Final Report of the IMET project WP-E.02.40

Document information	
Project Title	IMET: Investigating the optimal approach for future trajectory prediction systems to use METeorological uncertainty information
Project Number	E.02.40
Project Manager	Netherlands Aerospace Center NLR
Deliverable Name	Final Report of the IMET project
Deliverable ID	D0.3
Edition	01.00.00
Template Version	03.00.00
Task contributors	
Met Office; Météo France; NLR	

Abstract

This final report of the IMET project contains a summary of the IMET results. In addition, it lists all project deliverables, dissemination activities, eligible costs, deviations, bills, and lessons learned.

Authoring & Approval

Prepared by - *Authors of the document.*		
Name & Company	Position & Title	Date
[redacted] NLR	[redacted]	14/10/2015

Reviewed by - *Reviewers internal to the project.*		
Name & Company	Position & Title	Date
[redacted] Met Office	[redacted]	19/10/2015
[redacted] Météo France		19/10/2015

Approved for submission to the SJU by - *Representatives of the company involved in the project.*		
Name & Company	Position & Title	Date
[redacted] NLR	[redacted]	19/10/2015

Document History

Edition	Date	Status	Author	Justification
00.00.01	14/10/2015	Draft	[redacted] NLR	First draft
00.01.00	19/10/2015	Draft	[redacted] Met Office	Review, additions
00.01.01	19/10/2015	Final	[redacted] NLR	Proposed Final version
00.09.00	19/10/2015	Final	[redacted] Météo France	Review, corrections, additions
01.00.00	19/10/2015	Final	[redacted] NLR	Final version

Intellectual Property Rights (foreground)

This deliverable consists of SJU foreground.

Table of Contents

List of tables

List of figures

No table of figures entries found.

Summary

Introduction to the project and problem statement

The IMET project aimed to develop probabilistic trajectory predictor (PTP), or relevant requirements if a promising PTP algorithm could not be found, on research trajectory predictor systems, and demonstrate benefits to key Air Transport areas of the use of the uncertainty information present in specific MET forecast data to TP based decision support. More specifically, IMET aimed to investigate, and preferably provide recommendations, how to use the uncertainty information from Ensemble Weather Forecast (EWF) to optimize TP output with respect to the EWF, and hence the future weather, as it is assumed the EWF covers all possible futures.

Explanation of approach and methodology

The approach IMET used was essentially as follows. First, a PTP would be constructed by applying Deterministic Trajectory Predictor (DTP) to the members of an EWF, producing for each EWF member a trajectory which can be flown safely. The resulting trajectory ensemble would be used as input to a Decision Support Tool (DST), in order to similarly produce an ensemble of DST outputs. These outputs would then be evaluated according to user preferences, leading to the choice of one DST output, and hence a trajectory related to that DST output.

More specifically, the idea was to select flight parameters, for instance flight duration, or total fuel consumption, and determine through PTP the frequency distribution of the EWF members over (suitable intervals of) these parameters. The result would allow the end user, or the DST, to select one trajectory for the flight, according to user preferences such as minimal flight duration, or minimal fuel consumption and their predictability. Several use cases were considered that illustrate to which extent the additional computational effort can be beneficial to decision making.

The EWF would be investigated concerning its potential to cover all future weather scenarios.

Highlights and key results

IMET started with identifying ways of using MET forecast uncertainty information in TP algorithms, but decided to focus mainly on one approach, EWF, as it is well suited for use in an environment of deterministic applications. Indeed, EWF comprises multiple deterministic weather forecast, each determined using slightly different initial conditions, physics, and model parameters. Each member of the EWF describes a possible future of the weather. All members are assumed to have the same probability of predicting the weather correctly. Generally, none of them predicts the weather correctly. But the weather ensemble is constructed in such a way that it should cover all possible futures. As already described above, PTP was defined by applying existing DTP algorithms to each member of the EWF individually, producing a trajectory ensemble, i.e. an ensemble of trajectories. A similar approach using PTP accepting sampled probabilistic weather information (comprising over 10,000 samples) was considered too computationally intensive (EWF comprises 10 to 50 samples).

The statistical characteristics of the trajectory ensemble, specifically the mean value and spread of selected flight parameters, could be useful for Decision Support. Consider, for instance, an already planned flight, and use it, next to EWF, as input to PTP. The spread of the predicted total amounts of fuel calculated by PTP provides information to which extent the total amount of fuel actually carried by the aircraft can safely be minimised with respect to the EWF, and hence with respect to all possible futures of the weather. If the route is not fixed, applying multiple user preferences is possible, for instance, choosing the trajectory which provides, from a user perspective, the best balance between fuel efficiency and sensitivity to the EWF. If the weather is predictable, the members of the EWF are almost identical, and the focus can be on fuel efficiency. If the weather is less predictable, priority should, for safety reasons, be given to minimising the sensitivity to the EWF.

The approach is promising as well for its allowing DTP, and related DST to immediately be used in experiments. This explains why MET parameters which are already included in existing TP systems were considered: temperature, wind, and pressure. It should be noted, however, that many other MET parameters could potentially be taken into account as well, e.g. convection, visibility, cloud cover, precipitation, cross wind. Each of these might be useful, or even required, in future TP systems. The

MET information used in IMET were operational ensemble Numerical Weather Prediction (NWP) forecasts, available approximately three hours after start of a NWP model run, and valid for the time frame of one to two days ahead, which reflects the time frame for determining Reference Business Trajectories (RBTs). Thus, the IMET approach turned out to be immediately applicable to flight planning. However, it is expected to be applicable as well to the preparation for the execution phase (e.g. Network flow management).The project kept close contact with WP11.1, and WP11.2.

Using a simplified version of NLR's TP system, IMET studied the variation in flight duration with MET uncertainties along a fixed route from John F. Kennedy International Airport, New York (KJFK) to Aéroport Paris–Charles de Gaulle (LFPG). For the fixed route considered, the variation in flight time due to MET uncertainties was generally small (at most 1%) compared to the total flight time, although it can be significant in specific MET circumstances. IMET proposed several ways of visualising MET uncertainties and quantifying their impact on TP. These approaches can be used to integrate MET uncertainties in TPs by developing new cost indices to account for MET uncertainties in the selection of an optimal route.

IMET demonstrated using ensemble scores that the three state-of-the-art Ensemble Prediction Systems (EPSs) used within the IMET project (ECMWF, MOGREPS and PEARP) are capable of capturing specific weather events observed from a large data sample of Aircraft Meteorological Data Relay (AMDAR) measurements 36 hours in advance of take-off. We use one of these EPSs to illustrate the methodology and show that if some end users require low uncertainty in the Required Time of Arrival (RTA), e.g. at large congested airports, the total fuel cost may necessarily increase, whereas other end users may prefer minimisation of cost at the expense of higher uncertainty of flight time.

IMET has also shown that the performance can be improved by combining the different Ensemble Prediction Systems (EPS) to form a so-called SUPER ensemble. Having shown that existing EPSs are capable of capturing the reality within the time frame specified by the RBT, IMET demonstrated that ensemble-averaging of weather forecasts is inappropriate for TP as time-space correlation is lost.

During the project, the IMET team became aware of the 2010 work of Steiner et al (STEINER, et al., 2010) on the same topic, and has referred to their work since. The team considers the Steiner results a confirmation of IMET's.

Future steps based on the outcomes of the project

Based on the results of the project, some future steps could be:

1. Validate the fixed route fuel minimisation approach, via trials at FOC, for different types of weather.
2. Validate the variable route weather sensitivity minimisation approach via trials at FOC, for different types of weather scenario, e.g. convection, low visibility, cross wind, rain, hail, snow, icing.
3. Extend the approach to other trajectory parameters, introduce appropriate metrics (incorporating cost indices) and evaluate the usefulness of the approach to the end user.
4. Apply the approach to different TP dependent DSTs, e.g. Network Flow Management, and investigate the usefulness to the end user.
5. Investigate the applicability of the approach for the time interval close to the execution phase, or even, for some applications (e.g. trajectory update in the FMS, or Medium Term Conflict Detection (MTCD)) in the execution phase.

Conclusion

The proven concept of EWF can be used as input to existing deterministic TP based Decision Support Tools to derive an ensemble of impacts. EWF can also be processed to derive probabilistic MET information as input to probabilistic TP. The latter approach, however, requires DST based on probabilistic TP, which is currently not widely available, or extensive sampling of the probabilistic MET information, which is computationally intractable.

The EWF based approach can be applied by FOC for minimising the amount of fuel necessary to perform the flight. The approach can be extended in such a way that the end user may select a route based on the (probability density function of the) distribution of this, and other flight parameters, with respect to the weather ensemble. Specific use cases, based on simulations, indicate the validity of the concepts. It is recommended to perform additional validation exercises.

IMET has also shown that state-of-the-art EWF is fit for purpose regarding TP application in the time frame up to 36 hours ahead. However, the run time of the NWP being several hours, limits the scope of the approach to beyond approximately three hours after observation time.

1 Introduction

1.1 Purpose of the document

The purpose of this document is to:

- Summarise the technical results and conclusions of the project (Publishable Summary);
- Provide a complete overview of all deliverables;
- Provide a complete overview of all dissemination activities (past and in progress). Where appropriate, provide feedback from presentations. Describe exploitation plans.
- Provide a complete overview of the billing status, eligible costs, planned and actual effort (incl. an explanation of the discrepancies).
- Analyse the lessons learnt at project level.

1.2 Intended readership

This document's may be of interest to anyone concerned with the potential impact of uncertainty inherently present in meteorological data on Trajectory Based Operation, or even Performance Based Operation.

Particularly, users of Decision Support Tools depending on TP, e.g. airspace users, or ATM, may be interested. But also developers of TP and TP clients, in particular members of SESAR or SESAR 2020 projects linked directly or indirectly to TP may find this document relevant for their (future) work.

1.3 Inputs from other projects

This document does not depend on input from other (SESAR) projects.

1.4 Glossary of terms

Term	Definition
Deterministic forecast	A single forecast of event of specific magnitude, time and location, with no account of its likelihood to happen.
Ensemble forecast	A set of deterministic forecasts using different initial conditions and different physical parameterisations, within their range of uncertainty. An ensemble forecast does not take into account the error probability distribution of the initial condition.
Ensemble TP	An ensemble of trajectories produced by applying a single deterministic trajectory predictor to the individual members of a MET ensemble forecast.
Probabilistic TP	A TP producing trajectories supplied with a probabilistic distribution function using outputs from a MET ensemble forecast

1.5 Acronyms and Terminology

Term	Description

Term	Description
AMDAR	Aircraft Meteorological Data Relay (filtered by Met Office for Europe)
AROME	French Limited Area MET model (France non-hydrostatic, 2 km grid 90 levels 3-36 hr forecast)
ARPEGE	French Global Model (world hydrostatic 10 km grid, 90 levels 3-104 hrs forecast)
DST	Decision Support Tool
ECMWF	European Centre for Medium-Range Weather Forecasts
FOC	Flight Operations Centre
IMET	Investigation of the Optimal Approach for Future Trajectory Prediction Systems to Use METeorological Uncertainty Information
MET	Meteorological
MOGREPS	Met Office (UK) Global and Regional Ensemble Prediction System
MTCD	Medium Term Conflict Detection
NLR	Nederlands Lucht- en Ruimtevaartcentrum (Netherlands Aerospace Center)
NWP	Numerical Weather Prediction
PEARP	Ensemble Forecast on ARPEGE dynamical data.
PDF	Probability Density Function
PTP	Probabilistic TP
ROC	Receiver Operating Characteristic
RBT	Reference Business Trajectory
RTA	Required Time of Arrival
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research
TBO	Trajectory Based Operations
TP	Trajectory Prediction / Trajectory Predictor
WOC	Wing Operations Centre

2 Technical Project Deliverables

Number	Title	Short Description	Approval status
1.1	Report on selected MET-AT topics	Key Air Transport areas are determined, for which the IMET project results can be beneficial.	Approved
2.1	Report on sensitivity of deterministic TP from the MET input uncertainty	Assessment of the sensitivity of deterministic TP to the uncertainty in the MET information, and description of an initial model of the error propagation from MET uncertainty to the uncertainty in the TP output, e.g. ETA or duration of a flight.	Approved
2.2	Report with requirements on development of probabilistic trajectory prediction	Introduction of the IMET approach, exposition on capturing all weather scenarios within the time frame specified by the RBT, and evaluation for selected transatlantic flights for nominal weather scenarios.	Approved
2.3	Report on optimisation of probabilistic TP and MET input	Verification of the IMET approach, introduced in deliverable 2.2, for selected traffic over (mainly) France, in convective weather situations.	Submitted

Table 1 List of Project Deliverables

3 Dissemination Activities

3.1 Presentations/publications at SESAR Innovation Days

3.1.1 KTH Royal Institute of Technology, Stockholm, November 2013

In 2013, only a poster was presented (CHEUNG, et al., 2013). The poster describes briefly the objectives of the project and the intended approach. Positive responses from, and interesting conversations with many people, amongst whom: Soufiane Bouarfa (TU Delft), Jose Antonio Cobano (University of Seville), Louisa Polley (NATS), Xavier Prats and Dr Menendez (TU Catalonia, UPC), Chiara Scaini (Barcelona Supercomputing Center), Viktoria Tsitsoni (EUROCONTROL).

3.1.2 Universidad Politécnica de Madrid, November 2014

In 2014, a paper was submitted, and accepted (CHEUNG, et al., 2014). Responses to the related presentation were similar to those to the poster at SID 2013.

- Professor Hauf (Leibniz Universität Hannover) brought a PhD student, and an MSc student to SID 2014, and each of them gave a presentation in the meteorology section. Their studies focused on the estimation of flight time uncertainty using nowcast and RADAR data.
- Dr Menendez (TU Catalonia, UPC) had shown great interest in our 2013 poster back in SID 2013 and was very interested in our talk this year. He asked a couple more questions on the methodology after the session.
- Dr Netjasov (University of Belgrade) also mentioned he found the talk very interesting.

3.1.3 Università di Bologna, December 2015

The IMET team is awaiting acceptance of our paper (CHEUNG, et al., 2015). The paper summarizes the achievements up to deliverable D2.2, in which the IMET approach for selected transatlantic flights under nominal weather is discussed.

3.2 Presentations/publications at other conferences/journals

None.

3.3 Web presence

The IMET web site can be accessed here using any modern web browser, including Google Chrome, Mozilla Firefox, Microsoft Internet Explorer, OSASA Opera, and Apple Safari.

3.4 Demonstrations

Apart from the presentations at SESAR Innovation Days, the IMET project has not performed any demonstrations to date.

3.5 Exploitation plans

NLR

NLR, and the Air Transport (AT) community at large, will be increasingly aware of the benefits MET can provide to AT. For the IMET project in particular, the fact that the meteorological community has a grip on the uncertainty in the MET data, is of great interest to MET dependent DST, Trajectory Prediction being just one example. SESAR WP11.1 has implemented the IMET approach for use in VAL EXE 791. The IMET project illustrates synergetic cooperation between MET and AT partners. In order to make a successful next step, one could check the list of “Future steps based on the outcomes of the project” in this document’s Summary. An initiative, which started as part of IMET, and was completed outside of the project is the promising PhD work of Mademoiselle Cécile Ichard (ICHARD, 2015). NLR has approached airline operators Air France (AF) / KLM and Transavia on IMET approach. AF/KLM is interested in further discussion at OCC Schiphol, while Transavia prefers to wait for industrial implementation in Lufthansa Systems’ Lido/FlightPlanning dispatch support tool.

Météo France

We consider the IMET team and the WP11.2 team as one, as all IMET partners are also cooperating in the WP11.2 consortium. The IMET approach has been presented to, and adopted and tested by SESAR WP11.1. In this sense, IMET is already successful. Moreover, Sabre Airline Solutions is actively supporting the IMET approach at different authority levels in Europe.

Met Office

Working with the air traffic management industry has provided valuable insight into the methods and requirements for managing airspace safely, effectively and efficiently. Development of a more accurate and more adaptable path finding algorithms for flight routing will enable improved accuracy and the flexibility to account for unavailable airspace in a range of applications in the future. Finally, the opportunity to expose the potential of ensemble numerical weather prediction to the ATM community has opened up valuable debate about handling uncertainty in decision-making.

4 Total Eligible Costs

Date	Deliverables on Bill	Contribution for Effort	Contribution for Other Costs (specify)	Status
INVOICE 1 no. 133106 (DATED: 20-DEC-2013)	D0.1, D0.2.1, D0.2.2, D1.1, D0.4.1, M0.1	Total EUR 81,279.85 (excl. VAT); of which Co-financing EUR 57,132.72 (excl. VAT)	Of which Total EUR 4.234,71 (excl. VAT) for travel	PAID
INVOICE 2 no. 134935 (DATED: 26-NOV-2014)	D2.1, D0.2.3, D0.2.4, D0.2.5,	Total EUR 145,780.60 (excl. VAT); of which Co-financing EUR 103,646.00 (excl. VAT)	Of which Total EUR 3,032,64 (excl. VAT) for travel	PAID
INVOICE 3 no. 136224 (DATED: 14-JUL-2015)	D0.4.2, D0.2.6, D2.2, D0.2.7, D0.2.8,	Total EUR 178,936.08 (excl. VAT); of which Co-financing EUR 120,003.69 (excl. VAT)	Of which Total EUR 1,710,47 (excl. VAT) for travel	PAID
INVOICE 4 *STILL TO BE ISSUED*	D2.3, D0.3, M0.3, D0.4.3	*Approximation Total* EUR 207,651.25 (excl. VAT*); Co-financing* EUR 166,121.00 (excl. VAT)	*Of which Approximatly: EUR 3.000,000* (excl. VAT) for travel	*Billed, not paid as yet*
GRAND TOTAL		***Total* EUR 613.647.79** of which **Approximation Co-financing EUR 446,903.41** (excl. VAT)	EUR 11.977,82 (excl. VAT) for travel	

Table 2 Overview of Billing

Company	Planned man-days	Actual man-	Total Cost	Total Contribution	Reason for Deviation

		days[1]			
Coordinator: STICHTING NATIONAAL LUCHT EN RUIMTEVAARTLABORATORIUM (NLR)	*23*	*11.7 + 12 = 23.7*	*EUR 201,251.90 + Approx EUR 207.651,25 (invoice 4)*	*EUR 150.938,25 + EUR 166,121.00 (invoice 4)*	*NO MAJOR DEVIATION*
Member: Met Office	*15*	*11,1*	*EUR 94,859.94*	*EUR 47,429.97*	*NO MAJOR DEVIATION*
Member: Météo France	*15*	*11.7*	*EUR 109,884,70*	*EUR 82,413.52*	*NO MAJOR DEVIATION*
GRAND TOTAL		46.5	*EUR 405,996.54 + Approx EUR 207.651,25 = Total EUR **613,647.79***	*EUR 280,782.41 + Approximation EUR 166,121.00 (INVOICE 4) = **Co-financing EUR 446,903.41***	

Table 3 Overview of Effort and Costs per project participant

[1] The values presented are estimates based on data, available October 19th, 2015.

5 Project Lessons Learnt

What worked well?
The IMET Approach is a very promising one, very extensible.
High level of interest from end users (airlines).
Work in MET-ATM can be readily split between MET and AT, but benefits from cooperation.
Excellent IMET team spirit, excellent mutual support, e.g. in case of shortage of personnel.
Excellent communication with and guidance by Project Officer. Customer patience and flexibility proved beneficial to keep work stress at an acceptable level.
What should be improved?
Remove technical limitations on the trajectories considered, e.g. allow flight level changes, and add climb phase and descent phase.
Better research on what has been accomplished previously, viz. (STEINER, et al., 2010).
More research and results on the probabilistic approach.
More use cases and results on the impact of the IMET approach on Decision Support.
Better adherence to the project planning, particularly the milestones.

Table 4 Project Lessons Learnt

6 References

CHEUNG, J. et al., 2013. *IMET - Investigating optimal approach for future trajectory prediction (TP) systems to use METeorological uncertainty information.* Stockholm: s.n.

CHEUNG, J. et al., 2014. *Sensitivity of flight durations to uncertainties in numerical weather predictions.* Madrid, s.n.

CHEUNG, J. et al., 2015. *Recommendations on trajectory selection in flight planning based on weather uncertainty.* Bologna, s.n.

ICHARD, C., 2015. *Random media and processes estimation using non-linear filtering techniques : application to ensemble weather forecast and aircraft trajectories.* Toulouse: l'Université Toulouse 3 Paul Sabatier (UT3 Paul Sabatier).

STEINER, M. et al., 2010. Translation of ensemble weather forecasts into probabilistic air traffic capacity impact. *Air Traffic Control Quarterly, 18(3),* p. 229 – 254.