ASCloud - TC: All Sky Camera Cloud Type Classifier

PRINCIPAL ACADEMIC TUTOR
Emanuele Giovanni Carlo Ogliari,
Department of Energy, Politecnico di Milano

ACADEMIC TUTORS
Paolo Garza,
Department of Control and Computer Engineering, Politecnico di Torino

Daniele Rege Cambrin,
Department of Control and Computer Engineering, Politecnico di Torino

EXTERNAL INSTITUTIONS
Reuniwatt
RSE – Ricerca sul Sistema Energetico

EXTERNAL TUTORS
Sarah Vadillo-Quesada, Reuniwatt

Lucia Barbagelata,
Politecnico di Milano,
Electrical Engineering

Quintilla Berti,
Politecnico di Torino,
Aerospace Engineering

Lorenzo Carletta,
Politecnico di Milano,
Management Engineering

Enrico Miotto,
Politecnico di Torino,
Communications Engineering

Leonardo Pavarino,
Politecnico di Torino,
Computer Science and Engineering

Paolo Pertino,
Politecnico di Milano,
Computer Science and Engineering

Executive summary

Climate change is heavily influenced by human activities, particularly in two critical areas: energy production and aviation. Energy production still relies on methods that emit substantial greenhouse gases, while carbon emissions from aircraft contrails—thin clouds formed by exhaust gases—contribute to 2.5% of total global emissions. These contrails can trap heat or reflect sunlight, significantly affecting local and global climates. Addressing these challenges is vital to mitigating global warming and improving the efficiency of renewable energy sources.

The ASCloud-TC project offers a solution through an innovative cloud detection and classification system. Using all-sky, 360-degree ground images, the system detects and classifies cloud types, including contrails. This approach is key for both solar energy production forecasting and minimizing contrail-related climate impacts. Accurate cloud predictions can enhance photovoltaic system efficiency by optimizing self-consumption of solar energy, reducing external electricity reliance, and minimizing surplus losses. Demand for this technology is evident, with interest from companies like Reuniwatt and potential users.

In aviation, contrails contribute significantly to global warming, comparable to greenhouse gas emissions. These clouds form under specific atmospheric conditions, which could be avoided with slight flight route adjustments. The ASCloud-TC system aims to provide the necessary data to support these adjustments, using machine learning algorithms to detect and classify contrails.

The project relies on two key components: effective data acquisition through all-sky cameras, and advanced machine learning algorithms for cloud classification. By integrating visible and infrared images, the system offers localized, frequent data, even in low visibility conditions. The project's creation of the first hand-labeled dataset for contrails using both visible and infrared images has produced promising early results, with 73.9% accuracy for visible-spectrum classification and 59.1% for infrared. Future improvements include merging data from both spectrums and incorporating time-sequenced images for better accuracy.

Ultimately, the ASCloud-TC system presents a dual solution: reducing aviation emissions and improving solar energy forecasting, both critical steps toward decarbonization and combating climate change.

Figure 1: Examples of contrails as seen from satellite images (left), taken from NASA's visible Earth project, and from the projects' ground camera (right).

Key Words

Cloud classification, contrail detection, machine learning, all-sky cameras, solar energy forecasting, aviation emissions, sustainability, decarbonization

Project description written by the Principal Academic Tutor

The project aims to research, develop and implement a highly accurate 24/7 cloud-type classification system (CTCS). This classification system uses two advanced all-sky smart cameras that capture images in both visible and infrared domains, enabling accurate sky coverage classification. Smart all-sky cameras sensors refine and improve data collections and incorporate numerous measures to ensure a consistent data flow and minimize classification errors. Deep learning techniques are employed to classify clouds and detect contrails.

The project is a collaboration between Politecnico di Milano and Politecnico di Torino and involves Reuniwatt as industrial stakeholder, which provided the hardware and is specifically concerned about this project subject and research results. The main goal has been to identify and develop innovative CTCS methodologies, engaging students into its design, development and final implementation, to achieve a persistent, productive and profitable impact. The definition of exploitation strategies to support the adoption of the proposed tool in different application domains was another crucial goal.

Both universities have been actively involved in research activities that involve deep interdisciplinary knowledge and advanced skills in multi-disciplinary projects managing, providing the necessary expertise to support the development of innovative solutions. Industrial and institutional stakeholders have played an active role in identifying their specific needs for innovative CTCS solutions, in requirements definition, in providing feedback on the proposed approach and in final user-side refining.

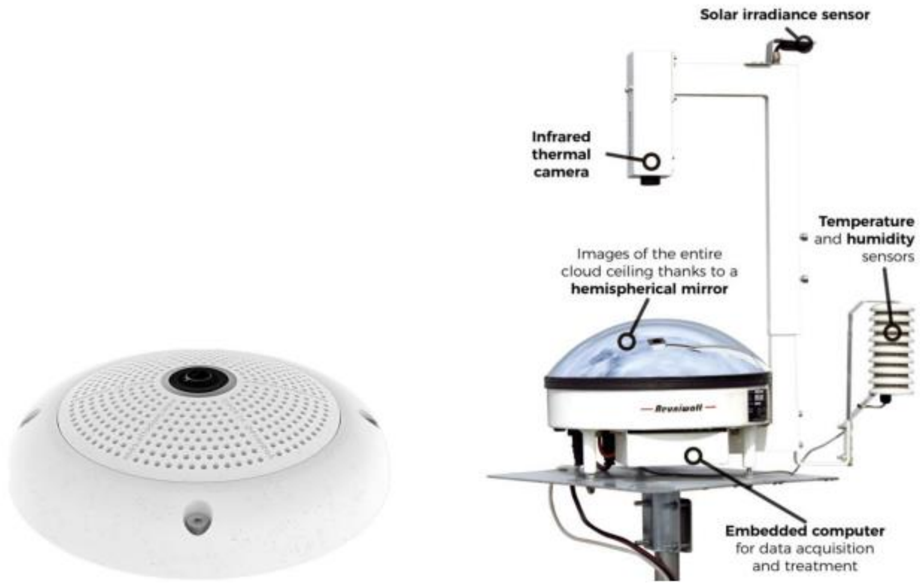


Figure 2: The cameras used in this project – Mobotix Q26 (left) & Reuniwatt Sky Insight (right).

Team description by skill

ASCloud-TC is an only engineers team composed by Leonardo Pavarino (Software Engineer), Paolo Pertino (Machine Learning Engineer), Lucia Barbagelata (Electrical Engineer), Quintilla Berti (Aerospace Engineer), Lorenzo Carletta (Management Engineer) and Enrico Miotto (Communications Engineer).

Despite the common denomination the team is rather diverse with an optimal mix of skills to best tackle the problems at hand by compensating each other's blind spots. Beyond the cold hard technical skills, the mix of different personalities has proven to be rather helpful in balancing each other's traits, strengths and weaknesses.

Leonardo Pavarino - Leonardo boasts deep technical knowledge in coding in front-end, back-end and database management effectively making him a quite handy full stack developer. His contribution has been particularly significant in project-related tasks like writing the algorithm or suggesting proper software work tool, as well as setting up the framework to solve important problems thanks to his rigorous logic.

Paolo Pertino - Equipped with deep knowledge in machine learning, Paolo has been the technical leader of this project by setting the big picture vision but also by getting into the weeds of the development of the training and testing model. Moreover, his easygoing and laid-back personality has managed to loosen up group tensions during the most challenging moments of the School.

Lucia Barbagelata - Despite her highly technical background Lucia decided to work on the business side of the project, providing incredible insights into the technical utility of the machine learning algorithm to tame energy costs for companies and institutions. She has acted as a "translator" between the technical and the business group, effectively allowing for the full exploitation of the project potential. Last but not least, her uplifting and joyful personality has been a key motivator for all the team members.

Quintilla Berti - Quintilla has a background in Aerospace Engineering and has had impressive work experience which has revealed to be particularly useful in bridging the gap between the hefty technical side requirements of the projects and the economic utility of proper contrails detection. Moreover, her native-like level of English coupled with her charming personality has made her a formidable weapon during public presentations.

Lorenzo Carletta – Despite his less technical background, Lorenzo has been a key component in unlocking the economic potential of the idea, allowing for the discovery of potential business opportunities amid project constraints. His finance background has proven its utility in the assessment of business viability and in the valuation of the idea. His introverted yet insightful personality struck a harmonious balance in the group.

Enrico Miotto – Possibly one of the most knowledgeable members of the group, Enrico has provided deep contribution to the algorithm development as well as in many other tasks of the School thanks to his multitude of talents and speed of learning effectively making him a jack-of-all-trades. Lastly, his humorous personality has lightened the mood of the group in many moments, making him a coveted team member on all occasion.

Goal

The primary goal of the ASCloud-TC project is to develop a real-time classification solution that leverages 360-degree all-sky cameras, capturing images in both visible and thermal infrared spectrums. This approach allows for continuous monitoring of atmospheric conditions, even during low visibility or nighttime, offering a comprehensive dataset essential for accurate cloud and contrail detection.

A key objective of the project has been to create a robust, hand-labeled dataset of cloud formations and contrails, which is one of the first of its kind. This dataset has been crucial for training machine learning models to accurately detect contrails, an area previously underexplored, which was one of the goals of the project. ASCloud-TC also aimed at developing a solution able to classify the sky into five distinct cloud conditions, ranging from clear skies to thick clouds, and has demonstrated promising results in classifying visible spectrum images.

The project's ultimate goal has been creating a reliable Deep Learning-based system to be deployed in real-time applications, where it can continuously detect contrails and classify clouds, providing valuable insights for environmental monitoring and improving the accuracy of weather and solar energy forecasts.

Figure 3: Contrails - Comparison of annotations within RGB images, in particular, on the left a simple case with a single clearly defined contrail and, on the right, a more complex case with multiple and less defined contrails.

Figure 4: Clouds - Examples of images from the RGB dataset: from left to right clear sky, patterned clouds, thick dark clouds, thick white clouds, and veil clouds.

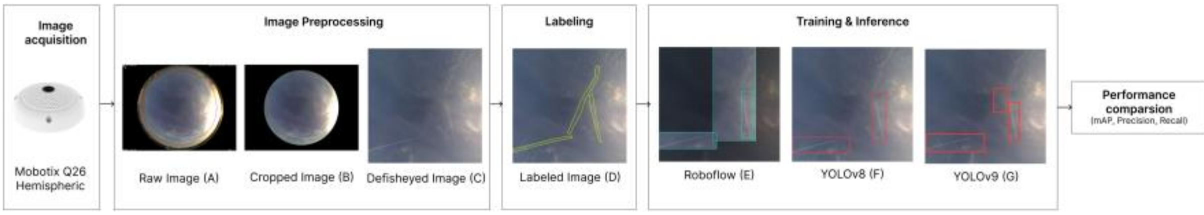
Understanding the problem

The core of the project's idea is a technology-push innovation which layers on top of another technological innovation. Indeed, the use of the All Sky Camera allows capturing images at all times, unlocking the possibility of a faster and more effective analysis of the images.

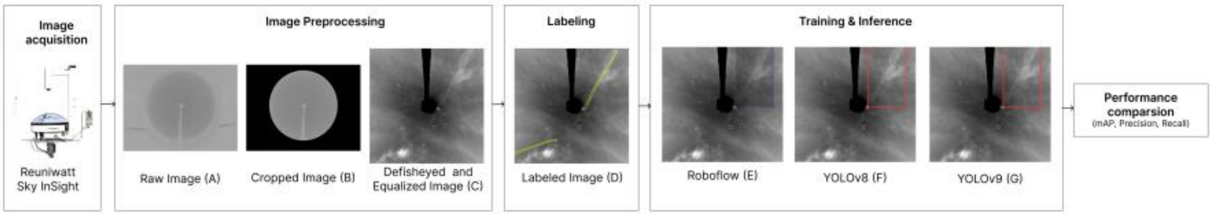
Starting from the same piece of hardware, the project branched into two different ramifications: cloud classification and contrails detection. The two ideas are essentially two algorithms which serve two different purposes while exploiting the same underlying technology.

The cloud classification algorithm is a supervised model which allows the instantaneous recognition and classification of clouds. This has the opportunity to be game-changing in the field of renewable energy by allowing facilities to better manage controllable energy consumption fluctuations by aligning it to favorable weather condition.

The contrail detection algorithm is a recognition model which allow the automatic identification of aircraft-generated contrails with the goal of creating a database of identified contrails with an attached date and time. This data could be later cross-checked with aviation pathways with the goal to exactly pinpoint which aircraft models generate environmental unfriendly contrails under which weather conditions.



a) RGB Pipeline.



b) IR Pipeline.

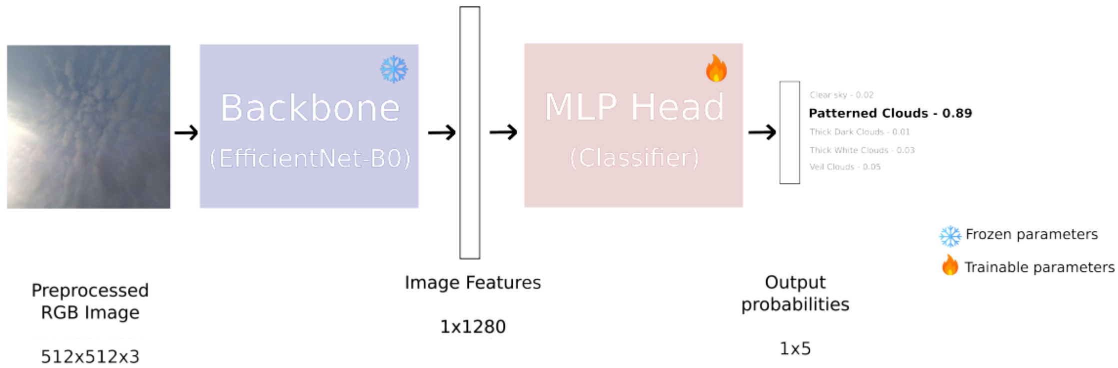
Figure 5: The complete processing pipeline for RGB (a) and IR (b) images for the contrails detection task. The image is padded, cropped, and resized. Then it is "defisheyed". In (b), the IR image is also equalized and then follows the same preprocessing steps.

Exploring the opportunities

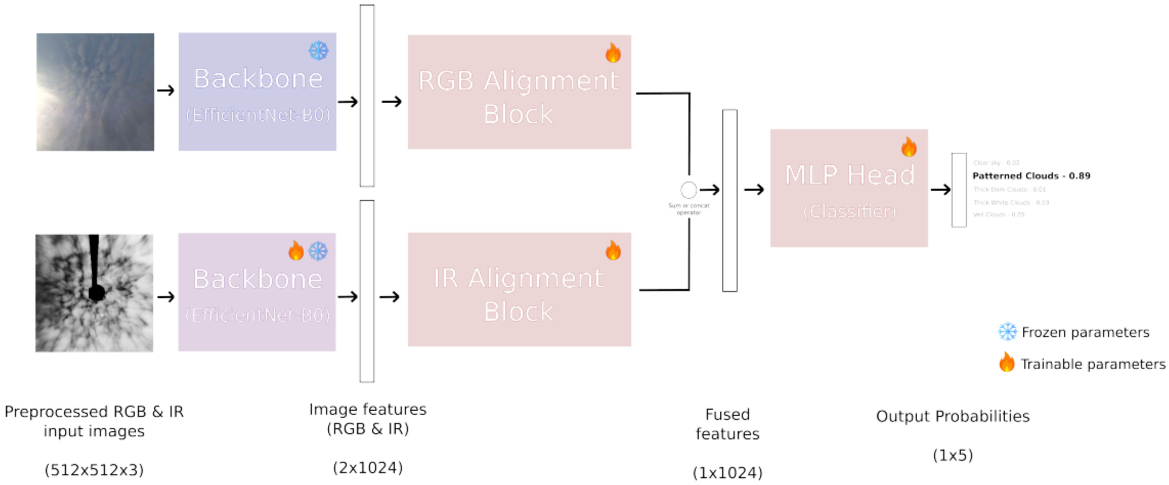
The development of the ASCLOUD-TC system was a multi-phase process that involved research on cloud classification, data acquisition, stakeholder analysis, and the design of Deep Learning models. The project began with research into existing cloud classification methods, focusing on the different types of clouds and how they could be distinguished in all-sky images. Using all-sky cameras, the team gathered a large dataset of cloud and contrail images. These cameras enabled continuous monitoring, making the data highly reliable and versatile.

A significant step was the creation of a comprehensive, hand-labeled dataset of these images, a crucial resource for training the Deep Leaarining models. The team manually annotated thousands of images, building one of the first datasets specifically designed for contrail detection using both visible and infrared images. Simultaneously, the team conducted a stakeholder analysis to better understand the needs of potential users. This analysis identified key stakeholders, including renewable energy companies, aviation firms, and government agencies, and helped refine the technical goals of the project. Renewable energy companies expressed strong interest in using cloud classification to improve solar energy forecasts, while aviation stakeholders highlighted the need for contrail detection to mitigate the environmental impact of flights.

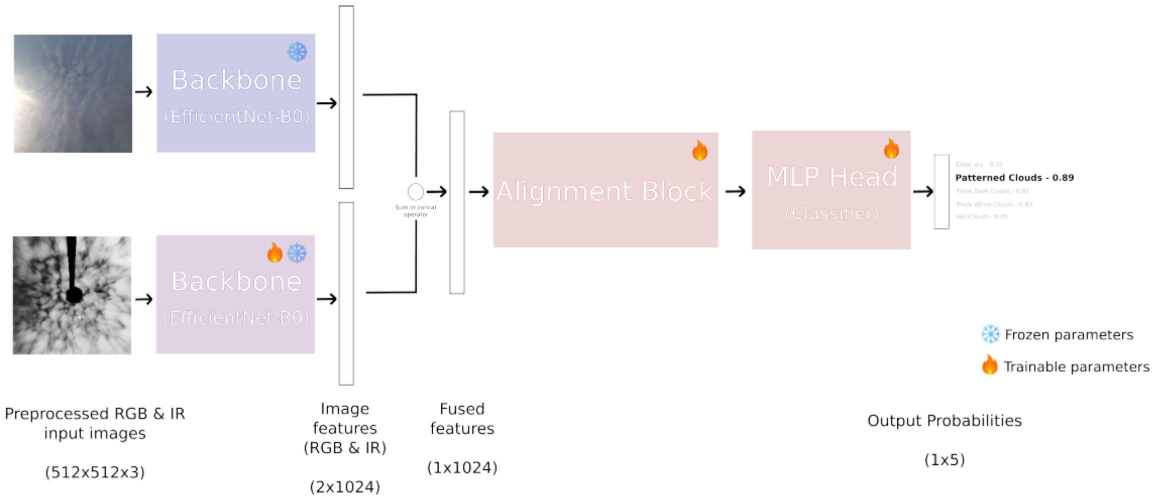
Since the solar energy forecasting application of the technology is also aimed at individual users, the team developed and distributed a questionnaire to assess how individuals with a photovoltaic system might value the system's ability to provide highly accurate solar irradiation predictions, giving them insights into their panels' production potential and helping them better manage their energy consumption.



a) RGB only model.



b) RGB & IR model.



c) RGB & IR model, second version.

Figure 6: The three models used for cloud type classification.

Generating a solution

Deep Learining plays a central role in the ASCLOUD-TC system, with several state-of-the-art algorithms being used for both cloud and contrail classification. Based on the insights gained from stakeholders, the project focused on designing Deep Learning models tailored to these needs. Several models were explored, and the team ultimately selected YOLO (You Only Look Once) for real-time object detection and EfficientNet for cloud classification, due to their convenient trade-off between computational efficiency and performances. These models are particularly well-suited for edge devices, where rapid data processing is necessary due to the high frequency of images generated by the all-sky cameras. They also pop up for their lightweight design and their ability to run efficiently on embedded systems, making them practical for real-time applications and making the solution scalable for practical use. They were trained and tested using the labeled dataset, achieving promising results in distinguishing cloud types and detecting contrails. A critical part of the solution was integrating both visible and infrared spectrum data. While visible spectrum data is effective in clear conditions, the inclusion of thermal infrared images allows the system to perform well in low visibility or nighttime conditions, thus offering 24/7 functionality.

By testing, refining, and optimizing the Deep Learning models, the project achieved promising results, with high accuracy in visible spectrum images. However, challenges remain, particularly in improving feature extraction techniques, such as neural networks, for the infrared domain, which could be a key area for future research. Further advancements may include more precise matching of detected contrails to their originating flights and refining the cloud classification system for deeper insights. Additionally, framing the task as a time-series forecasting problem, given the temporal correlation between consecutive images, could offer further opportunities for improvement.

Model	# Parameters	P [%]	R [%]	mAP [%]
RT 3.0	-	-	-	64.0
YOLOv8s	11.2M	70.9	58.7	65.0
YOLOv8m	25.9M	70.4	63.3	67.1
YOLOv9c	25.3M	72.1	71.9	73.9

a) RGB images.

Model	# Parameters	P [%]	R [%]	mAP [%]
RT 3.0	-	-	-	39.0
YOLOv8s	11.2M	56.2	55.9	54.8
YOLOv8m	25.9M	62.2	53.6	56.0
YOLOv9c	25.3M	61.3	63.4	59.1

b) IR images.

Figure 7: Contrails detection results. RT 3.0 stands for Roboflow Train 3.0. For Roboflow Train some parameters are missing because they are not provided by the system.

	Precision	Recall	F1-score
Clear sky	0.88	0.78	0.82
Patterned	0.58	0.49	0.47
Thick Dark	0.75	0.74	0.73
Thick White	0.71	0.75	0.73
Veil	0.87	0.91	0.89
Accuracy			0.83
Macro Avg	0.76	0.74	0.73
Weighted Avg	0.82	0.83	0.82

a) RGB images.

	Precision	Recall	F1-score
Clear sky	0.84	0.77	0.79
Patterned	0.71	0.68	0.68
Thick Dark	0.85	0.65	0.66
Thick White	0.72	0.75	0.73
Veil	0.89	0.90	0.90
Accuracy			0.83
Macro Avg	0.80	0.75	0.75
Weighted Avg	0.84	0.83	0.83

b) IR & RGB images – alignement strategy.

	Precision	Recall	F1-score
Clear sky	0.85	0.78	0.81
Patterned	0.71	0.64	0.64
Thick Dark	0.74	0.77	0.74
Thick White	0.74	0.75	0.73
Veil	0.89	0.91	0.90
Accuracy			0.84
Macro Avg	0.78	0.77	0.76
Weighted Avg	0.84	0.84	0.84

c) IR & RGB images – second alignement stategy.

Figure 8: Clouds classification results.

Main bibliographic references

P. Jaramillo, S. Kahn Ribeiro & P. Newman (2022). *Climate Change 2022 - Mitigation of Climate Change*. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1049 – 1160).

K. McCloskey, S. Geraedts, B. Jackman, V. R. Meijer, E. Brand, D. Fork, J. C. Platt, C. Elkin C. Van Arsdale (2021). *A human-labeled Landsat-8 contrails dataset.* In: ICML 2021 Workshop on Tackling Climate Change with Machine Learning.

E. Ogliari, M. Sakwa, P. Cusa (2024*). Enhanced Convolutional Neural Network for solar radiation nowcasting: All-Sky camera infrared images embedded with exogeneous parameters*. In: Renewable Energy (vol. 221).

J. Redmon, S. Divvala, R. Girshick & A. Farhadi (2016). *You Only Look Once: Unified, Real-Time Object Detection*.

D. Soumyabrata, Yee Hui Lee & S. Winkler (2015*). Categorization of cloud image patches using an improved texton-based approach*. In: 2015 IEEE International Conference on Image Processing (pp. 422–426).

World Meteorological Organization (1975). *International Cloud Atlas* (vol. 2). Secretariat of the World Meteorological Organization.

J. Yue-Hei Ng, K. McCloskey, J. Cui, V. R. Meijer, E. Brand, A. Sarna, N. Goyal, C. Van Arsdale & S. Geraedts (2023*). OpenContrails: Benchmarking Contrail Detection on GOES-16 ABI*.