Robust and Trustworthy AI for Green Aviation

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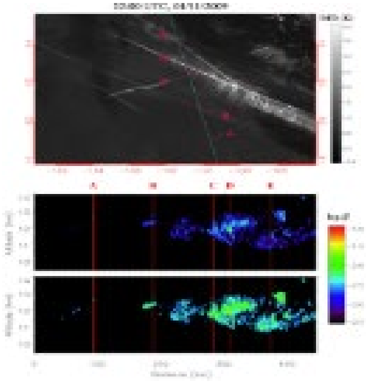
Thales

7-8 November 2023

EUROCONTROL’s Brussels HQ

Contrails presence can be verified in a variety of sources

Satellite | Lidar | Ground-based cameras



Iwabuchi et al, 2012, MODIS/CALIPSO

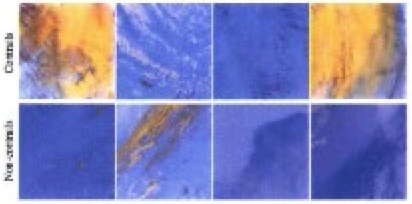
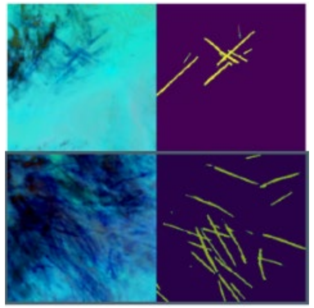


Figure 2-3: Examples of contrail and non-contrail labeled tiles

Kulik, MIT, 2019

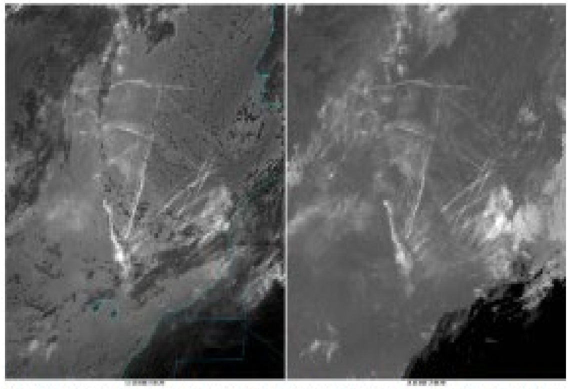


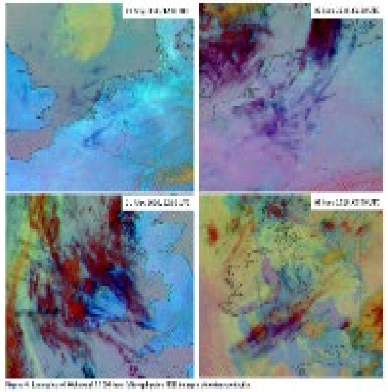
OpenContrails, 2023

CCSN database, Zhang et al., 2018

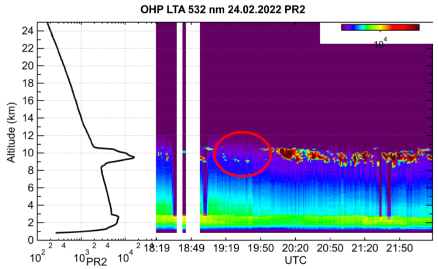
BeCoM

EUMETSAT: contrails-when-do-we-see-them-satellites





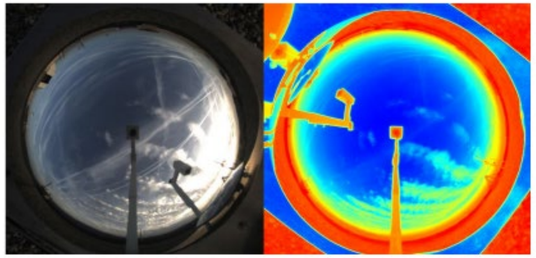
FRIPON database web frontend



LATMOS: LIDAR & sky images Courtesy Ph. Keckhut & Sergey Khaykin

contrails

©Sky Cam Vision, 2023-july-06, CONTRAILS project database



Sky images of contrails in the visible (left) and infrared (right) observed in 2016 from Reuniwatt cameras

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© Reuniwatt sky imagers

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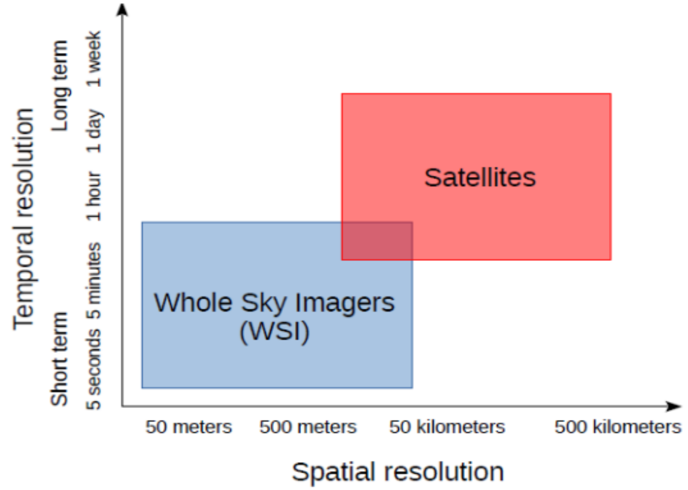
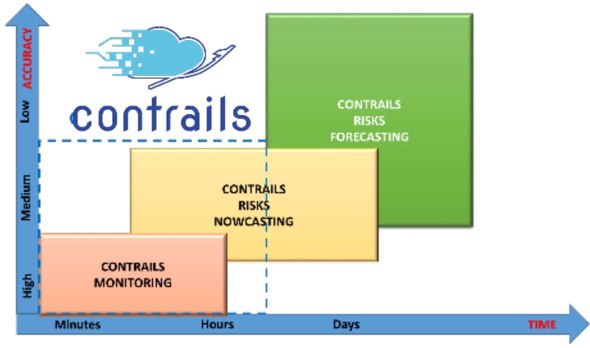
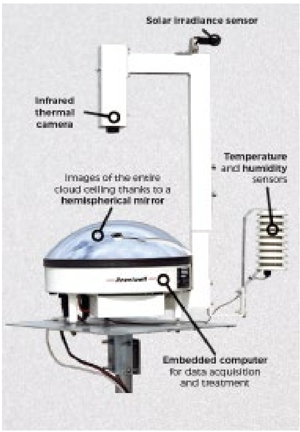
Ground-based imagery is promising for early stage, low-altitude contrail detection & monitoring

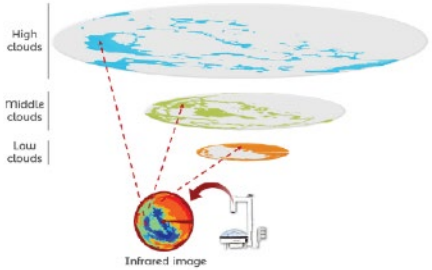
- All-sky (fisheye) cameras complement satellite observations
  - Enhanced spatial and temporal resolution of images
  - Can capture lower altitude clouds
- Detect contrails using AI methods – in particular Convolutional Neural Nets
  - Inspiration from CNN for cloud classification, irradiance forecasting, cloud motion prediction
  - Apply to contrails with appropriate representation (spherical geometry)



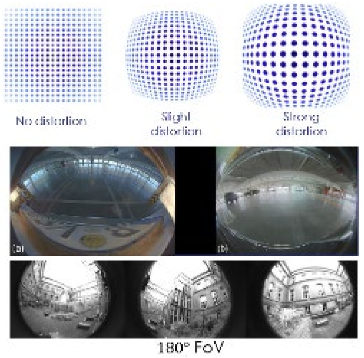


- Challenge: the distortion of fisheye images
  - CNN not directly suited in this particular geometry
- **Geometric Deep Learning** (Geometry-Informed Neural Network) works in non-Euclidian geometries and introduces robustness and frugality



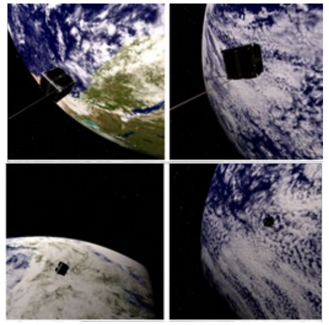


Reuniwatt ©SkyInSight: a patented **infrared sky imager** for continuous tracking and forecasting of the cloud cover.



Ahmad, Lecue – AAAI 2022

Conventional CNN lack robustness to input variations: rotations, scaling, deformations



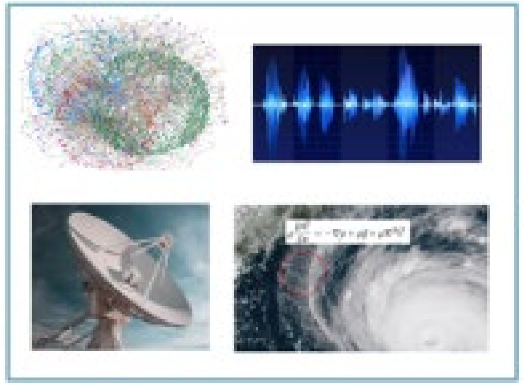
- Generic tensor encoding breaks native dependencies

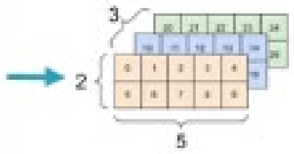
  → **Have to learn things back**

  bigger models, more training data,…,

  → Ad-hoc tricks e.g., data augmentation, encoding, …

  → **Sensitive to adversarial attacks**





- Algorithm validation both at design step and during operational usage is tedious
  - Training data needs to cover all possible perturbations
  - Out-of-domain samples can drastically impact performance

We want trustworthy contrail detection methods working directly in the native geometry of the cameras + validation metrics and methodology

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Convolution is the key element

The success of CNN : intrinsic translation equivariance, local filters, weight sharing and pooling (for planar images)

$$\forall x \in \mathbb{Z}^2, \qquad \psi(x) = (I \star K)(x) = \sum_{y \in \mathbb{Z}^2} K(x - y) I(y)$$

$K: \mathbb{Z}^2 \rightarrow \mathbb{R}$ 2D convolution kernel
$I: \mathbb{Z}^2 \rightarrow \mathbb{R}$ is the functional representation of the image
L_h: translation operator for $h \in \mathbb{Z}^2$, so that $L_h(f)(x) = f(x - h)$

Equivariance: **Feature maps built from convolution kernels transform consistently with the original image translation :**

$$L_h \psi(x) = (L_h I \star K)(x)$$

Convolution as a discretized integral

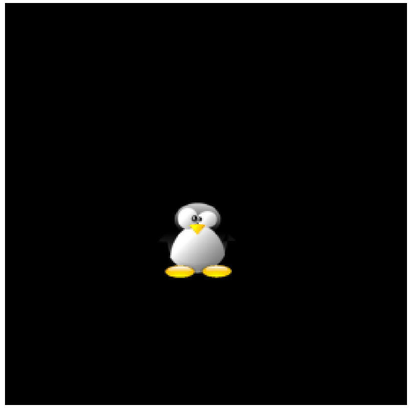
$$\psi(x) = (I \star K)(x) = \int_{\mathbb{R}^2} K(x - y) I(y) dxdy$$

Can be generalized to:

- ✓ **other transforms than translations**
- ✓ **other geometries than planar**

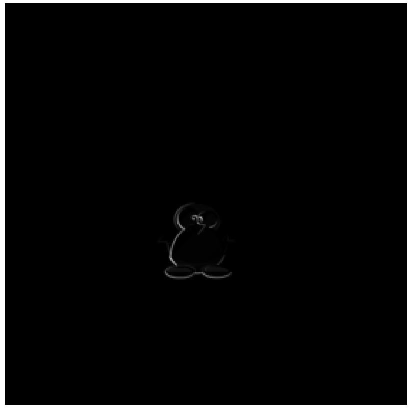
→ fisheye cameras!

input



Original image

conv map

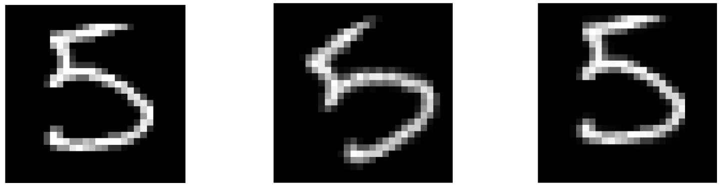


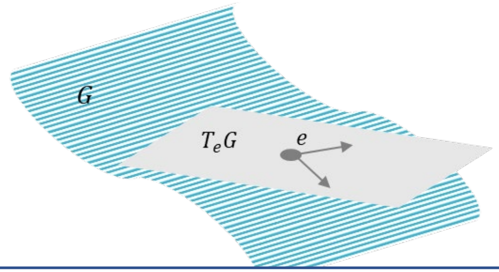
Convolution feature map with Sobel filter

Generalization to different transforms & geometries: rotations, scaling, deformations, …

- Group theory: mathematical tools to deal with structured transforms (express symmetries)
  - Transformations are represented by elements g of a group G
  - Transformations $g \in G$ act on the data X as $g \circ X$
- Examples of Groups of 2D-plane transforms
  - Translation group $\mathbb{R}^2$: $T_x \oplus_{\mathbb{R}^2} T_y = T_{x+y}$, for $x, y \in \mathbb{R}^2$
  - Rotation group $SO(2)$: $R_{\theta_1} \oplus_{SO(2)} R_{\theta_2} = R_{\theta_{1,2}}$, for $\theta_1, \theta_2 \in [0,2\pi]$ and $\theta_{1,2} = \theta_1 + \theta_2 \; [2\pi]$
  - Special Euclidean group $SE(2)$: $H_{x,\theta_1} \oplus_{SE(2)} H_{y,\theta_2} = H_{R_{\theta_1} y+x, R_{\theta_{1,2}}}$ $(SE(2) = \mathbb{R}^2 \ltimes SO(2))$
- Examples of actions on a single image

$\mathbb{R}^2$ $SO(2)$ $SE(2)$





Build Equivariant Neural Nets with generalized convolution operator

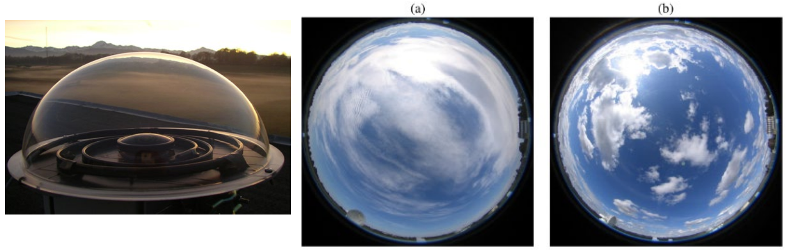
$$\forall g \in G, \qquad \psi_G(g) = (f \star_G K)(g) = \int_G K(h^{-1}g) f(h) d\mu^G(h)$$

$$L_h \psi_G(g) = (L_h f \star_G K)(g)$$

Needs much less training data

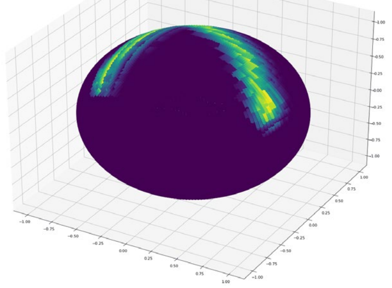
Martin, Lagrave. On the Benefits of SO(3)-Equivariant Neural Networks for Spherical Image Processing. 2022. ⟨hal-03763121⟩

Robust contrail detection: build equivariant neural nets in the native geometry of the data



The RAPACE sky imager system. **https://hal-insu.archives-ouvertes.fr/insu-02321633**

$f: S^2 \rightarrow \mathbb{R}^3$



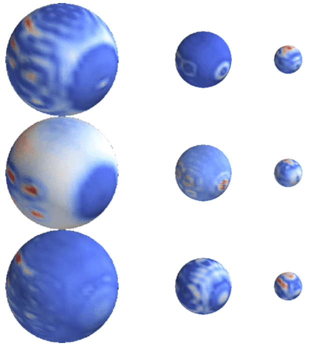
Reuniwatt, ©SkyCam Vision, 2023

contrails

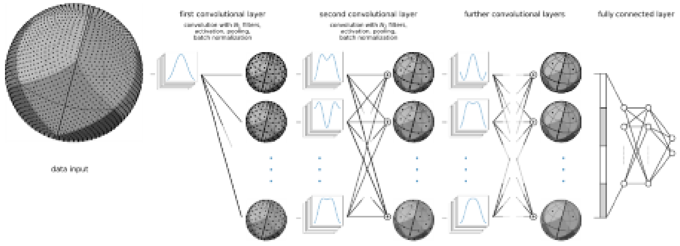
Dual fish-eye lenses can be projected onto the Unit Sphere S^2
°360 images can be represented as signals $f: S^2 \rightarrow \mathbb{R}^3$
The Lie Group of **3-dimensional rotations** $SO(3)$ acts on S^2
Data can be processed directly on the sphere

- Natural projection surface for fisheye image is a sphere (2 lenses) or a hemisphere (1 lens)
  - Unwrapping to a plane introduces significant distortion at the poles
- Process data directly on the sphere & introduce equivariance using the Lie Group of 3D rotations: $SO(3)$ equivariant convolutional layers to capture global symmetries

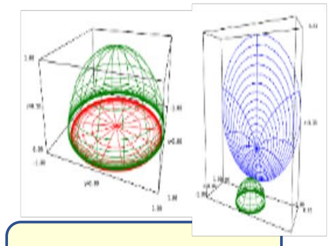
Su et al (2017



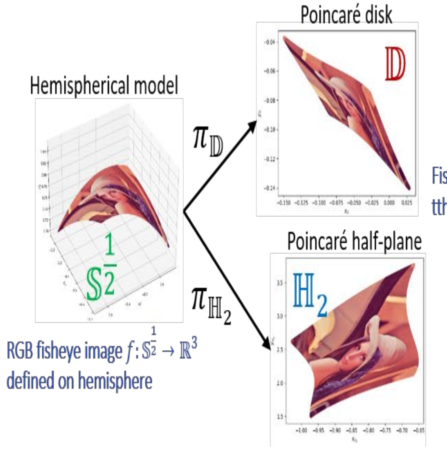
Esteves, C., et al., (2017)



N. Perraudin et al. (2018)



Lagrave, Barbaresco - GRETSI22



Fisheye image can be projected on tthe disk of the half-plane

Neural Nets with built-in robustness to rotations, scaling, translations

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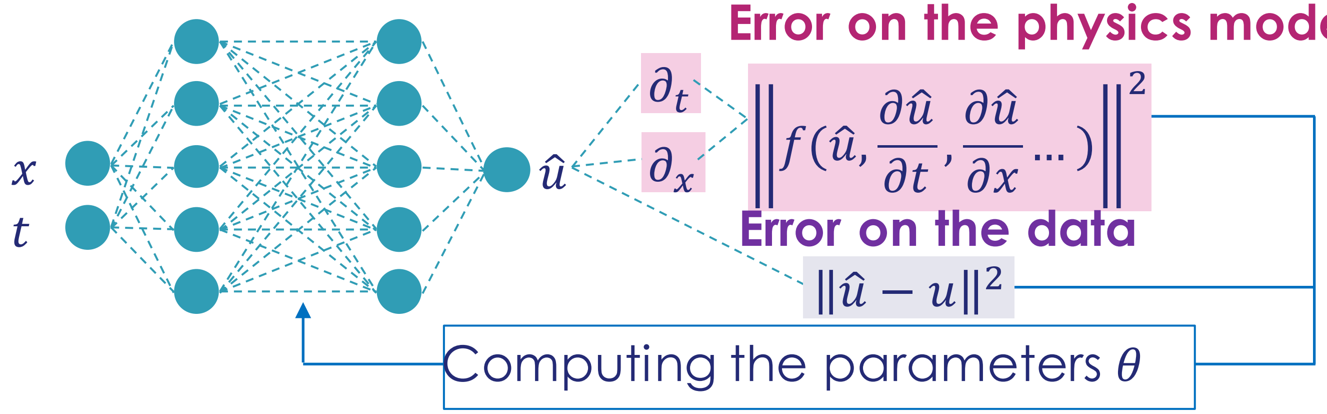
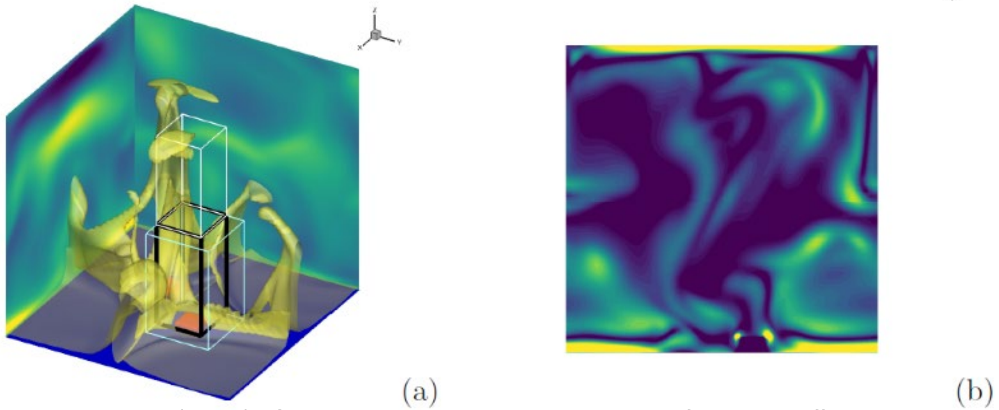
Contrail dynamics: Physics informed neural networks may help model turbulence in contrails or large scale contrail evolution

Physics Informed Neural Network embed the physics in the loss

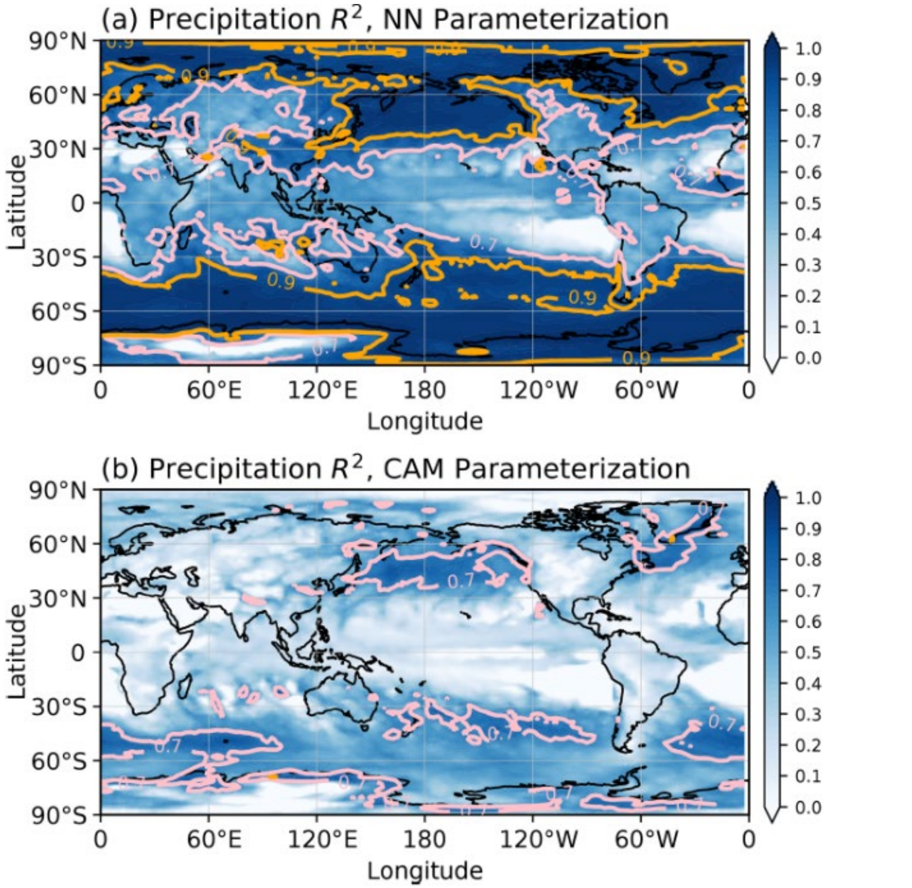


PINNs for turbulence modeling



Lucor, D. et al (2022): Simple computational strategies for more effective physics-informed neural networks modeling of turbulent natural convection.

Neural Network for GCM parametrization



Wang, X et al. (2022). Stable climate simulations using a realistic general circulation model with neural network parameterizations for atmospheric moist physics and radiation processes.

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THALES CONTRAILS GREEN OPERATIONS R&T STRATEGY

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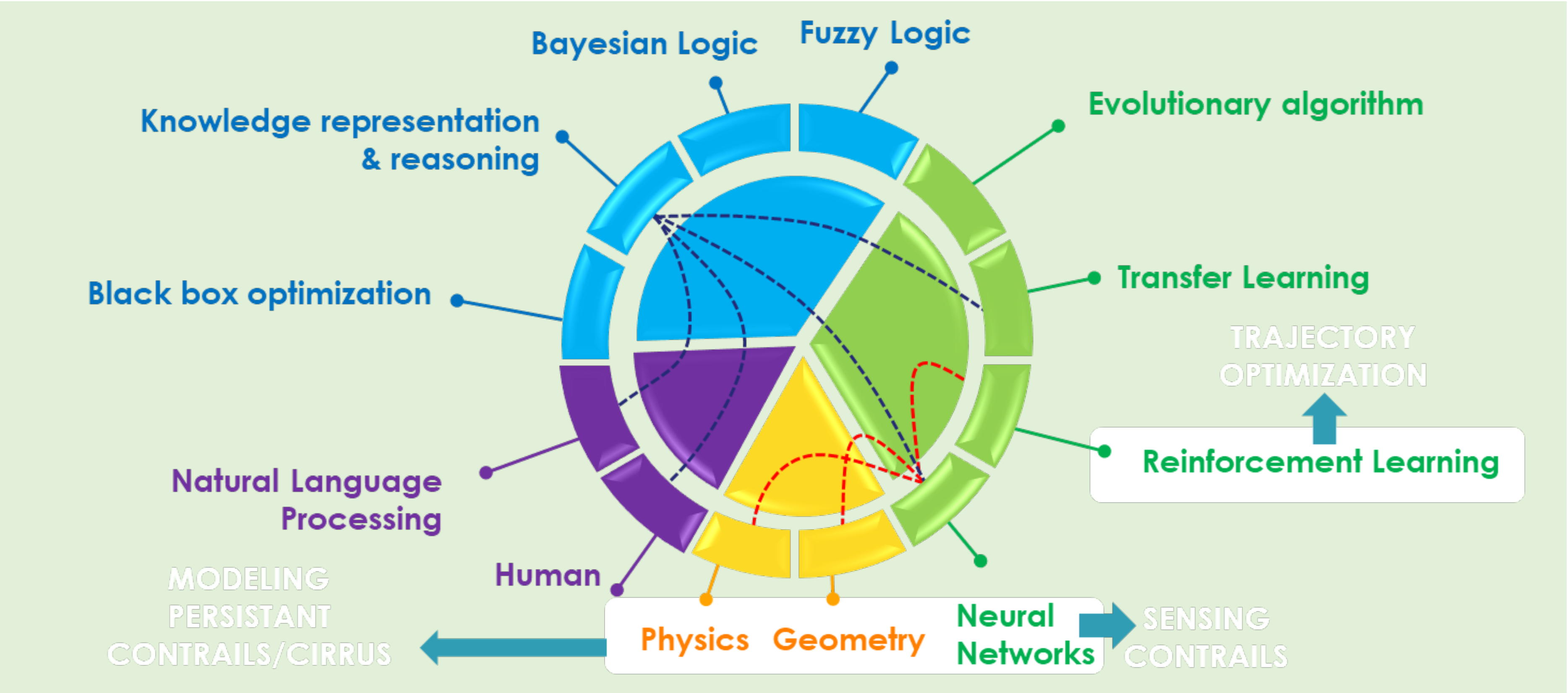
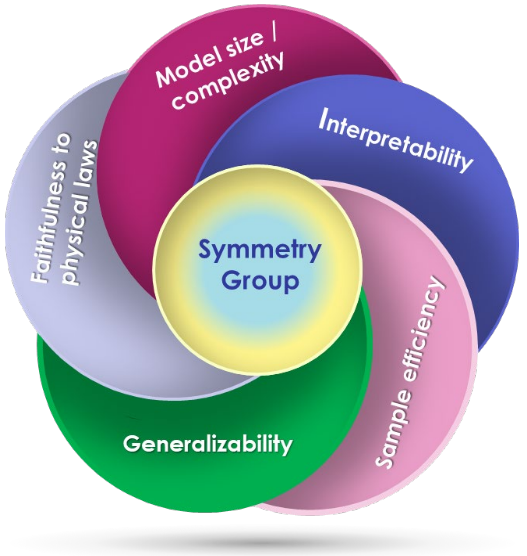
Frédéric Barbaresco

THALES Sensing Segment Leader

AI FOR GREEN OPERATIONS: hybridization of AI techs for Sensing & Modeling

- **Model-Informed HYBRID AI**: GINN, PINN & TNN





- **Geometry-Informed Neural Network** (hybrid data with symmetries constraints)
- **Physics-Informed Neural-Network** (hybrid data with analytical PDE models)
- **Thermodynamics-Informed Neural Network** (hybrid data with energy preservation and entropy production principles)

MODEL-INFORMED HYBRID AI is better adapted in case of frugal data and better compliant to AI validation/qualification/Certification

Model-Informed HYBRID AI FOR CONTRAILS: Geometry-Informed/Physics-Informed/Thermodynamics-Informed NN

$$\dot{z}_t = L(z_t)\nabla E(z_t) + M\nabla S(z_t), \quad z(0) = z_0$$

Poisson matrix: reversibility

Friction matrix: irreversibility

with

$$L(z)\cdot\nabla S(z) = 0,$$
$$M(z)\cdot\nabla E(z) = 0.$$

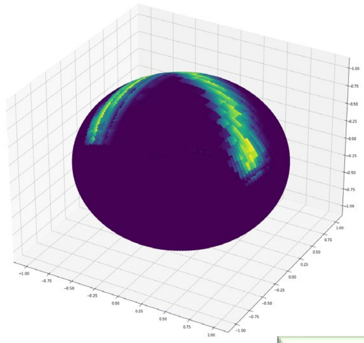
CONTRAILS MODELING

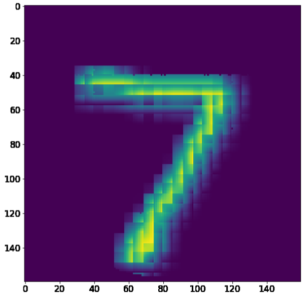
Thermodynamics-Informed NN

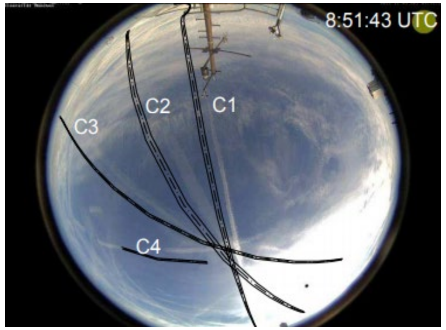
1st Principle: Energy/Moment preservation

2nd Principle: Entropy production (dissipation)

$$\forall g \in G, \qquad \psi_G(g) = (f \star_G K)(g) = \int_G K(h^{-1}g)f(h)d\mu^G(h)$$







Geometry-Informed NN

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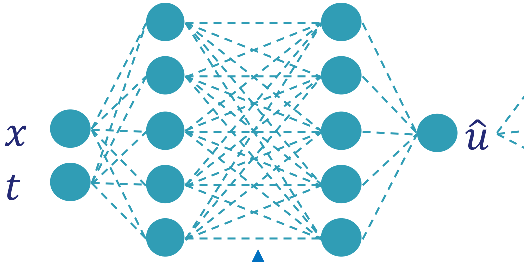
Symmetries: Lie Group Equivariance

Noether Th.: Preservation of Moment Map

Physical Model: Universal Approximation

Differential Invariant: PDE Symmetries



Error on the knowledge

∂_t ∂_x $f\left(\hat{u}, \frac{\partial \hat{u}}{\partial t}, \frac{\partial \hat{u}}{\partial x} \ldots\right)$

Error on the data

$\hat{u} - u$

Computing the parameters w_i

CONTRAILS MODELING

Physics-Informed NN

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AI for Green Operations: Research of new algorithms for Trajectories Optimization / Conflict Detection & Resolution by Reinforcement Learning

- **Medium Term Conflict Detection (MTCD)**
  - Flight Plan based 4D trajectory estimation
  - Minimum separation:
    - Horizontal: 5 NM
    - Vertical: 1000 feet
  - Time horizon:
    - Usually 20 minutes look-ahead
- **Conflict Resolution Advisory**
  - Propose a resolution for an MTCD conflict

RL Actions

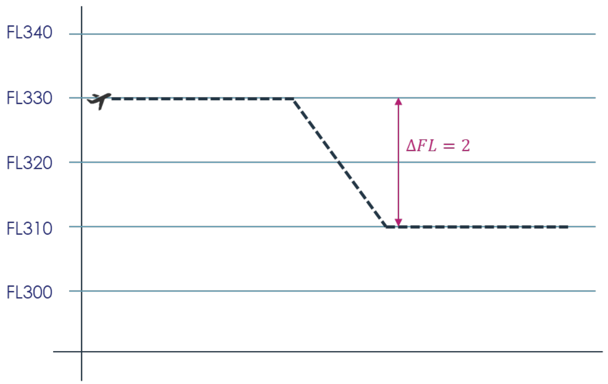
- DCT (Direct)
- Heading
- Cleared Flight Level
- Change speed

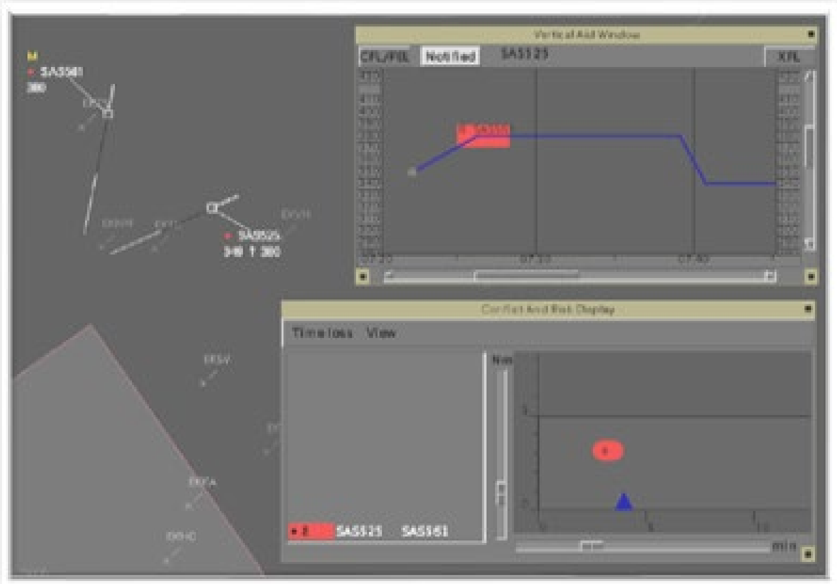
Cleared Flight Level

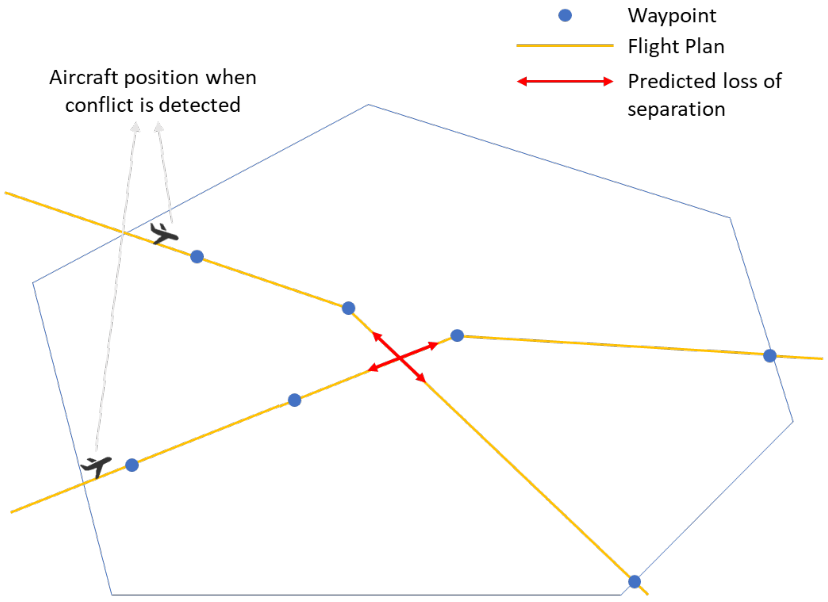
Agent changes its flight level.

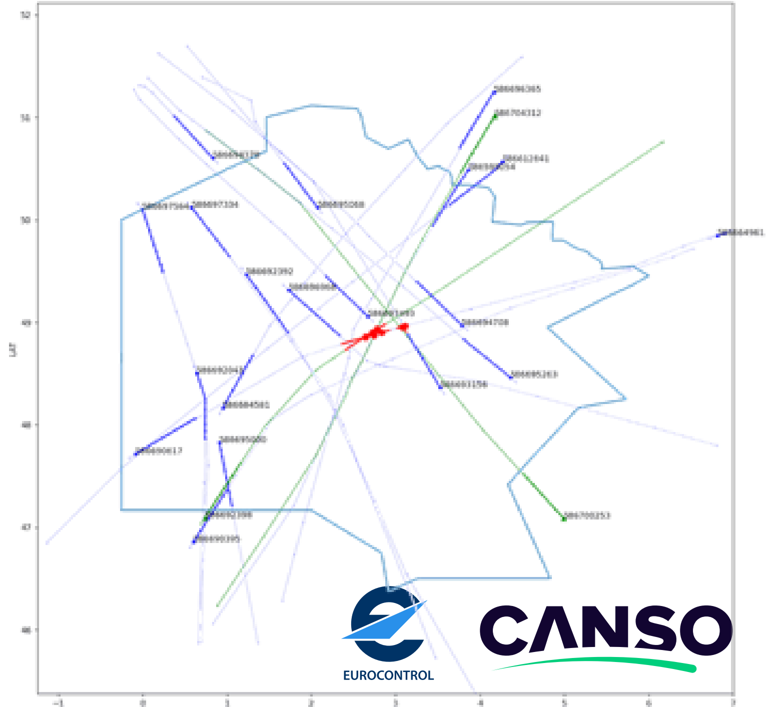
$\Delta FL \in \{-2, -1, +1, +2\}$

If the agent tries to climb from FL500 or go down from FL300, action is cancelled.









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Transparent
Understandable
Ethical

FEDERATIVE ENVIRONMENT, METHODS, TOOLS AND USE CASES — Open / Interoperable / Maintained

- Data and knowledge
- Design
- Evaluation
- Embedded systems

QUALITY ASSURANCE – ENGINEERING

End 2 End

End-to-end engineering approach; ODD; MBSA for Safe AI; Assurance case

Trustworthiness Assessment

Trustworthiness Attributes, Metrics & KPIs (incl. data quality, uncertainty robustness, explainability, usability…)

Data Life Cycle

From ODD to data
Dataset for robustness assessment
Bias mitigation (domain adaptation)
Data Frugality (smart / synthetic data)

Confiance ai

Explainability / Interpretability

Model, Feature importance
Robust ML (eg. k-Lipschitz)
Interpretability

Robustness / Monitoring

White/Grey/Black Box Monitoring
Robust ML (eg. k-Lipschitz, GAN, attack by patch)

Embedability

Embedded AI components & ressources estimation
Benchmarking env.

Confiance.ai workbench

Confiance Evaluation, Maturation & Transfer (CEMT) Methodology
Documents structure and access – Companion
Confiance.ai Asset Catalogue

Misc

Standard & Label: AFNOR collaboration & ISO, conformity assessment,

TRUST AND ALGORITHM

- Global approach to data ODD / knowledge ODD and quality assessment
- **Trustworthy AI Components design methodologies**

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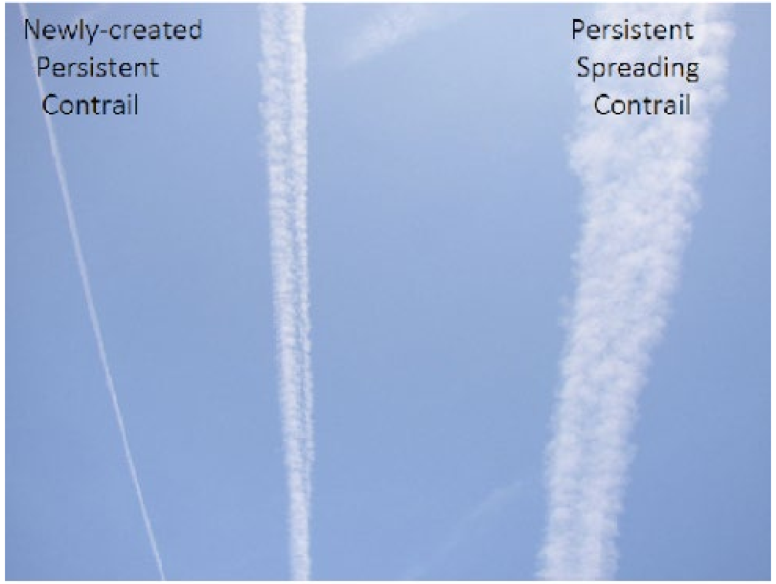
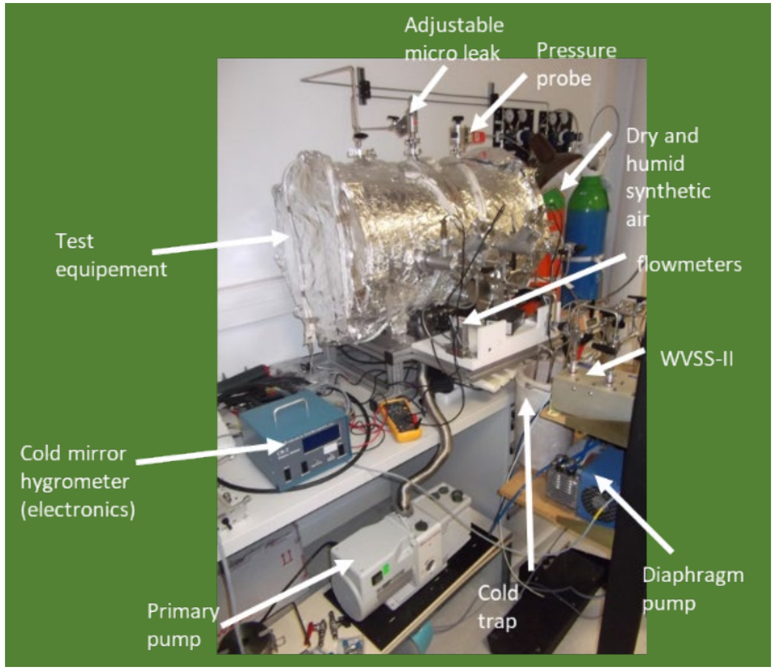
PERSISTANT CONTRAIL MODELING /NOWCASING:
Airborne hygrometry measurement

- Thales area of interest: **Persistent Contrail Formation Regime Assesment by Humidity Sensors**
- Experience acquired during **HYPATIE study** lead by Dassault Aviation (CORAC, 2012)
  - Comparison of various hygrometer technologies
  - Specific characterization of WVSSII (Spectra Sensors) (Development of characterization bench with reference hygrometer at low pressure, downto less than 10 ppmv, WVSSII : Second harmonic detection @ 1,37 µm))
- **State of the art of AC hygrometer**
  - **None of the available technologies fully meet the specifications**
  - **Recent progress in IR could lead to increased sensitivity for this later technology**
  - Among the closest to the specifications : Cooled mirror hygrometers, Capacitive hygrometers, Absorption spectroscopy





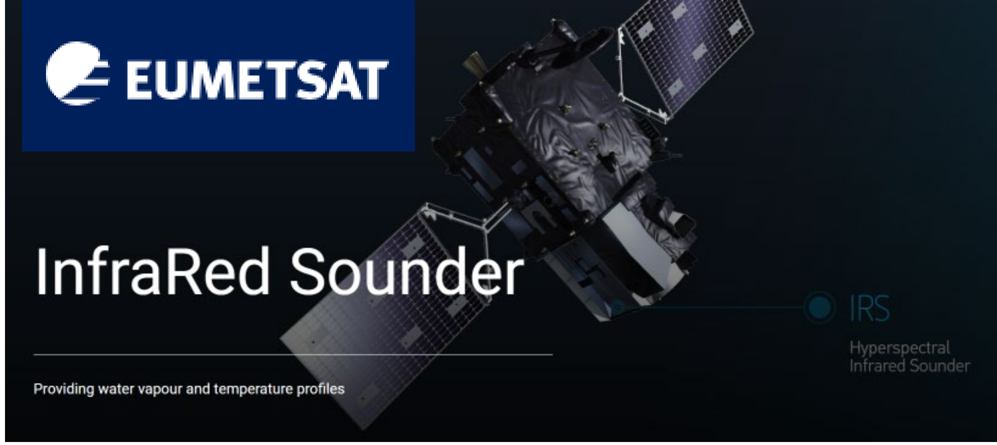
PERSISTANT CONTRAILS are powered by atmosphere water vapour (the plane only sows initial contrail crystals)

PERSISTANT CONTRAIL MODELING /NOWCASTING:

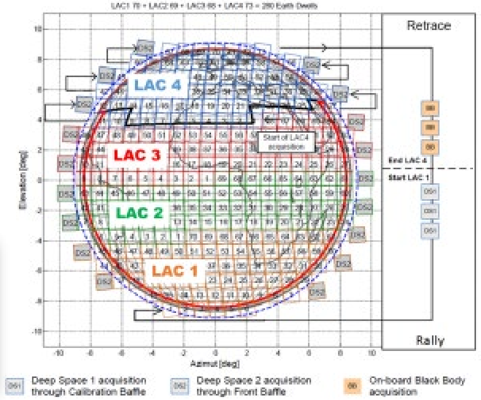
Spaceborne Water Vapour Measurement

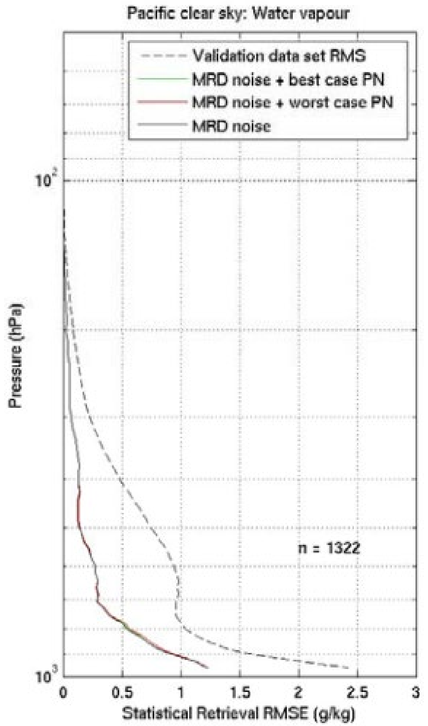
- **WATER VAPOR MEASUREMENT:** The IRS (InfraRed Sounder) of EUMETSAT's GEO (geostationary) MTG (Meteosat Third Generation) satellite allows 3D water vapour measurement by infrared hyperspectral sounding (LWIR 700 to 1210cm^{-1} and MWIR 1600 to 2175cm^{-1}):
  - Spatial on ground resolution: **4 km x 4 km**
  - Repeat cycle over Europe: **30 minutes**
  - **Vertical column water vapour**
- The IRS (also referred to as GeoSounder) objectives are to provide **"break through" measurements on the time evolution of horizontal and vertical water vapour structures in the atmosphere**.
- The prime objective of IRS is to support the dynamics via tracking of vertical water vapour structures.
  - The IRS will provide information on vertically resolved atmospheric motion vectors with improved height assignment.

PERSISTANT CONTRAILS are powered by atmosphere water vapour (the plane only sows initial contrail crystals)



https://www.eumetsat.int/mtg-infrared-sounder
https://www.youtube.com/watch?v=kuLkXq2VKXE&t=5s





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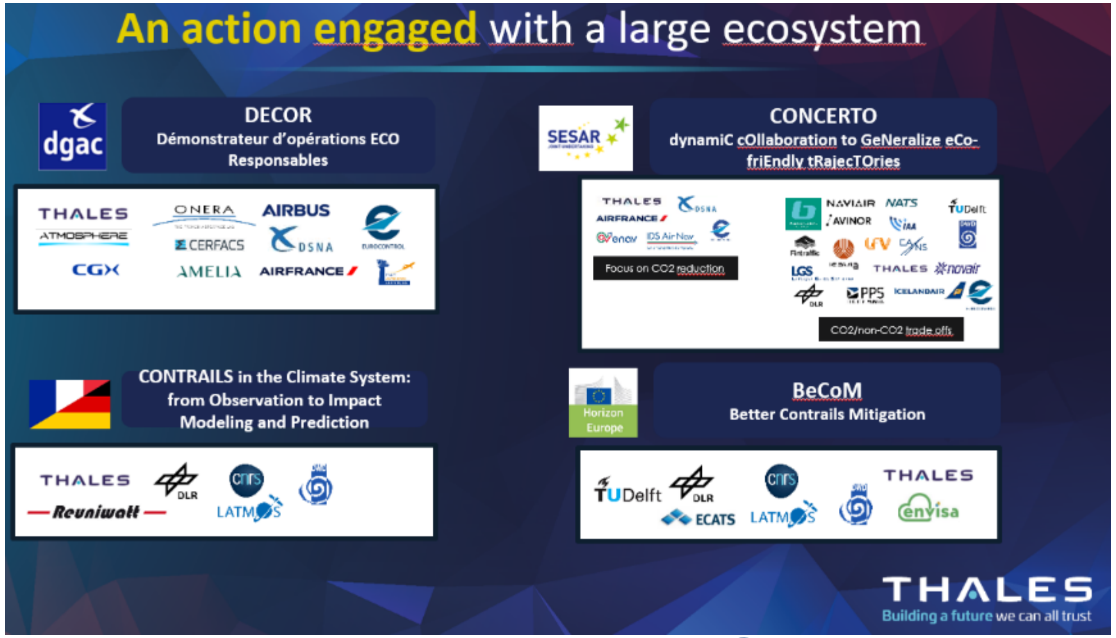
CONCLUSION

- **Thales TrUE AI for CONTRAILS Detection/Modeling/Nowcasting**: Trustworthy AI based on validity, explainability, security & responsibility
- **Use of physics-informed/thermodynamics-informed neural-networks** for better modeling of persistant contrails and persistent aircraft induced cirrus clouds and use of “robust by design” **geometry-informed** equivariant neural network to automatically detect persistent contrails with ground and space sensors.
- **AI-based hybrid digital twin** mixing analytical model and learning on data to refine forecast model of contrail forming conditions
- **New airborne hygrometer SENSORS** capable of measuring upper atmospheric humidity could be needed for nowcasting and forecasting of contrail forming conditions and the assessment of the persistent contrail formation regime
- **MTG InfraRed Sounder** will provide 3D water vapour (Horizontal 4 km x4km, verical column) measurement by infrared hyperspectral sounding every 30 minutes, that will help to forecast contrail forming conditions



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Building a future we can all trust

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