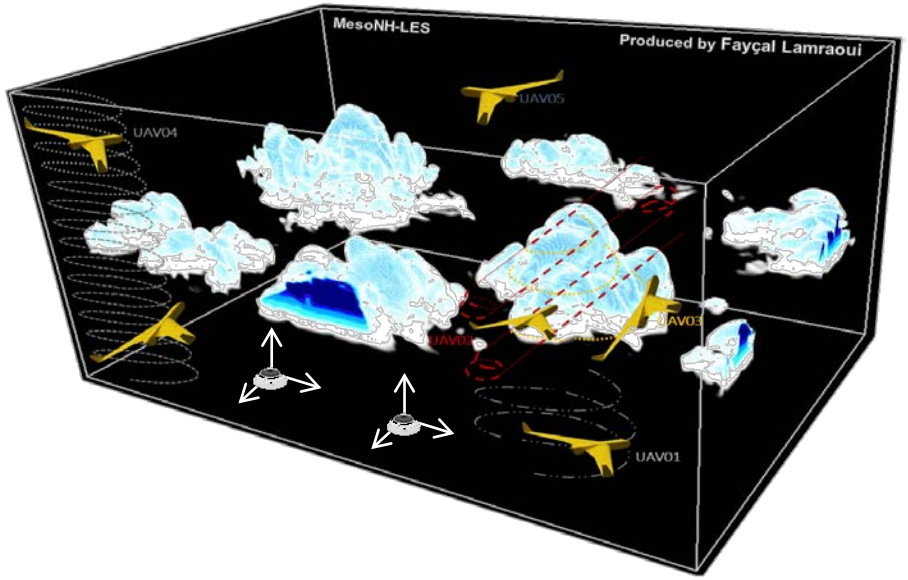
NEPHELAE: Network for studying Entrainment and microPHysics of cLouds using Adaptive Exploration



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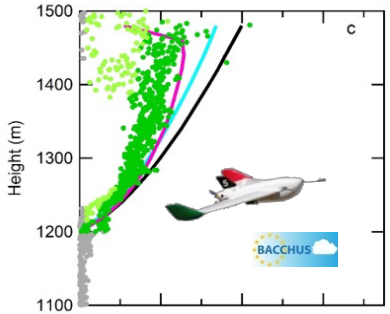
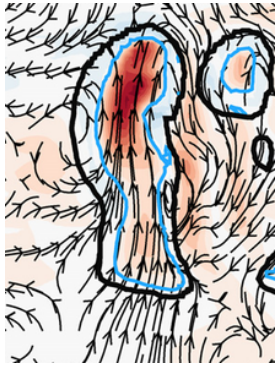
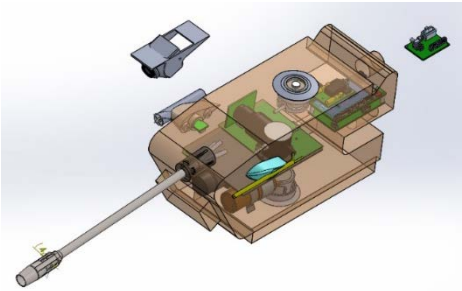
ISARRA, Lugo, Spain; July 2019

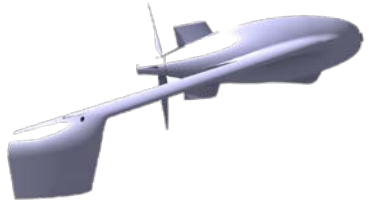
Outline

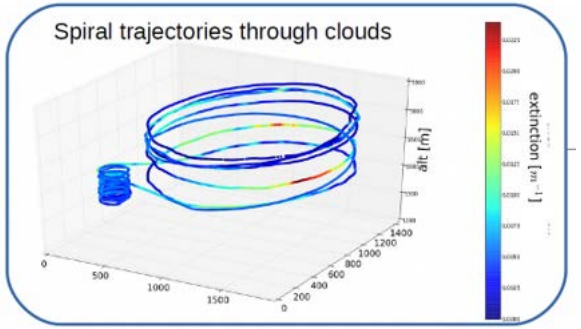


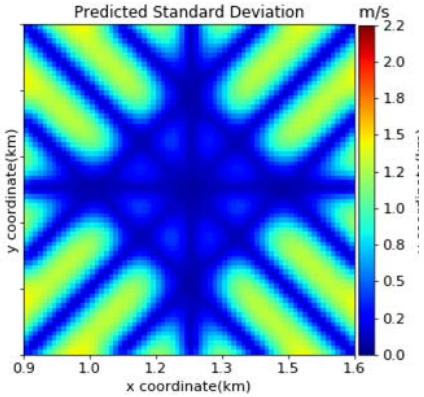
- Motivation / science questions
- Payload / platform development
- Recent campaign in La Réunion
- Cloud sampling / trajectory planning
- Towards a fleet control architecture

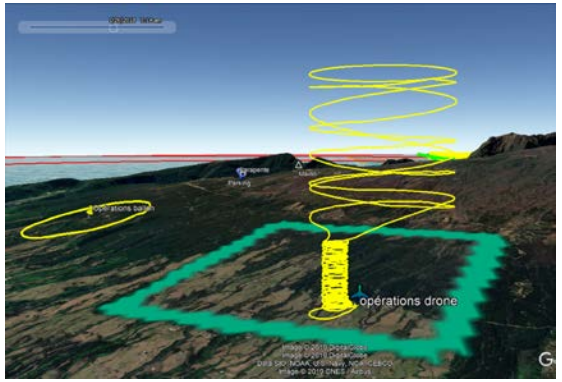








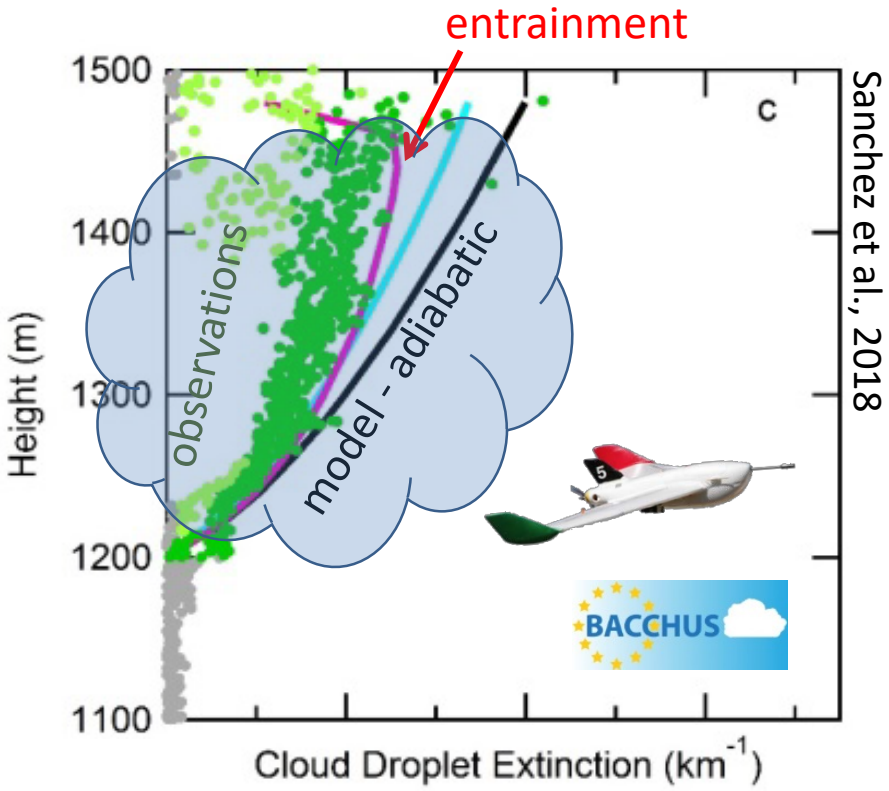




Motivation

Science Question:

What are the dominant mixing mechanisms in clouds?



Entrainment/Detrainment

Still an active field of research since several decades

The existing **mixing models** yield diverse results

Lateral mixing models

Cloud-top mixing models

- Difference between adiabatic and observed cloud properties
  → entrainment/detrainment or decoupled atmosphere
- Adiabatic models overestimate cloud radiative fluxes (up to 100 W m^{-2} for shallow Cu)

Motivation

Science Question:

What are the dominant mixing mechanisms in clouds?

Bouyancy and U-W streamlines

G. Dagan et al., 2018

Mixing between cloud air and environment occurs at cloud boundaries.

- Cloud-free air mixed into the cloud (**entrainment**); dilution effect.
- Cloudy air ejected outside cloud (**detrainment**); loss of cloud mass.

Entrainment/Detrainment

Still an active field of research since several decades

The existing **mixing models** yield diverse results

Lateral mixing models

Cloud-top mixing models

The lack of in-situ observations of cumulus cloud microphysical properties has left a divergence in of cloud models

NEPHELAE Payloads

Standard instruments (all)	Standard Parameters
Pressure, temperature, humidity	PTU → T_{dew} → lifting condens. level
Autopilot & Pitot	u, v → horizontal winds
Video camera	Θ_E, $z_{inversion}$
Data acquisition	data downlink

Cloud dynamics	3D winds and solar fluxes
5-hole probe; IMU; FPGA; $\Delta P + P_{abs}$	*u, v, w*; flux; TKE; turbulence
Cloud sensor (3-λ)	σ_e → n_D x r^2 ; R_{eff}

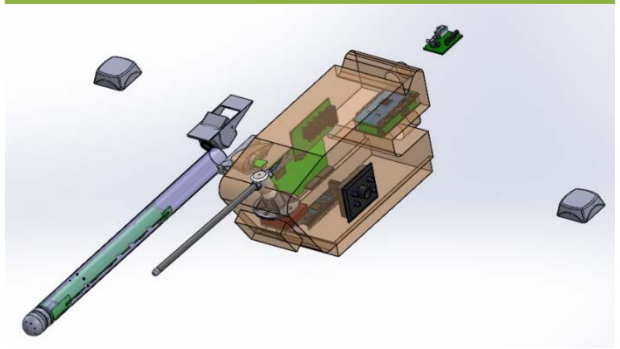
Cloud lwc	Cloud microphysical properties
Cloud sensor (3-λ)	σ_e → n_D x r^2 ; R_{eff}
LWC sensor **	lwc → n_D x r^3

** LWC TBD

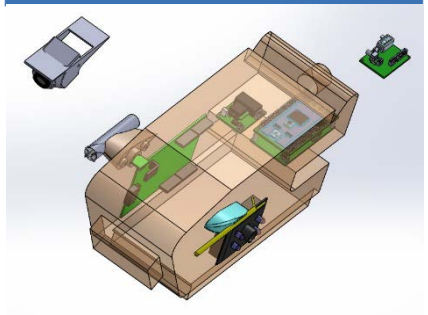
Aerosol / irradiance	Aerosol properties & solar flux
Optical Particle Counter	number concentration (D_p > 0.3 μm)
Aerosol Inlet	unbiased size distribution (0.3 < D_p < 3 μm)
Pyranometer (up & down)	$\Delta F_{aerosol}$ → W m^{-2}; $F_\uparrow$ / $F_\downarrow$ → Albedo

⇒ Payloads based on mission specific designs for mass less than 800 g.

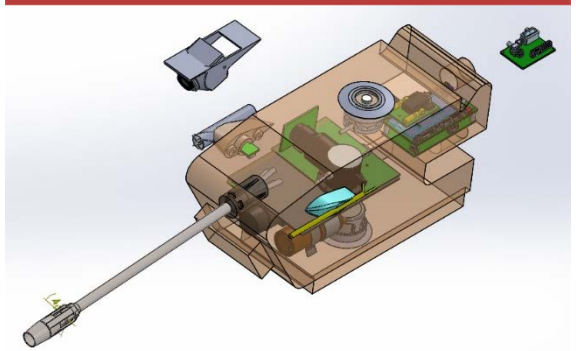
Cloud dynamics



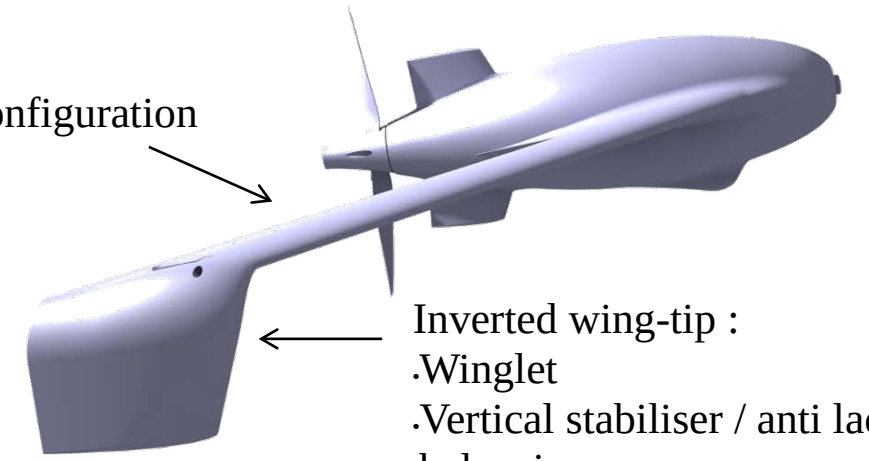
Cloud lwc



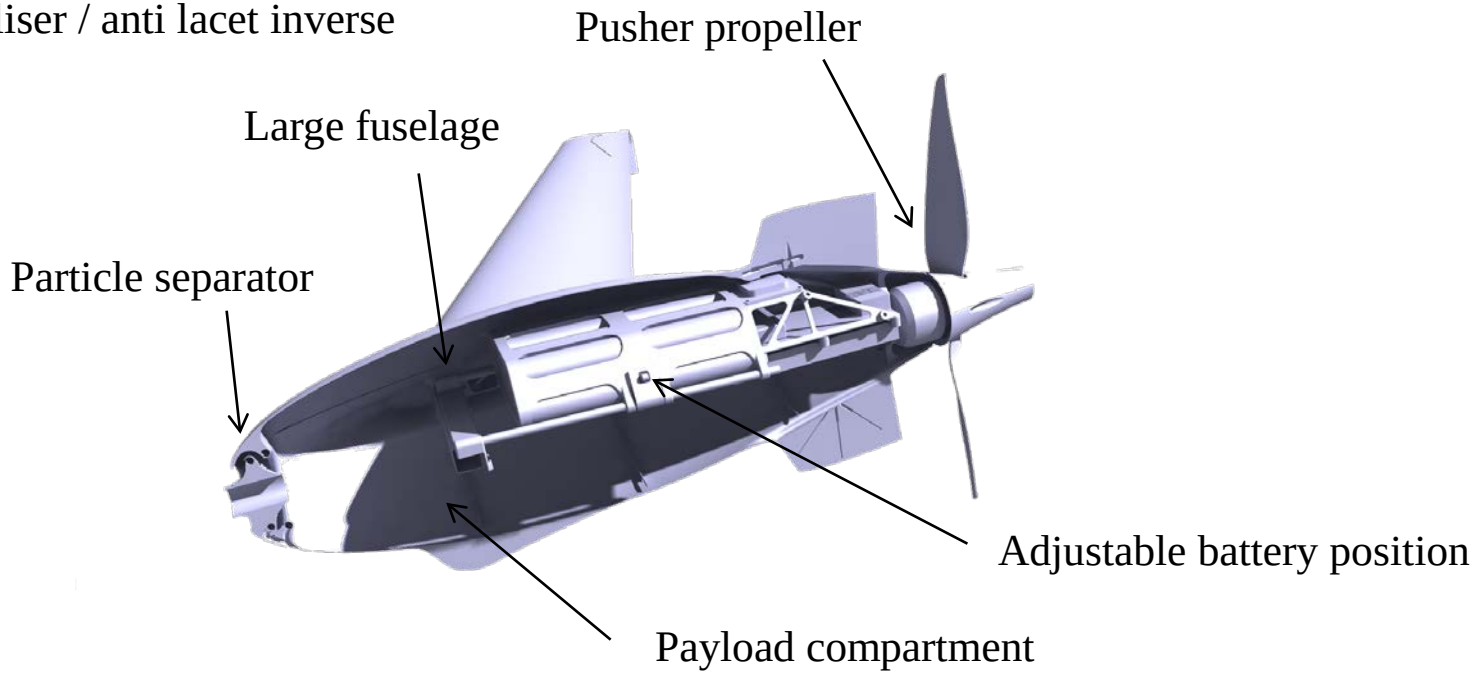
Aerosol / irradiance



UAV platform under development



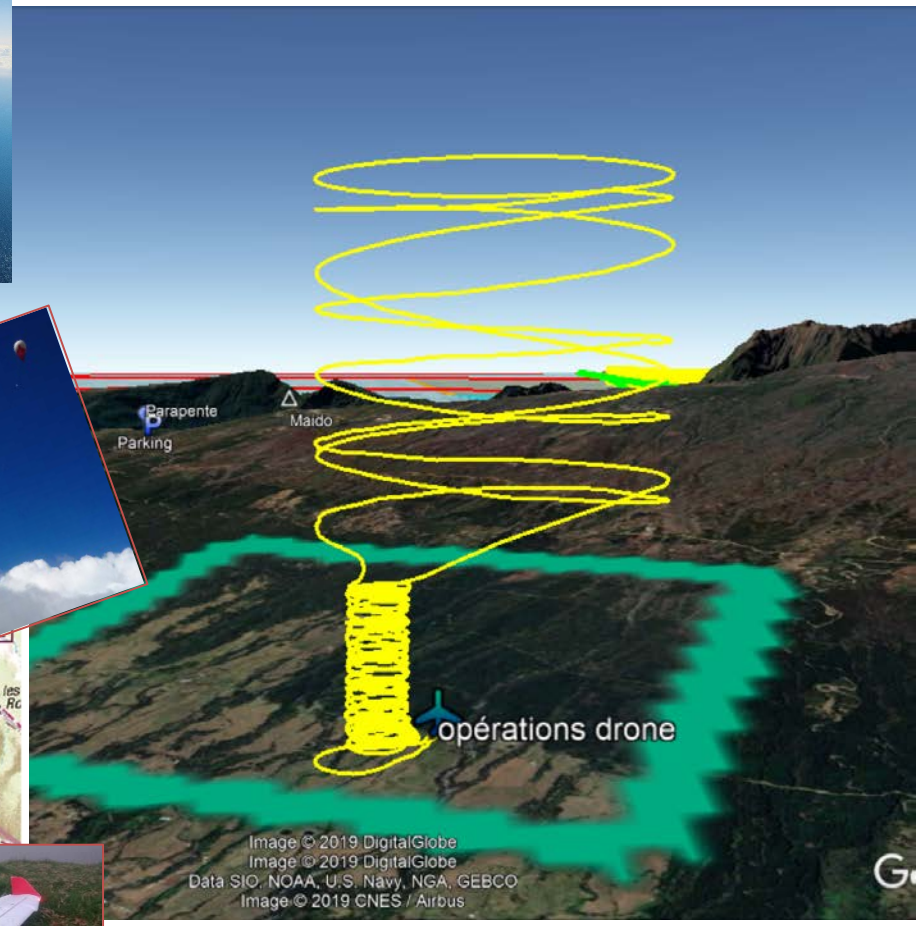
- 2+ hour flight endurance
- Cruise speed : ~25 m/s
- Cruise alt: ≤ 3000 m
- Payload mass: ≤ 800 g



MDO (Multidisciplinary Design Optimization) design

Cloud study at La Réunion

March – April 2019



ZRT authorization

- Aerosol/cloud flights with balloon and UAVs
- Balloon flights consisted of vertical profiles and constant altitude sampling (1000 m.agl)
- UAV flights consisted of spiral climb ascent / descent
- Operations 1400 m.asl; flight ceiling at 2000 m.agl)
- 2 km max distance from GCS

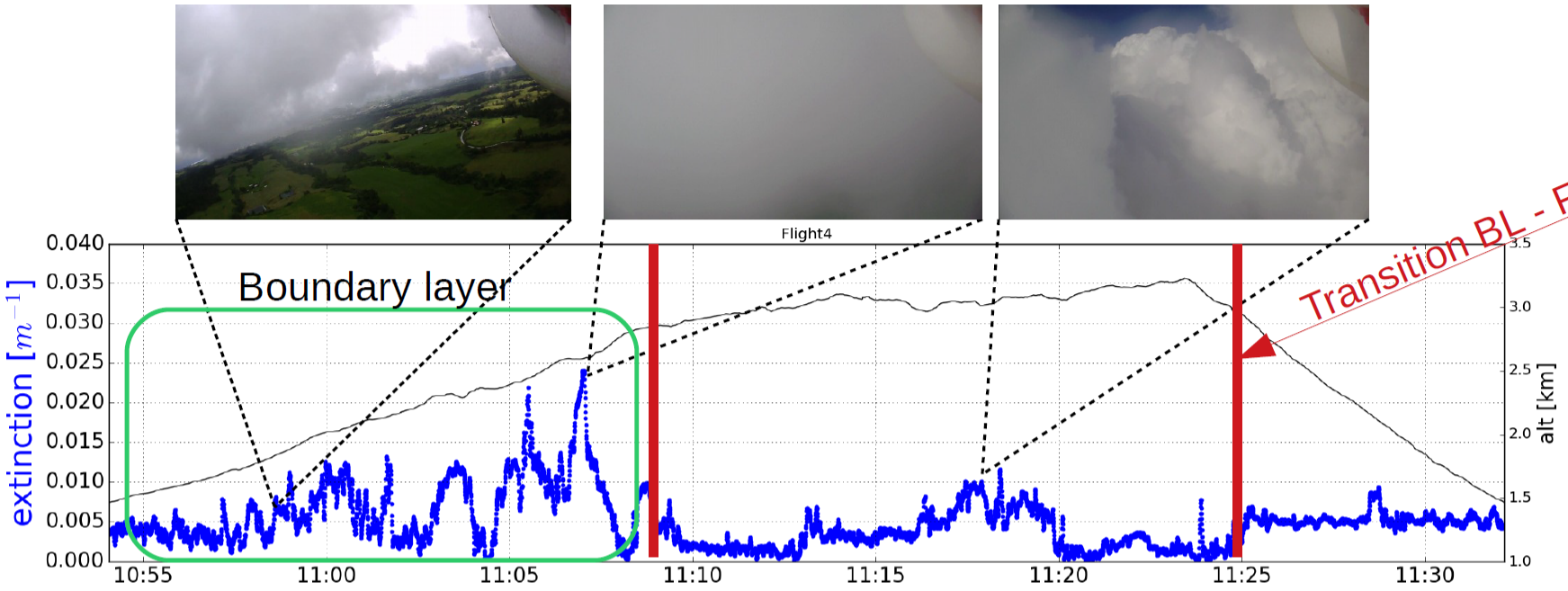
UAV operations at La Réunion

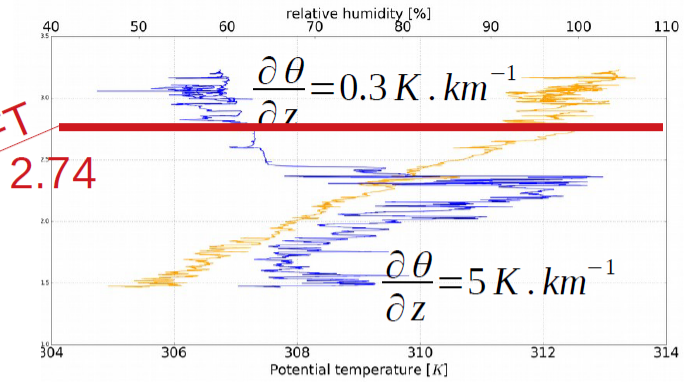
- UAS operations conducted in pasture on the western slope of Maido
- Infrastructure installed / removed daily
- Bungee/ramp take-off; net landing

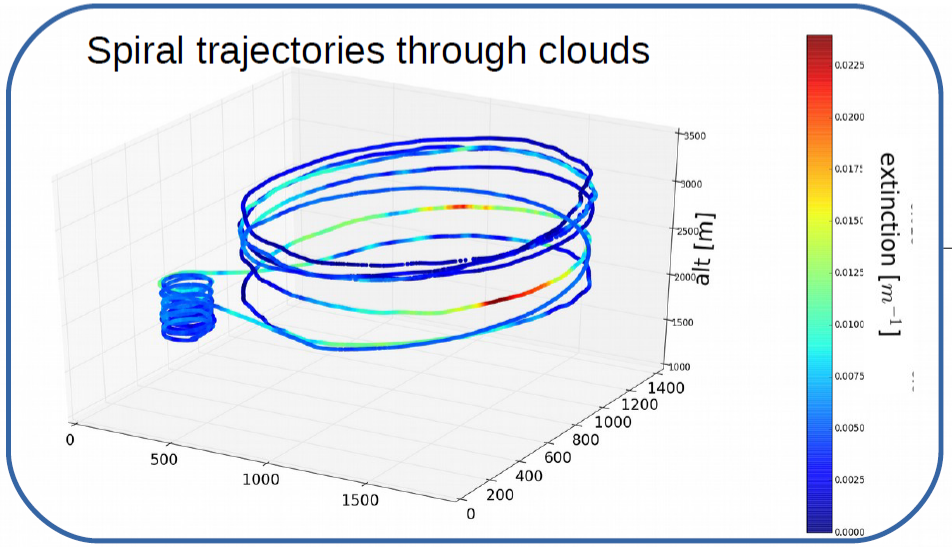
Overview of campaign (NEPHELAE)

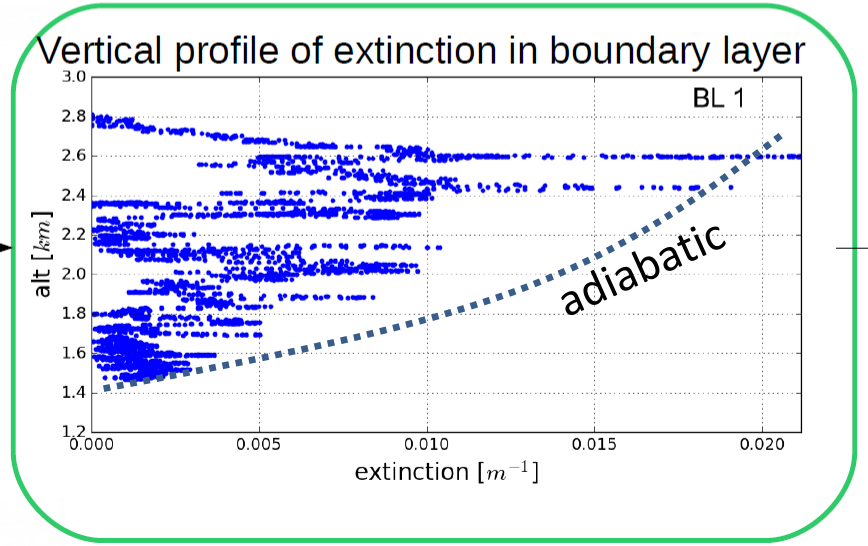
- Flights on five days (2, 3, 4, 6, 7 April); between 9:00 to 18:00; four flights / day
- Flew single UAV in circular pattern in/out of clouds to study mixing at cloud interface
- 17 flights total; 15:16 total flight time
- Flights in convective clouds, precipitation, winds up to 8 m/s

Cloud profiling (Flight 4; 3 April 2019)





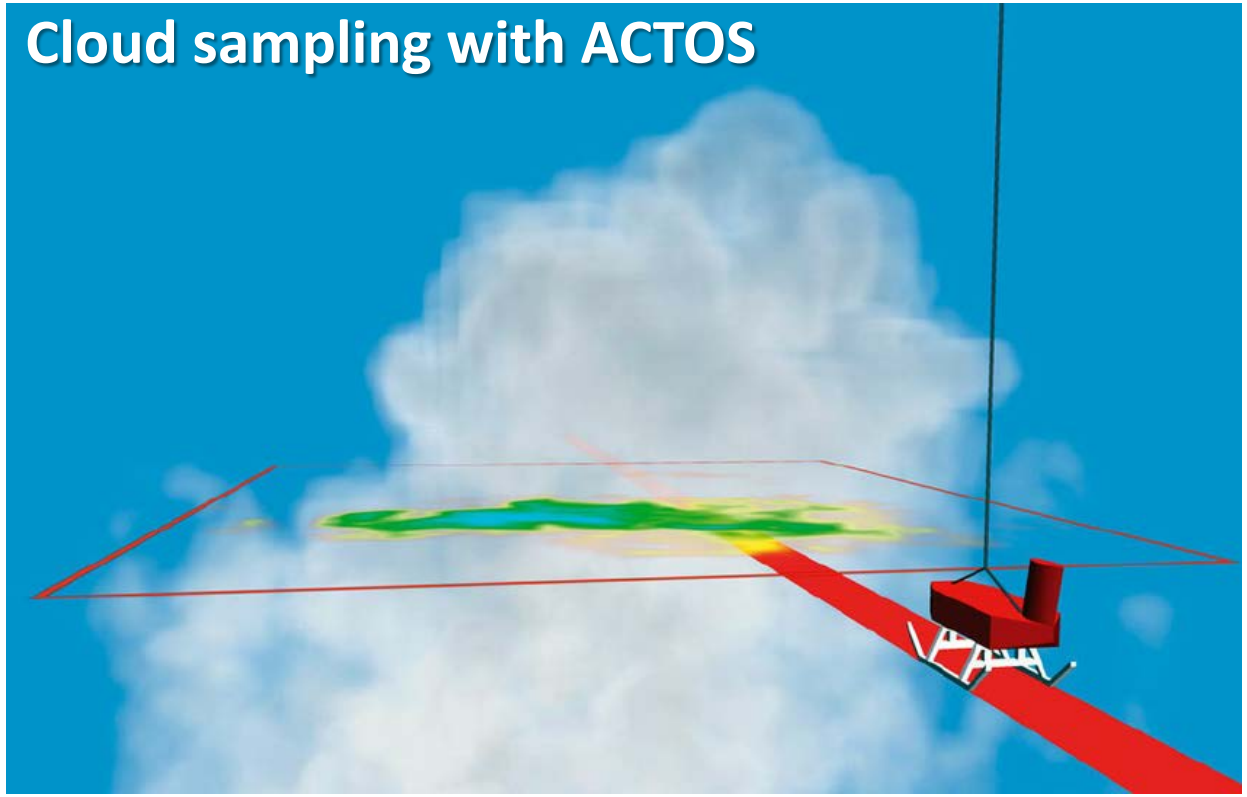




Compare theory and observation with LWC

Calculate mixing process in clouds

How do you study a cloud ?



Hoffmann et al., 2014

- Generally a cloud is sampled via a single trajectory (line through a cloud)
- The relative amount of cloud edge (yellow) and cloud core (green) depends on the position of the trajectory relative to the cloud
- Single trajectories tend to bias the observations towards cloud core and underrepresent those of cloud edges

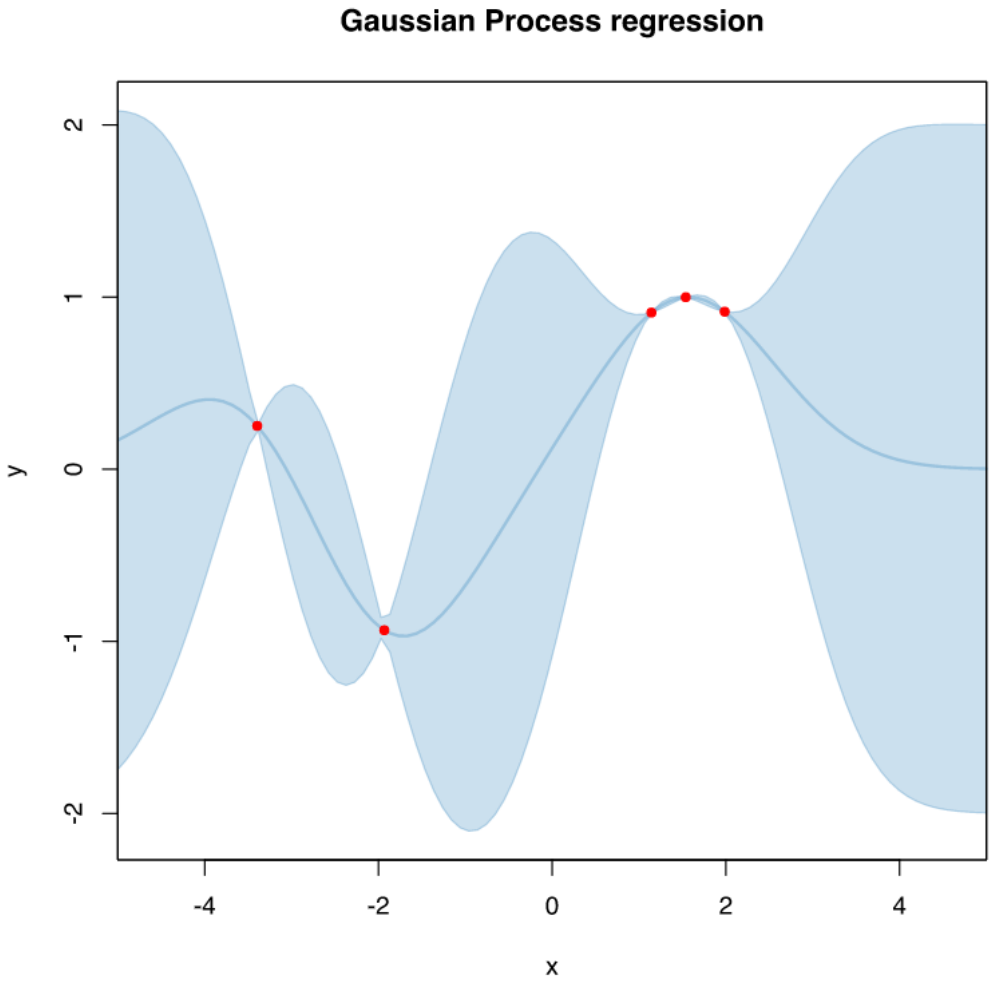
→ As cloud lifetime ~ 20 minutes, need to optimize trajectories and deploy multiple observations simultaneously

Cloud mapping

Role: compile UAV gathered data into a 3D + Time map of the cloud (i.e., LWC, 3D winds)

Approach:

1. Due to sparse, uncertain and dynamic nature of data: use of Gaussian Process Regression (GPR)
2. Incorporation of prior cloud knowledge (*e.g.,* conceptual model, measurement history)
3. Building of dense layered maps with associated uncertainty
4. Extraction of macroscopic cloud properties (cloud border, surface area, volume, max. updraft)

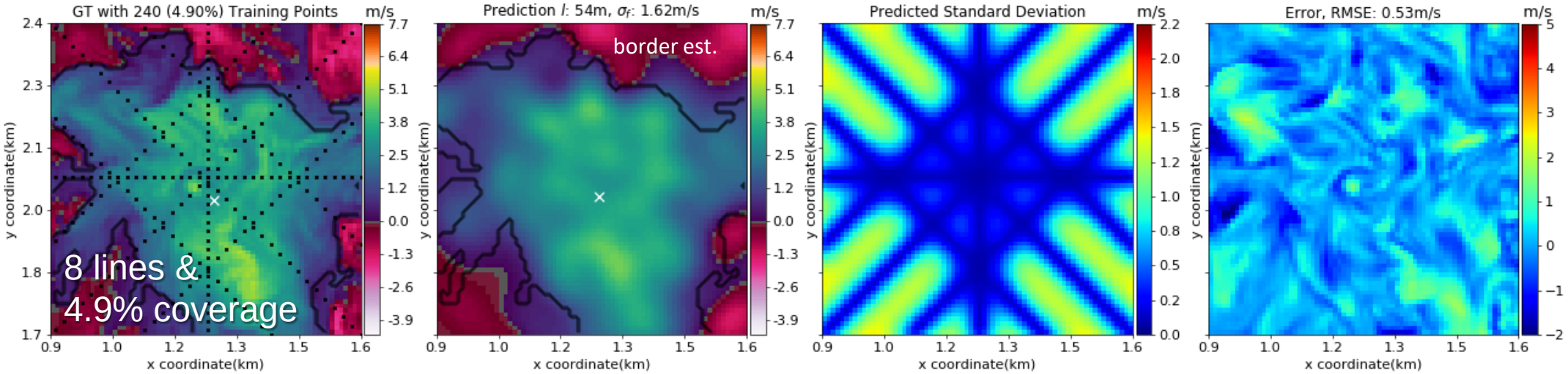


simulation (MesoNH)

Cloud mapping results

Liquid Water Content values (with border estimation)

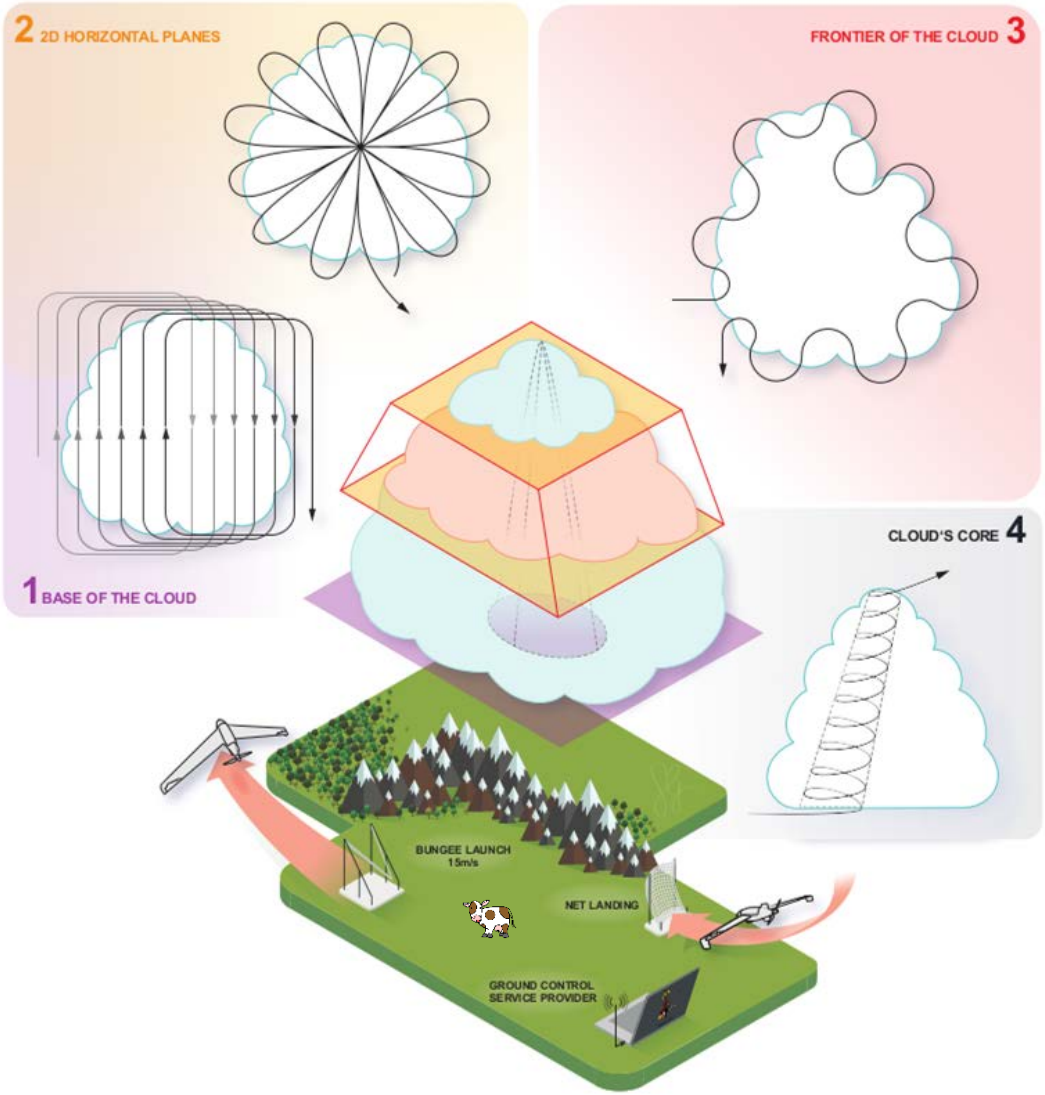
Linear trajectories



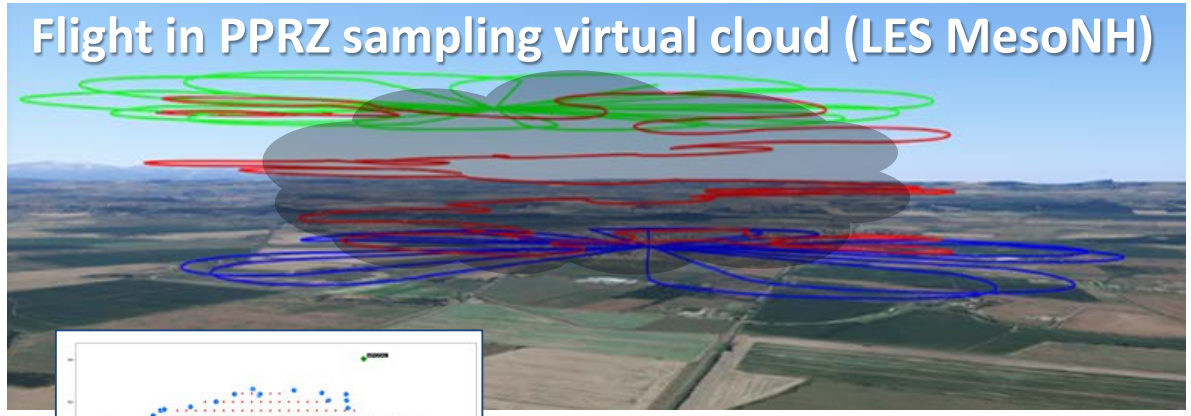
Circular trajectories

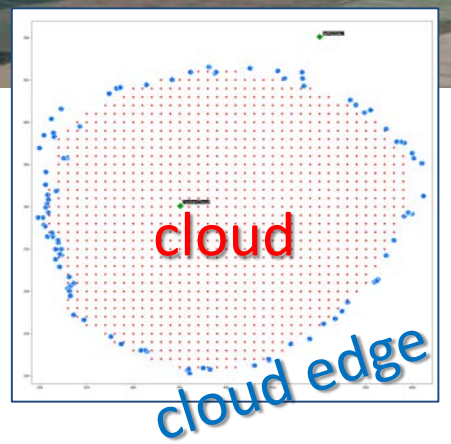
Ground truth *Built map* *Map uncertainty* *δ (truth – map)*

Flight patterns for adaptive cloud sampling



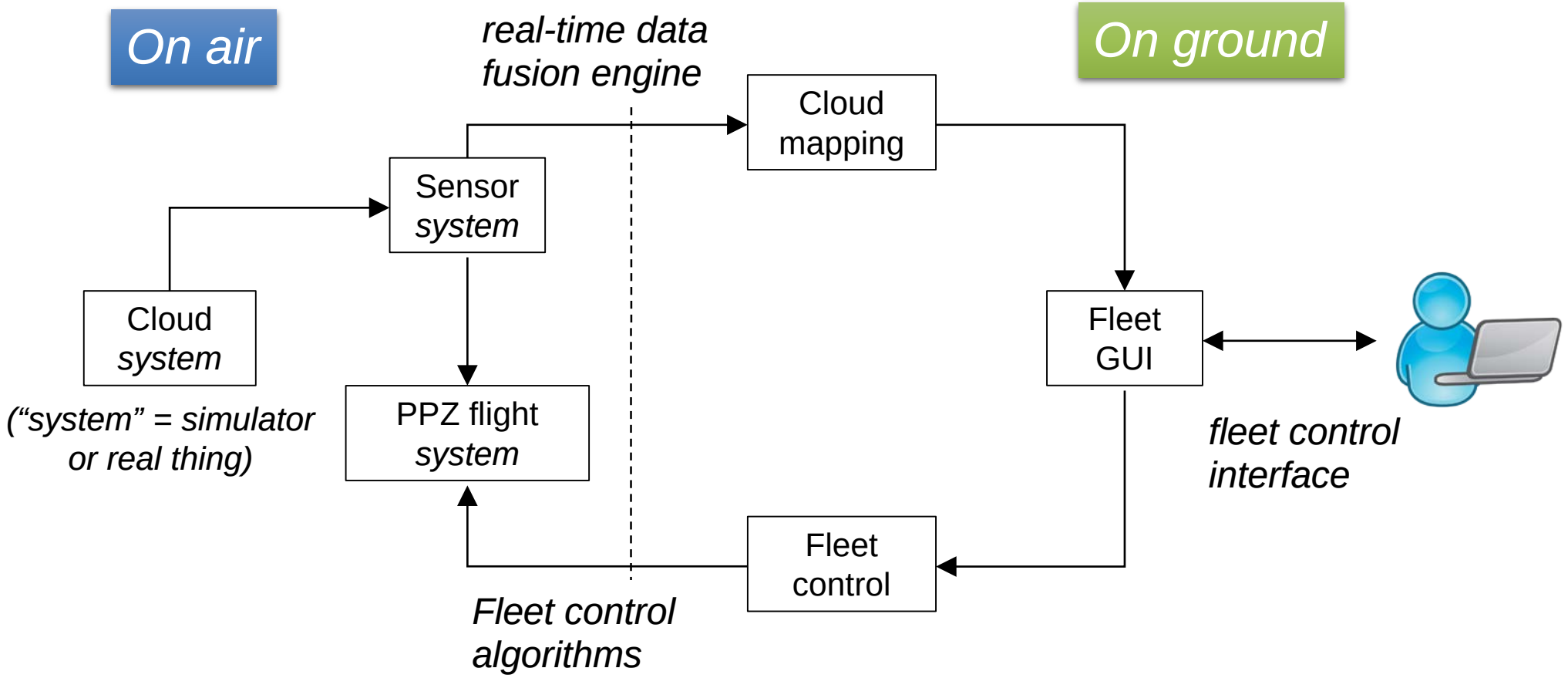
- Define flight plans for zones of interest (i.e., cloud core, edge, base, top)
- Adaptive flight patterns combine cloud position and sensor feedback





Flight simulation with lace pattern determines the frontier of the cloud.

Fleet control: system overview



"An intelligent perception machine dedicated to in-situ cloud data gathering"

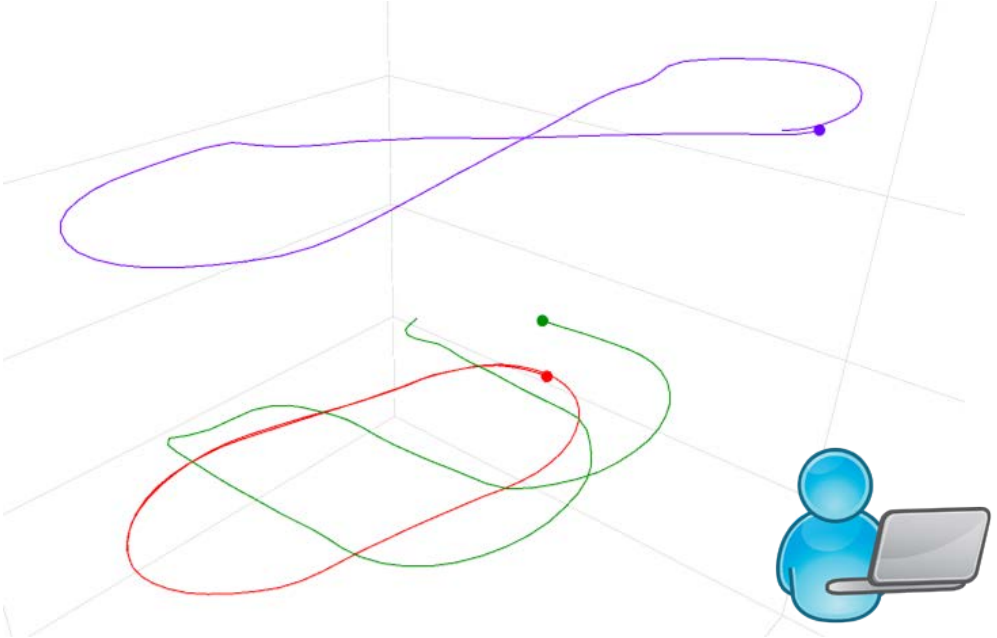
→ development of a UAS fleet with cooperative sampling

Fleet user interface

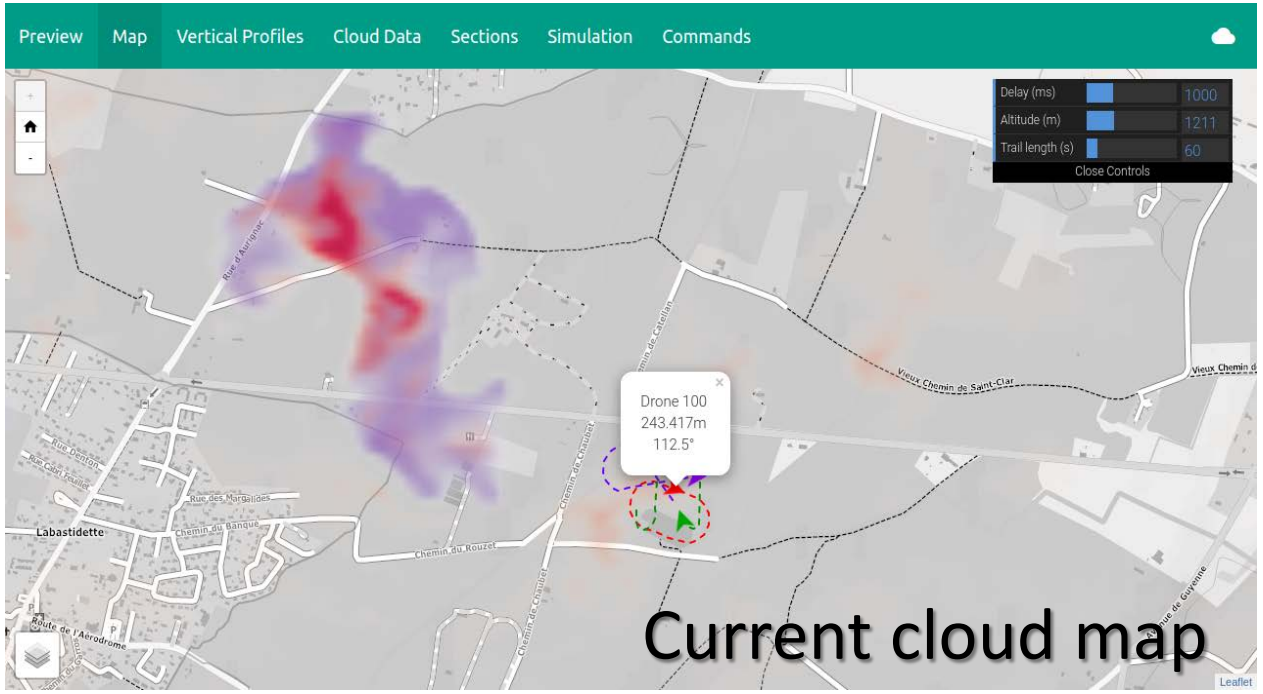
Role of GUI:

1. Inform the fleet commander of the current cloud or atmospheric state.
2. Provide a high level command interface for fleet control

Currently defining 2D and 3D interactive tracking tools with sensor data layers



Fleet trajectories w/ history



Current cloud map

Takeaways / Perspectives

- NEPHELAE is atmospheric science driven with focus on cloud microphysical processes → identify dominant entrainment mechanism and timescale of cloud development
- Mission-specific payloads and platform designed to study the evolution and life cycle of clouds

- NEPHELAE aims to develop a UAS fleet with cooperative sampling → adaptively plan and control fleet to maximize usefulness of gathered data
- Gaussian Process Regression and optimized trajectories to effectively map evolution of cloud structures.
- Development of flight trajectory planning and fleet GUI underway