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E-CONTRAIL

Exploratory Research Plan

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Abstract

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E-CONTRAIL

ARTIFICIAL NEURAL NETWORKS FOR THE PREDICTION OF CONTRAILS AND AVIATION INDUCED CLOUDINESS

E-CONTRAIL

This document is part of a project that has received funding from the SESAR 3 Joint Undertaking under grant agreement No 101114795 under European Union's Horizon Europe research and innovation programme.

We provide a high-level summary of the project E-CONTRAIL:

Contrails and aviation-induced cloudiness effects on climate change show large uncertainties since they are subject to meteorological, regional, and seasonal variations. Indeed, under some specific circumstances, aircraft can generate anthropogenic cirrus with cooling. Thus, the need for research into contrails and aviation-induced cloudiness and its associated uncertainties to be considered in aviation climate mitigation actions becomes unquestionable.

We will blend cutting-edge AI techniques (deep learning) and climate science with application to the aviation domain, aiming at closing (at least partially) the existing gap in terms of understanding aviation-induced climate impact.

The overall purpose of E-CONTRAIL project is to develop artificial neural networks (leveraging remote sensing detection methods) for the prediction of the climate impact derived from contrails and aviation-induced cloudiness, contributing, thus, to a better understanding of the non-CO2 impact of aviation on global warming and reducing their associated uncertainties as essential steps towards green aviation.

Specifically, the objectives of E-CONTRAIL are:

- O-1 to develop remote sensing algorithms for the detection of contrails and aviation-induced cloudiness.
- O-2 to quantify the radiative forcing of ice clouds based on remote sensing and radiative transfer methods.
- O-3 to use of deep learning architectures to generate AI models capable of predicting the radiative forcing of contrails based on data- archive numerical weather forecasts and historical traffic.
- O-4 to assess the climate impact and develop a visualization tool in a dashboard.

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1 Executive summary

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- O-2 to quantify the radiative forcing of ice clouds based on remote sensing and radiative transfer methods.
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- O-4 to assess the climate impact and develop a visualization tool in a dashboard.

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2 Introduction

2.1 Purpose of the document

E-CONTRAIL project is a SESAR exploratory research project. As such, the purpose of the document is to introduce the Exploratory Research Plan for Solution “E-CONTRAIL Climate Hotspot Prediction Service”.

The purpose of this experimental plan is to secure the application of scientific best practices when assessing the results of E-CONTRAIL project. For this purpose, we will first identity the reference guidance documents, we will then identify the research questions to answer and/or the hypotheses to test, and finally, we will define the experiments to be conducted and the metrics/methods to assess the achieved results.

2.2 Intended readership

The intended readership for this Deliverable, focusing on the Experimental Research Plan, comprises aviation researchers, industry innovators, regulatory authorities, and SESAR program stakeholders. This document is tailored to guide and inform those actively engaged in experimental research endeavours aimed at enhancing air traffic management and advancing the SESAR program's objectives.

2.3 Background

There is no previous project or activity in which E-CONTRAIL is building up.

The reference document to prepare this plan is the Experimental Approach guidance ER [AD1]. In addition, we rely on E-CONTRAIL’s Grant Agreement [AD2], where the research questions and hypotheses were established.

2.4 Structure of the document

The document begins with an abstract, followed by an executive summary providing a concise overview. The introduction outlines the document's purpose, intended readership, background, structure, and includes a glossary of terms and a list of acronyms. The context of the experimental research plan is discussed in Section 3, covering its scope, key research and innovation needs, estimated performance contributions, and initial and exit maturity levels. Section 4 details the experimental plan, including the approach, stakeholders' expectations, validation objectives, assumptions, a list of validation exercises, and planning. Any deviations from the SESAR 3 JU project handbook [AD3] are addressed. Section 5 delves into the specifics of individual validation exercises, providing plans for each exercise. The document concludes with a comprehensive reference section, encompassing applicable and reference documents.

2.5 Glossary of terms

Term	Definition	Source of the definition

Table 1: glossary of terms

2.6 List of acronyms

Term	Definition
ATM	*Air traffic management*
DES	*Digital European Sky*
EXE	*Exrecise*
GA	*Grant agreement*
HE	*Horizon Europe*
ID	*Identifier*
KPA	*Key performance area*
KPI	*Key performance indicator*
OSED	*Operational service and environment description*
SESAR	*Single European sky ATM research*
SESAR 3 JU	*SESAR 3 Joint Undertaking*

Table 2: list of acronyms

3 Context of the experimental research plan

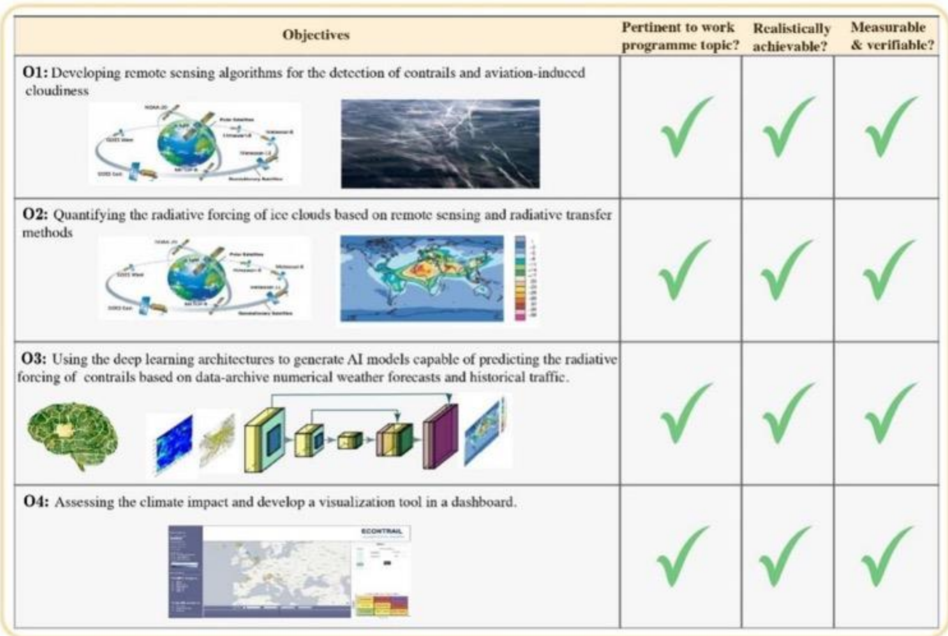
3.1 Experimental research plan context and scope

The experimental plan shall ensure that the specific objectives of the project are achieved, yet measured and quantified.

3.1.1 E-CONTRAIL Objectives

The overall purpose of E-CONTRAIL project is to develop artificial neural networks (leveraging remote sensing detection methods to estimate radiative forcing and effective radiative forcing) for the prediction of the climate impact derived from contrails and aviation-induced cloudiness, contributing, thus, to a better understanding of the non-CO_2 impact of aviation on global warming and reducing their associated uncertainties as essential steps towards green aviation.

The specific objectives are included in Figure 1. The description, including its achievability, measurability, and verifiability is exposed in the sequel.



Objectives	Pertinent to work programme topic?	Realistically achievable?	Measurable & verifiable?
O1: Developing remote sensing algorithms for the detection of contrails and aviation-induced cloudiness	✓	✓	✓
O2: Quantifying the radiative forcing of ice clouds based on remote sensing and radiative transfer methods	✓	✓	✓
O3: Using the deep learning architectures to generate AI models capable of predicting the radiative forcing of contrails based on data-archive numerical weather forecasts and historical traffic.	✓	✓	✓
O4: Assessing the climate impact and develop a visualization tool in a dashboard.	✓	✓	✓

Figure 1: Specific Objectives of ECONTRAIL

1. **<u>O-1 is to develop remote sensing algorithms for the detection of contrails and aviation-induced cloudiness.</u>**

Is O-1 realistically achievable? Remote sensing technology, in particular the Meteosat Third Generation (MTG) satellites (when available), can be used for the detection of clouds. The synchronization of aerial traffic with the latter allows to discriminate linear contrails and aviation-induced cloudiness from natural cloudiness [RD1].

Is O-1 measurable and verifiable? The output provided by the contrail tracking and aviation-induced cloudiness module will be verified by means of a Deep Neural Network (e.g., Convolutional Neural Network (CNN)) Image classifier. The proposed model will be first trained with a dataset containing images of actual contrails and other types of clouds (labelled by experts) so it can later be used to classify alerts from the contrail tracking module as true or false detections. **We expect to obtain**

contrail detection accuracies greater than 80%. State of the art quantitative indicators used in image recognition will be used.

2. **O-2 is to quantify the radiative forcing of ice clouds based on remote sensing and radiative transfer methods.**

Is O-2 realistically achievable? Measuring the radiative forcing of contrails can be achieved by retrieving the cloud physical properties and combine them with radiative transfer models to simulate the radiative fluxes and forcings. This approach has proved to be the most effective way to achieve quantification of the RF and ERF and has been applied in many past (e.g. ISCCP-F [RD2]), current (e.g. ESA Cloud Climate Change Initiative [RD2]), and future missions (e.g. the ESA Earth Cloud Aerosol Radiation Explorer[RD2] (EarthCARE) [RD2]).

Is O-2 measurable and verifiable? The fulfilment of the objective will be assessed through the production of a long record of ice cloud ERF over the extended European area. A minimum of 5 years of gridded data will be processed. The quality of the ERF will be assessed, in case studies, by intercomparison with other instruments, on low orbit satellites, such as the Cloud and Earth Radiant Energy System (CERES) and the upcoming EarthCARE that will provide very fine spatial resolution (600m) of the RF and ERF. We expect to obtain instantaneous ice cloud RF and ERF with accuracy better than 10 mW/m² (1-sigma). [1]

3. **O-3 is to use of deep learning architectures to generate AI models capable of predicting the radiative forcing of contrails based on data-archive numerical weather forecasts and historical traffic. We will make use of Convolutional Neural Networks (CNNs), together with transfer learning from already-existing models, as well as recurrent networks such as Long-Short Terms Memory (LSTM), and generative models such as Generative Adversarial Networks (GANs) and variational autoencoders (VAEs).**

Is O-3 realistically achievable? The feasibility of the objectives proposed for data-driven forecasting of contrails is supported by the previous experience of the partners (Jardines, Soler et. al., 2021 [RD2] and Jardines, Soler, and Vinuesa, 2024 [RD2]) in the identification of convective weather with satellite data with CNNs. The usage of transfer learning methodologies facilitates more efficient utilization of the resources and quicker training of the networks.

1 this accuracy refers to the instantaneous RF due to (and in presence of) the AIC. A typical value can be something like 100 W/m². The overall RF and ERF of the aviation has to account for the AIC occurrence (in time and space). Thus, a 0.1% of occurrence in time/space, would result in a RF and ERF is 100 mW/m².

Is O-3 measurable and verifiable? The predictions made with deep learning will be compared to existing methodologies to quantify and verify the improvement over the state-of-the-art. We will split our dataset into training, testing, and validation datasets, as usual in machine learning techniques. **<u>We expect to get accuracies and true positive rates of 80-90% in the prediction of radiative forcing derived from contrails and aviation-induced cloudiness.</u>** This is supported by previous joint work by KTH and UC3M for the prediction of thunderstorms by Jardines, Soler et. al., 2021, and Jardines, Soler, and Vinuesa, 2024 [RD2]. This accuracy will be key to reduce the uncertainties in the prediction of the climate impact of contrails and aviation-induced cloudiness (currently, looking at Figure 2, uncertainties are around 70-80% of the median value and we expect to bring them down to 10-20%).

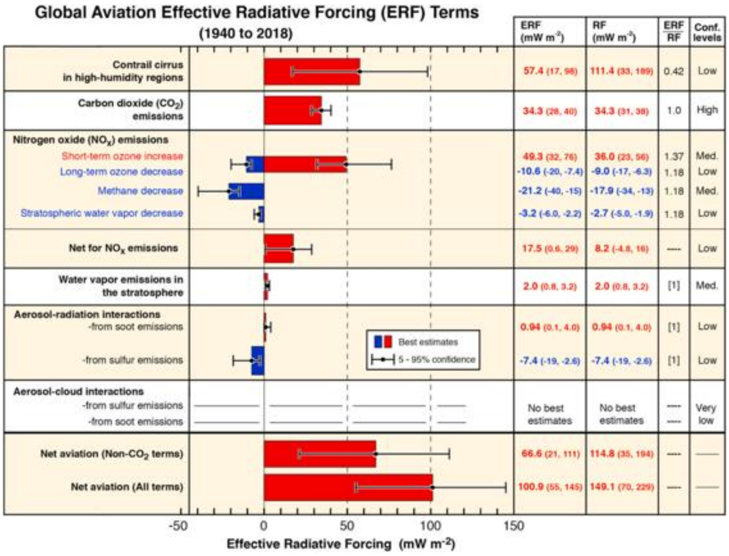


Figure 2: Radiative forcing from the global aviation for the years 1940-2018. Best estimates and their confidence intervals (showing the 5% and the 95% percentiles) are given. Red bars indicate warming and blue bars cooling effects. This figure is taken from Lee et al [3].

4. <u>O-4 is to assess the climate impact and develop a visualization tool in a dashboard.</u>

Is O-4 realistically achievable? Partners of E-CONTRAIL consortium have experience in satellite retrievals (detection of aerosols and ice particles) and the combined detection of hazard with flight trajectory, both actions conducting to contrails detection. E-CONTRAIL consortium is also expert in estimating radiative transfer of atmospheric cloud, and in the implementation of AI forecasts of atmospheric condition favourable to contrails initiation. This expertise shows the realistically achievement of build E-CONTRAIL dashboard visualization tool.

Is O-4 measurable and verifiable? The E-CONTRAIL dashboard tool is a way to visualize the detection and the forecasts of contrails. This can clearly be verifiable by human eyes using imagery in the visible. The measurement of the radiative forcing induced by contrails is a challenging task which is an outreach of E-CONTRAIL proposal. **The predicted of contrails and aviation-induced cloudiness using the remote sensing algorithm can be compared with the existing state-of-the-art methods, including the** algorithmic Climate Change Functions **(aCCFs; by Dietmuller et al., 2022** [RD2]**) and Contrail Cirrus Prediction Model (CoCiP)** [RD2]**.** The comparison will serve to benchmark the quality of E-CONTRAIL results.

3.1.2 Models and Assumptions

Models to be used and assumptions are listed in Table 3.

Models	Description
CLIMaCCF	The Python Library CLIMaCCF is a software package developed by UC3M and DLR. The main idea of CLIMaCCF is to provide an open-source, easy-to-use, and flexible software tool that efficiently calculates the spatial and temporal resolved climate impact of aviation emissions by using aCCFs. The individual aCCFs of water vapour,

	NOx-induced ozone and methane, and contrail-cirrus and merged non-CO2 aCCFs that combine the individual aCCFs can be calculated. https://github.com/dlr-pa/climaccf
Python Libs	The open-source Python frameworks for deep-learning Keras, TensorFlow, and PyTorch provide state-of-the-art models and functionalities in order to design, implement, and deploy artificial neural networks. Additionally, these frameworks are specially tailored to high-performance computing servers, which enables high parallelization of the resources.
libRadtran	LibRadtran is a widely used software package for radiative transfer simulations. Based on atmospheric parameters, libRadtran enables the computation of radiances and fluxes in the solar and thermal region of the spectrum. The library is available under the open-source GNU General Public License. See http://www.libradtran.org and related publications.
Nowcasting SAF & CPP	We will use the cloud retrieval components of (i) the NWCSAF v2021 package, provided by the Nowcasting Satellite Application Facility (SAF) group of EUMETSAT and (ii) the Cloud Physical Properties (CPP) package developed by KNMI. See the projects' webpages for general information and related scientific publications: https://www.nwcsaf.org and https://msgcpp.knmi.nl
Assumptions	
Assu #1	Geographical scope limited to EUROPE and half of the North Atlantic.
Assu #2	We will use the Meteosat Second Generation (MSG) data from years 2018 to 2022. We will use the Meteosat Third Generation (MTG) data from years 2023 (when available) to 2024

Table 3: E-CONTRAIL models and assumptions

3.2 Key R&I needs

We have identified 4 challenges and formulated the following Research Questions (RQ):

- RQ#1 (linked to O-1): Can we develop remote-sensing algorithms (including cloud detections and the synchronization with aerial traffic) to detect contrail and aviation-induced cloudiness?
- RQ#2 (linked to O-2): Can we integrate ice-cloud radiative models with a satellite retrieval scheme to measure contrail and aviation-induced cloudiness radiative forcing over the full diurnal cycle?
- RQ#3: Can we develop novel deep-learning models to predict the forcing of contrails with high accuracy and spatiotemporal resolution?
- RQ#4: Can we obtain critical information about contrails (detection, climate impact, forecasts) in a single visualization dashboard?

The following two hypotheses are to be verified:

- H1: The radiative forcing of contrails and aviation-induced cloudiness can be detected using remote-sensing instruments with accuracies greater than 90%. In addition, the RF can be further used to calculate other metrics including Global Warming Potential (GWP), and Average Temperature Response (ATR) for different emission scenarios and time-horizons. (To be verified by the achievement of O-1 and O-2).
- H2: The climate impact of contrails and aviation-induced cloudiness can be predicted using deep learning models with look-ahead times of 24h and with accuracies of 80-90%. The climate impact prediction can be provided using different metrics (RF, GWP, ATR) and time-horizons, in a user-

friendly manner, in such a way that stakeholders can later use it for a green-oriented decision-making. (To be verified by the achievement of O-3 and O.4).

3.3 Estimated performance contributions.

The main contribution of E-CONTRAIL in terms of Key Performance Areas (KPA) is on the environment, particularly on better understanding non-CO2 impacts.

The outcome related to the Environment specified in the call (as a high level ambition at European level) was: achievement of the objectives of a 55% reduction in greenhouse gas emissions by 2030 and net-zero greenhouse gas emissions by 2050, from a gate-to-gate perspective, by introducing new concepts enabling proper modelling of non-CO2 emissions and their impact on optimum green trajectories, taking into account the expected interoperability with new entrants (i.e., U-space flights) [RD2].

E-CONTRAIL's R&I goals will enable advanced AI-powered prediction of the radiative forcing of contrails and aviation-induced cloudiness, thereby enabling non-CO2 emission related climate mitigation actions by the aviation industry. Our unique contributions towards 55% reduction in climate impact of aviation by 2030 and climate neutrality by 2050 (a context indicator for reduction of 55% GHG emissions) will be:

1. Introducing AI driven models to predict, 24 hours in advance, the climate impact of contrails and aviation-induced cloudiness with 80-90% accuracy. We expect to achieve this accuracy based on the results obtained in our previous research activities related to predicting thunderstorms using AI. [RD2] [RD2].
2. Reducing the uncertainty in the climate impact (measured in terms of Radiative Forcing (RF) and/or Effective Radiative Forcing (ERF)) of contrails and aviation-induced cloudiness. We expect to contribute to this research on contrails and other non-CO2 effects by comparing E-CONTRAIL's AI-Driven approach with existing methods (e.g., the aCCFs) by better understanding the atmospheric conditions (related to ice-supersaturated regions) in which contrails form and persist.

By 2030, E-CONTRAIL will work towards the following, specific impact targets that will lead to the reduction of aviation-induced climate impact:

1. Identify contrail cirrus-forming in ice-supersaturated regions of the atmosphere and its radiative forcing.
2. Enable more efficient navigational avoidance & operations management and, therefore, the climate impact is reduced by 20-50%
3. Optimize airlines' operational costs and the climate impact. Trade-off solutions will be obtained, expecting an increase of the operational costs ranging from 0.5% to 3% to achieve climate mitigation reduction of 20-50%.
4. Developing indicators that enable the concept of green trajectories for the first time, and the quantified indicators lead evidence-based policy making (fees and incentives for the airlines to compensate the extra costs).

All in all, our Climate Hotspot Prediction Service can be used as a meteorological enabler for the airlines and flight dispatchers towards reducing in 20-50% the aviation-induced climate-impact [RD2] by 2030 via climate-optimized trajectories [RD2], at an increased operational cost ranging from 0.5% to 3%, (FlyATM4E D4.4) [RD2].

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3.4 Initial and exit maturity levels

This project can be classified as "Pre-TRL1 Scientific Research". E-CONTRAIL has the overall objective of the future integration of the project's outcome into the ATM processes, thus a strategic goal is to be able to show readiness for TRL2. At the end of the project, we ambition to showcase the maturity level of the E-CONTRAIL solution and, thus, readiness for TRL2 and future incorporation into the industrial research.

E**-CONTRAIL Solution** (which we have coined at this project stage "**E-CONTRAIL Climate Hotspot Prediction Service"**) will consist of an AI-driven model (already trained using historical data) capable of predicting the volumes of airspace with the conditions for large global warming impact due to contrails and aviation-induced cloudiness. A user-friendly visualization tool tailored for stakeholders' needs will be also implemented.

The foreseen activities are:

- Scientific studies on remote sensing (of contrails, aviation-induced cloudiness) and deep learning.
- Algorithms for remote sensing (of contrails, aviation-induced cloudiness) and implementation of deep learning architectures.
- Concept analysis, via visualization tool, oriented towards aviation stakeholders.

The expected outcomes are:

- We will state the basic principles about the studies and algorithms related to remote sensing and deep learning architectures.
- We will identify the potential application and the end users. They will be invited to participate in the conceptual design of the visualization tool.
- We aim at formulating the technological concept and/or application as a met service.

Project/ Proposed SESAR solution(s) ID	Proposed SESAR solution(s) title	Initial maturity level	Exit maturity level	Reused validation material from past R&I Initiatives
E-CONTRAIL	E-CONTRAIL Climate Hotspot Prediction Service	TRL0	TRL2	-

Table 4: maturity levels table

4 Experimental plan

This Chapter will be completed in the Intermediate version of the Experimental Plan. So far, we are still waiting for the MTG data. We have not been able to run any test, nor to start delimiting the specific scope of the different experiments.

4.1 Experimental plan approach

4.2 Stakeholders' expectations and involvement

Air traffic is expected to double by 2040 and developing eco–efficient aviation becomes increasingly challenging both for the aviation industry and the policy makers:

Aviation Industry/ Airline operators: Contrails which heighten the effect of global warming may account for more than half (57%) of the entire climate impact of aviation [RD2]. However, more research is needed to bring knowledge about contrails and chemical interactions in the atmosphere to a level at which the aviation industry can be more confident about the route forward. The uncertainty distributions (see Figure 2) show that non-CO_2 forcing contributes about 8 times more than the CO_2 to the overall uncertainty in the aviation net forcing (EASA, 2018) [RD2].**With our accurate prediction of persistent contrails and radiative forcing, we will enable the aviation industry to carry out operational changes and prompt mitigatory actions (such as navigation avoidance and others).**

Policy makers: Decarbonisation of aviation sector will continue (e.g., alternative fuels, electrical aircraft), however, requires high investments and results in stranded assets (aircraft, engines, etc.). Policy makers are increasingly looking for modernization of the Air Traffic Management (ATM) not only to consider both CO_2 and non-CO_2 effects in the long term, but also to enable short-term actions to mitigate aviation-induced climate change. The quantification of the cost linked to flying green and the development of indicators is mandatory to pave the road towards establishing fees and incentives. **Therefore, the results of E-CONTRAIL are highly relevant, and will result in actionable policy insights, to fast track the modernization of ATM.**

Stakeholder	Involvement	Why it matters to the stakeholder

Table 5: stakeholders' expectations and involvement

4.3 Validation objectives

4.4 Validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment

Table 6: validation assumptions overview

4.5 Validation exercises list

[EXE]

Identifier	*TVAL.xy.z-[ProjectAcronym]-[SolutionID]-TRLx*
Title	*Reduction of wake turbulence separation through new wake vortex detection equipment*
Description	*Live trial in airport A on reduction of wake turbulence separation through new wake vortex detection equipment.* *The objective is to assess the impact on arrival capacity in an Airport with complex layout in nominal conditions.* *A human performance analysis will be conducted as well as part of the activities.*
KPA/TA addressed	*<Capacity>*
Addressed expected performance contribution(s)	*Improvement in arrival airport capacity.*
Maturity level	*<TRL4>*
Use cases	*<UC1><UC2> from the SPR-INTEROP/OSED*
Validation technique	*<Expert Group>*
Validation platform	*N/A*
Validation location	*Paris CDG*
Start date	*01/04/2017*
End date	*28/04/2017*
Validation coordinator	*DSNA*
Status	*<in progress>*
Dependencies	*Other dependent exercises*

[EXE Trace]

Linked Element Type	*Identifier*
<SESAR Solution>	*SESAR solution identifier (if applicable)*
<Project>	*Project identifier*
<Sub-Operating Environment>	*Sub-operating environment 1 identifier*
<Validation Objective>	*Validation objective identifier (ERP)*

Table 7: validation exercise layout

4.6 Validation exercises planning

4.7 Deviations with respect to the SESAR 3 JU project handbook

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5 Validation exercises

This Chapter will be completed in the Intermediate version of the Experimental Plan. So far, we are still waiting for the MTG data. We have not been able to run any test, nor to start delimiting the specific scope of the different experiments.

5.1 Validation exercise #01 plan

5.1.1 Validation exercise description and scope

5.1.2 Stakeholder's expectations and benefit mechanisms addressed by the exercise

Stakeholder	Involvement	Why it matters to the stakeholder

Table 8: stakeholders' expectations

5.1.3 Validation objectives

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
Validation objective #1 (same as in section 4.3)	*Success criterion #1 (same as in section 4.3)*	*Fully covered*	*Exercise objective #1 (same description as validation objective #1 from section 4.3)*	*Exercise criterion #1 (same description as success criterion #1 from section 4.3)*
Validation objective #2 (same as in section 4.3)	*Success criterion #2 (same as in section 4.3)*	*Partially covered + free text to explain why*	*Exercise objective #2 (refined description from section 4.3)*	*Exercise criterion #1 (refined description from section 4.3)*

Table 9: validation objectives addressed in validation exercise #01

[...]

5.1.4 Validation scenarios

5.1.4.1 Reference scenario(s)

5.1.4.2 Solution scenario(s)

5.1.5 Exercise validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment

Table 10: validation exercise #01 assumptions

5.1.6 Limitations and impact on the level of significance

5.1.7 Validation exercise platform / tool and validation technique

5.1.7.1 Validation exercise platform / tool characteristics

5.1.7.2 Validation exercise technique

5.1.8 Data collection and analysis

5.1.8.1 Data and data collection methods

5.1.8.2 Analysis methods

5.1.9 Exercise planning and management

5.1.9.1 Activities

5.1.9.2 Roles and responsibilities in the exercise

5.1.9.3 Time planning

Activity	Week					
	1	2	3	4	…	n
Activity 1						
Activity 2						
…						

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Activity n						

Table 11: detailed exercise #01 time planning

[...]

5.1.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2-medium, 3-high)	Likelihood (1-low, 2-medium, 3-high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Risk 1				
Risk 2				
...				
Risk n				

Table 12: exercise #01 risks and mitigation actions

5.2 Validation exercise #02 plan

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6 References

6.1 Applicable documents

This ERP complies with the requirements set out in the following documents:

Project and programme management

[AD1] SESAR 2020 Experimental Approach guidance ER, 11/12/2020, edition 1.

[AD2] 101114795 - E-CONTRAIL Grant Agreement, [02/06/2023]

[AD3] SESAR 3 JU Project Handbook – Programme Execution Framework, 11/04/2022, edition 1.

6.2 Reference documents

[RD1] Kulik, L. (2019). Satellite-based detection of contrails using deep learning (Doctoral dissertation, Massachusetts Institute of Technology).

[RD2] Young, Alisa H., et al. "The international satellite cloud climatology project H-Series climate data record product." Earth System Science Data 10.1 (2018): 583-593.

[RD3] Poulsen, Caroline A., et al. "Cloud_cci ATSR-2 and AATSR data set version 3: a 17-year climatology of global cloud and radiation properties." Earth System Science Data 12.3 (2020): 2121-2135.

[RD4] Illingworth, Anthony J., et al. "The EarthCARE satellite: The next step forward in global measurements of clouds, aerosols, precipitation, and radiation." Bulletin of the American Meteorological Society 96.8 (2015): 1311-1332.

[RD5] Jardines, A., et al. "Convection Indicator for Pre-Tactical Air Traffic Flow Management using Neural Network. Machine Learning with Applications". 2021-06 | DOI:

[RD6] Jardines, A., et al. "Thunderstorm prediction during pre-tactical air-traffic-flow management using convolutional neural networks. Expert Systems with Applications." Jardines, A., 2024, Vol 241, 10.1016/j.mlwa.2021.100053

[RD7] Dietmüller, S., et al. (2022): A python library for computing individual and merged non-CO2 algorithmic climate change functions: CLIMaCCF V1.0, Geoscientific Model Development (GMD). Under Review.

[RD8] Schumann, U. (2012). A contrail cirrus prediction model. Geoscientific Model Development, 5(3), 543-580.

[RD9] Fundamental science and outreach for aviation green deal (HORIZON-SESAR-2022-DES-ER-01-WA1-6)

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[RD10] Jardines, A., Soler, M., et al. Convection Indicator for Pre-Tactical Air Traffic Flow Management using Neural Network. Machine Learning with Applications. 2021-06 | DOI: 10.1016/j.mlwa.2021.100053

[RD11] Jardines, A., Eivazi, H., Zea, E., Otero, E., Soler, M., et al. (2023) Thunderstorm prediction during pre-tactical air-traffic-flow management using convolutional neural networks Expert Systems with Applications.

[RD12] EASA report on aviation’s non-CO2 climate impacts highlights need for policy decisions and more research – GreenAir News

[RD13] Abolfazl Simorgh, Manuel Soler, et al. Robust 4D Climate Optimal Flight Planning in Structured Airspace using Parallelized Simulation on GPUs. Geoscientific Model Development (GMD). Under Review. Egusphere-2022-1010

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