Initial Implementation of Reference Trajectories for Performance Review

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***Abstract*—A reproducible and fair reporting of (European) Air Navigation Service Providers' performance needs to rely on open, curated and methodologically sound sets of aviation data. The work by EUROCONTROL Performance Review Unit (PRU) to combine Automatic Dependent Surveillance – Broadcast (ADS–B), Correlated Position Report (CPR), Airport and Network Manager (NM) data will allow for the definition of common open datasets, in particular flight trajectories, for research and post-ops analysis.**

I. Introduction

Aviation and air traffic management related information is no longer a "behind closed doors" phenomenon. In fact this data becomes increasingly ubiquitous through crowd-sourcing and community efforts. Throughout the recent years, the adoption of dependent surveillance technology in aviation and inexpensive receiver sets combined with ubiquitous and cheap broadband internet connectivity resulted in a variety of community sharing networks by aviation enthusiasts. These networks are making flight position reports massively available to industry, academia, the media and the general public. This development has lead to a number of non-commercial and commercial flight tracking applications (e.g. Flight Aware, Flight Radar 24).

At the same time, other flight information (airline, schedules, airspaces & routes, aircraft types, etc.) is similarly becoming more and more available. For example airlines offer respective web services, schedules (i.e. arrival and departure times) are obtainable from webpages via web scraping, or this information is readily collected and prepared by aviation enthusiasts.

While the information becomes readily available, there is a lack of practical implementations of an open data approach. In particular, this data can be fused with data processed by air traffic management in combination with surveillance data collected by air navigation service providers and movements reported by airports to produce a data set for post-ops analysis and research.

This paper addresses the conceptual building blocks of such an open data approach to establish a reference trajectory for operational performance review purposes. Identifying the need for change, the architecture of the proposed Reference Trajectory Dataset infrastructure is developed.

II. ANSP performance analisys

The evaluation of Air Navigation Service[1] (ANS) performance in Europe is not a fundamentally new topic. EUROCONTROL initiated an independent performance review system[2], governed by the Performance Review Commission[3] (PRC), in 1997 [1]. The PRC is supported by the Performance Review Unit[4] (PRU). The PRU is responsible for the day-to-day activities of the PRC work programme, including the regular preparation of performance data products. Next to the yearly performance review reports, the PRU publishes performance related data on a monthly basis (c.f. https://ansperformance.eu). Since the very beginning, the PRC's performance review mandate has been to impartially draw the attention to (and try to explain) trends of excellence that showcase and drive upwards safety levels, operational and financial efficiency.

In 2004 the European Commission (EC) developed the legal framework of the Single European Sky[5] (SES) initiative and adopted four Regulations (i.e. SES I package) covering the provision of air navigation services (ANS), the organisation and use of airspace and the interoperability of the European Air Traffic Management Network (EATMN). Later in 2009,

[1]**A**ir **N**avigation **S**ervice (ANS) refers to the totality of services provided in order to ensure the safety, regularity and efficiency of air navigation and the appropriate functioning of the air navigation system.

[2]Performance review is carried out for EUROCONTROL's 41 Member States.

[3]The **P**erformance **R**eview **C**ommission (PRC) was established in 1998 by EUROCONTROL's Permanent Commission. It provides objective information and independent advice to EUROCONTROL's governing bodies on European **A**ir **T**raffic **M**anagement (ATM) performance, based on extensive research, data analysis and consultation with stakeholders. Its purpose is "to ensure the effective management of the European air traffic management System through a strong, transparent and independent performance review," as stated in Article 1 of the PRC Terms of Reference and Rules of Procedure.

[4]The **P**erformance **R**eview **U**nit (PRU) supports the PRC by running EUROCONTROL's Performance Review System and executing the associated PRC work programme.

[5]**S**ingle **E**uropean **S**ky (SES) applies to EU's 28 Member States plus Norway and Switzerland. See [2] for further details.

these were revised and extended to establish a mandatory regulatory performance scheme for SES Member States (the SES II package) [3, 4]. The SES performance scheme – currently in its second reference period (2015-2019) – applies performance metrics developed by the PRC and EUROCONTROL performance review system. Similar to the PRC, the Performance Review Body (PRB) supports the European Commission in the execution of the performance scheme by providing policy advice and recommendations.

Both performance review systems are intended to drive economic, operational and societal – in particular safety and environment – improvements in the European aviation system.

Next to the European efforts, ICAO promotes a performance based approach on a global level. Throughout the recent years, regional efforts have been integrated into a wider framework under the Global Air Navigation Plan (GANP) [5]. At the time being, there are 16 so-called proposed ICAO GANP key performance indicators. These indicators are based on the European experience of PRC and build on a core set of indicators regularly utilized for the US/Europe operational ANS performance benchmarking.

In summary, performance review by PRC and PRB[6]/EC aims to:

- assess the status of the system against what was planned (PRB/EC);
- highlight trends and some relevant explanatory variables (PRC and PRB/EC);
- allow for comparative analysis and showcase best in class performers others can learn from (PRC) and financially reward above threshold results (PRB/EC).

A. Reference trajectory performance data

Quality of performance related data is one of the key factors that impact the quality of overall performance review and analysis performed at EUROCONTROL PRU. One of the guiding principles of PRU's approach is transparency in the data processes and performance indicator calculation. The ultimate goal is to enable stakeholders to reproduce the numerical performance results.

The PRU is working hard to make available *curated* flight data that will allow, for example, development of a *reference trajectory data set* which will in turn:

- foster an open and collaborative approach to performance review for its Member States and stakeholders,
- facilitate the production of studies in collaboration with International Partners (e.g. Brasil, Singapore, China, Japan)
- define a foundation for comparative studies between different world regions (e.g. EU-USA).

[6]The **P**erformance **R**eview **B**ody (PRB) is an advisory body to the European Commission. It assists the Commission and **N**ational **S**upervisory **A**uthorities (NSA) in the implementation of the performance scheme for air navigation services.

B. The need for change

Trajectories are the building block for a variety of operational performance metrics reported by the PRU. They are used to find airspace (sectors, FIR[7]) intersections in order to count the number of flight at various time intervals, to calculate CO_2 emissions and to assess horizontal/vertical flight efficiency or traffic complexity.

The need for transparency, openness to scrutiny and reproducibility of performance indicators calls for the publication of, not only, methodological approaches [6, 7, 8, 9, 10] and final results [11, 12, 13] but also of the relevant data used as input for the calculation of performance metrics.

Based on the aforementioned principles, the goal is therefore to establish an infrastructure to support the performance related data processing by external stakeholders. This includes the access and availability of the underlying data (e.g. reference trajectory, relevant aeronautical information), respective performance algorithms, and results.

Current PRU metrics use trajectories as assembled by the Network Manager[8] (NM) both at the pre-tactical, FTFM[9] or Model 1, and tactical stage, CTFM[10] or Model 3 and CPF[11] profile [see [15] 14.3 and 14.4 for NM's Tactical Flight Models (TFM) and handling of CPRs.] These profiles are devised and calculated by NM to fulfill its ATFCM mandate: slot (and hence delay) allocation and sector load monitoring. Hence the way a flight, an airspace, an aerodrome or a route are modeled is driven by the above goals *and* the need to keep the NM systems design robust/performant (memory consumption, CPU load) and maintainable (logically simple without bloated requirements yet useful.) For example SID[12] and STAR[13] concur very simply in the calculation of NM trajectories, i.e. the impacted portion of trajectory is calculated as a straight segment from point fix to the runway rather than a curved line. Similarly the left/center/right (when is the case) runways and eventually the relevant marked positions

[7]A **F**light **I**nformation **R**egion (FIR) is a specified region of airspace in which a flight information service and an **ALeR**ting **S**ervice (ALRS) are provided.

[8]The **N**etwork **M**anager (NM) administers air traffic management network functions (airspace design, flow management) as well as scarce resources (transponder code allocations, radio frequencies.) The European Commission nominated EUROCONTROL as the Network Manager in July 2011 [14] with a mandate that runs till December 31, 2019.

[9]The **F**iled **T**actical **F**light **M**odel (FTFM) or Model 1 is a flight trajectory constructed (by the ETFMS system of NM) from the last filed flight plan.

[10]The **C**urrent **T**actical **F**light **M**odel (CTFM) or Model 3 is a flight trajectory constructed (by the ETFMS system of NM) to tactically represent a flight being flown. It refines the previous Tactical Flight Models when CPRs show a significant deviation (1 min in time, more than 400 feet in en-route phase, more than 1000 feet in climb/descent phase or more than 10 NM laterally) and/or upon message updates from ATC (DCT, level requests, FPL update), see 14.3.1 [15].

[11]The **C**orrelated **P**osition reports for a **F**light (CPF) is a trajectory constructed (by the ETFMS system of NM) from CPRs (and ADEP/ADES.)

[12]A **S**tandard **I**nstrument **D**eparture (SID) route is a standard ATS route identified in an instrument departure procedure by which aircraft should proceed from take-off phase to the en-route phase.

[13]A **ST**andard **AR**rival (STAR) route is a standard ATS route identified in an approach procedure by which aircraft should proceed from the en-route phase to an initial approach fix.

(threshold, touchdown area) are not used in the construction of the flight profiles, see for example Figure 1).

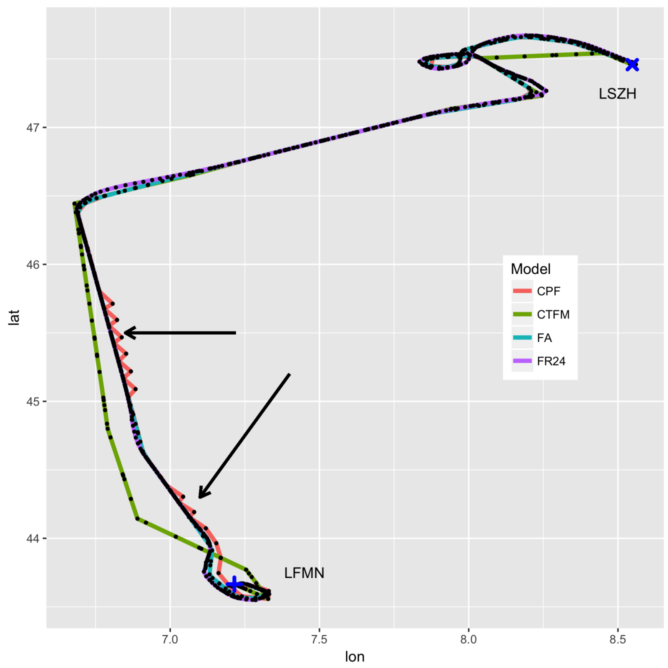

Figure 1. Comparison of CTFM, CPF, and ADS-B trajectories for flight SWR563, LFMN (Nice, France) - LSZH (Zurich, Switzerland), on 2017-07-15. The arrows show artifacts in CPF due to position reports from 2 overlapping radars.

Furthermore the low CPR[14] rate (approximately 1 every 30 seconds, see Figure 2) and reduced geographical coverage, can suffice for NM's operational purposes but limits the granularity and extent of performance analysis.

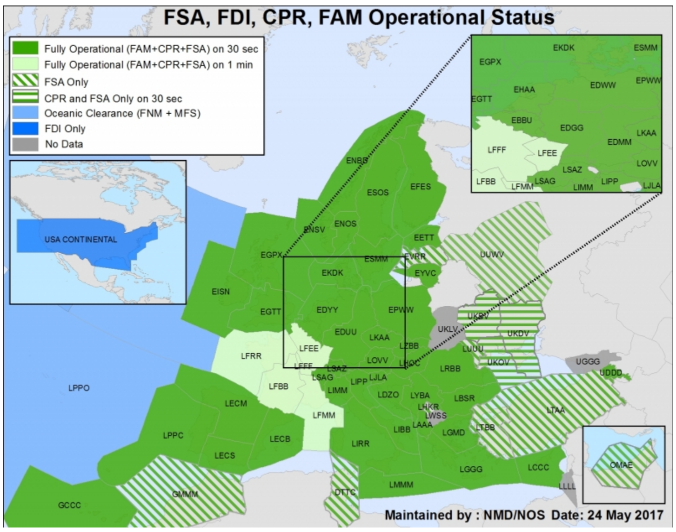

Figure 2. CPR reception map - May 2017 (source NM)

Especially around airports and within the terminal airspace a higher fidelity of the reference data is required, see for example Figure 3. An increase in positional information benefits current Performance Indicators (PI) like the additional ASMA time or new ones like vertical flight efficiency [8, 9] for which the identification of holding patterns, point merge procedures, level flight segments, etc. can help to better characterize operational performance.

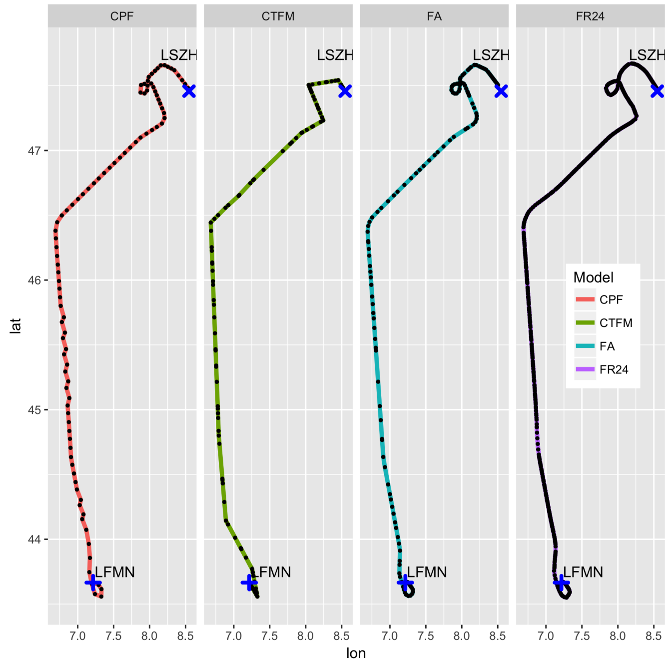

Figure 3. Comparison of CTFM, CPF, and ADS-B trajectories for flight SWR563, LFMN (Nice, France) - LSZH (Zurich, Switzerland), on 2017-07-15. Note the higher density of black dots (position reports) from FR24. Also see how CTFM *misses* the side of takeoff and the holding over Zurich.

Actual flown trajectory reconstruction using ADS-B[15] data is being pursued by other researchers, e.g. [17]. However, augmenting ADS-B with both CPR's and airport data will allow to fill the "last miles" gap and correctly link the en-route part of the trajectory with the departure and approach portions.

In addition, ground ADS-B positions and aircraft movement data as reported by airports (around 130, see Figure 4) can provide essential information to further model and analyse the surface operations from take-off/touchdown to the relevant terminal/gate/stand in order to better characterize taxi-in/out times and delays.

Moreover, the wider geographical coverage of ADS-B and higher rate (up to 1 position report every 5 seconds for FR24 live feed, Figure 5) complement the generally more accurate CPR's further enhancing both en-route, arrival and departure portions of the trajectory.

While the application of such a reference trajectory can be immediately linked with operational performance analyses,

[14]**C**orrelated **P**osition **R**eport (CPR) is a radar position report from Air Traffic Control which contains information about the flight it is associated to.

[15]**A**utomatic **D**ependent **S**urveillance **– B**roadcast (ADS–B) is a surveillance technology in which an aircraft determines its position via satellite navigation and periodically broadcasts it [16].

further data analytical applications will benefit from this approach as well. For example, similar to what is happening in the media [18, 19, 20], the availability of the reference trajectory data could trigger innovative analysis by both industrial actors and academia.

III. Methodology

For the purpose of this work, data fusion and mining of data from FR24 and other ADS-B providers, NM and airports is performed in order to synthesize a gate-to-gate reference trajectory, c.f. Figure 6.

Significant time instants are also computed for later use in performance metrics calculation:

- t_{ob}: off-block time,
- t_{to}: take-off time,
- t_{toc}: top-of-climb time,
- t_{tod}: top-of-descend time,
- t_{td}: touchdown time.

The resulting reference trajectory is made of 5-sec *synthetic* position reports. The 5-sec interval is chosen to address data fidelity requirements.

The production of a synthesized reference trajectory for performance analysis can be abstracted as a data-analytic

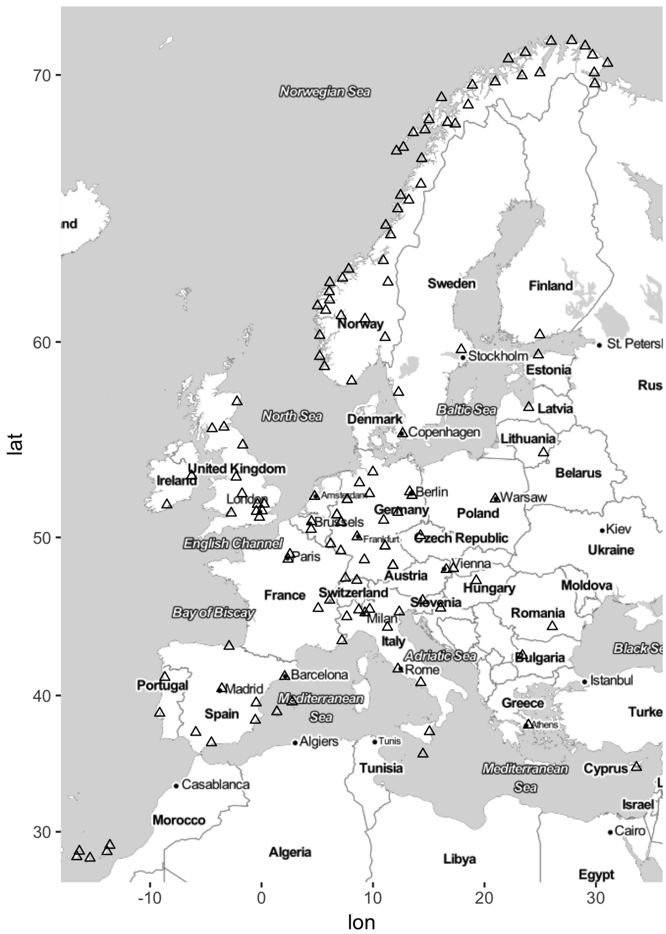

Figure 4. Airports providing flight information

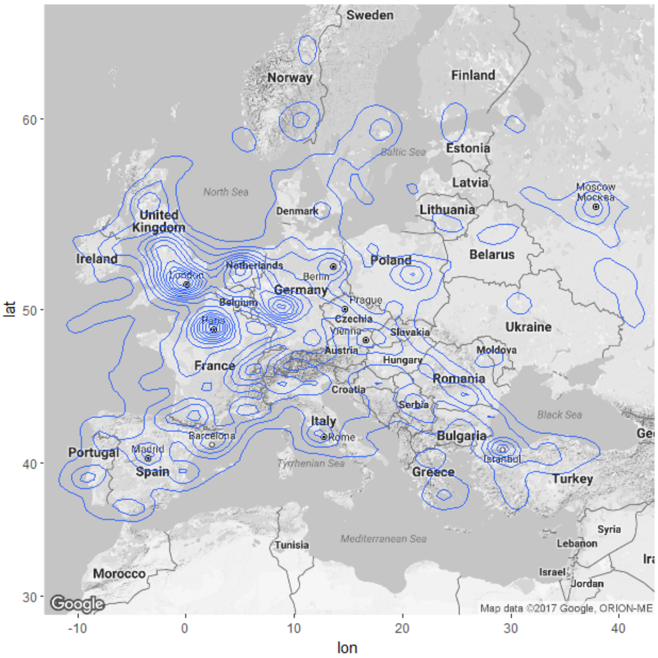

Figure 5. FR24 ADS-B, i.e. traffic, density map on 20170221 @ 11:00

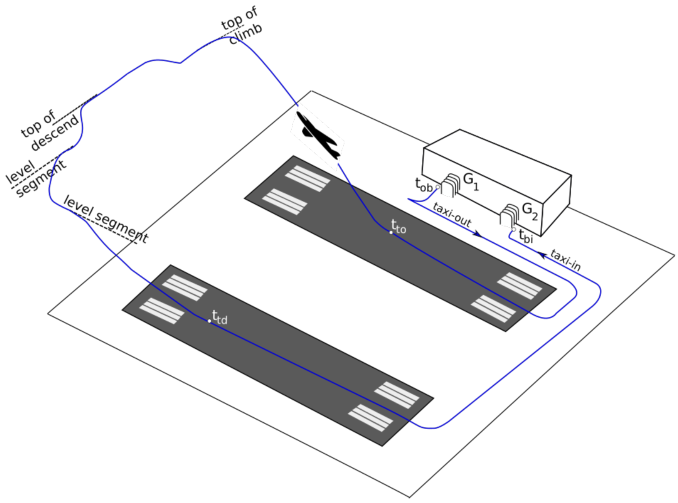

Figure 6. Gate-to-gate trajectory

process. Such a process extends from the data sources, through a series of processing steps, to the exploitation of the results (e.g. dissemination of metrics, access to data). The implementation of this process requires a dedicated Reference Trajectory Dataset (RTD) infrastructure (c.f. Figure 7.)

This infrastructure is composed of four parts:

1. data feeds processing;
2. trajectory synthesis;
3. repository;
4. dissemination.

A. Data

The first block, *data feeds*, is where raw source data is collected, stored and an initial batch of sanity checks is

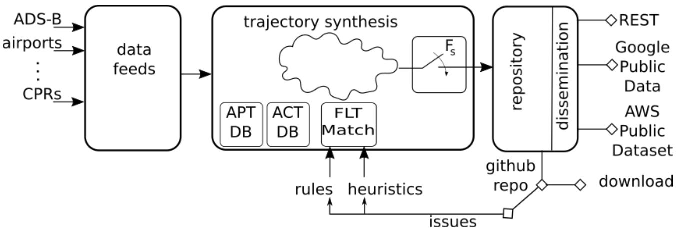

Figure 7. RTD infrastructure logical block diagram

performed. This is where the system verifies that all required data is available for each day, logging and eventually triggering alerts for missing and/or partial and/or corrupted data.

The current feeds used by the PRU are:

- FlightRadar24's live feed, geographically covering all EUROCONTROL Member States;
- CPR's, as received and processed by the Network Manager;
- Airport reported movements, as part of EUROCONTROL PRU & CODA[16] data collection process.

With a view to augmenting the data, PRU is contacting various groups of enthusiasts in order to extend, diversify and complement the above mentioned feeds. The inspiration for this approach comes from Natural Earth (NE) [21] and OpenStreetMap (OSM) [22] where crowd-sourcing has been successfully applied to establish high quality data sets.

The goal is to aggregate different sources under a crowd-sourcing model where enhancements, contributions, and updates can be managed in a distributed and non centralized way. Work is on-going to identify sources for the extension of the trajectory data with items such as airspaces (administrative [FIR] and operational [Elementary Sectors]), airports (especially aprons, gates/terminals), aircraft (airframe info, owner, registration, etc.)

B. Trajectory synthesis

The second process block in the RTD framework is the kernel of the system. In this step, ADS-B position reports are combined with CPR's, flight information and aircraft data is matched, and further airport flight movements are checked to enhance the trajectory data. The cloud in Figure 7 represents the data fusion process which is driven both by rules and by heuristics on the input data elements and relationships. The final stage/step samples the fused trajectory at 5 seconds intervals in order to build the reference trajectory.

C. Repository

The third block deals with the storage of the data sets. This capability allows saving (version controlled) releases of the data sets as well as data sets that are under development (e.g. missing data, new combinations of data sources.)

One or multiple relational databases with spatial capabilities are the candidates for this stage. Additional data sets stemming from RDT, e.g. airspace intersections, can be produced in this block.

As for previous blocks, PRU is investigating the use of cloud based offerings for both raw data storage and processing, the output data sets storage and version control, and data processing.

D. Dissemination

The final block deals with the sharing aspects of the project. Inspired by NE and OSM, PRU aims at providing Github repositories for the released versions of the data sets.

Other outreach possibilities are web services, Amazon Web Services (AWS) Public Dataset[17] (AWSPD) and Google Public Data[18] (GPD).

IV. Results and Discussion

A. Feasibility Study

In 2016 PRU launched a feasibility study contract aimed at exploring the opportunities offered by cloud providers for aviation performance monitoring analysis. In particular the goals of the project were to investigate solutions for:

- raw data storage and management;
- controlled and monitored sharing with external stakeholders of
  - data sets
  - computational resources;
- provision of datasets via web API.

The proposed use case for the project was the provision of trajectory intersections with airspaces given CPRs, ADS-B data, airport movements and airspace definitions.

The contract was awarded to and performed by INNAXIS Foundation & Research Institute. The work started in the last and finished in first few months of 2016 and 2017 respectively.

Architecture

The proposed PaaS, Amazon Web Services (AWS), has deemed the best one for the moderate load needs of the study. Other providers such as Google Cloud or Microsoft Azure have not been selected on the ground that they are targeting more high load applications.

The solution for storage has been as follows:

- *processed data storage and collection*: AWS RDS node (T2 medium instance, 2 virtual CPU and 4 GB of RAM, auto resizable SSD performance.) This is the node hosting a clustered Amazon Aurora database (based on MySQL) with InnoDB as storage engine.

The solution for the data processing and analysis has been as follows:

- AWS EC2 (T2 burstable large size instance, 2 virtual CPUs, 8 GB of RAM, general purpose SSD of 300 GB.)

[16] The **C**entral **O**ffice for **D**elay **A**nalysis (CODA) provides policy makers and managers of the ECAC air transport system with timely, reliable and comprehensive information on the air traffic delay situation in Europe.

[17] large datasets made publicly available on AWS can be analyzed using AWS compute and data analytics products, see https://aws.amazon.com/public-datasets/.

[18] Public Datasets on Google Cloud Platform are freely hosted and accessible using a variety of data warehouse and analytics software, from open source ones to Google technologies, see https://cloud.google.com/public-datasets/.

This is the node hosting the installed OS (Linux), libraries and tools (Python: numpy, pandas, shapely, geopandas, flask) for data analysis and web API.

Other services used are AWS API Gateway for API version management, AWS IAM for user profile and authorization management and AWS S3 for initial storage and audit of raw data.

Algorithms

The development of the use case considered the merge of the ADS-B data and CPRs with a point pruning strategy aiming at reducing the global trajectory error, E.

Given a trajectory, T composed of n nodes (i.e. position reports), where n_i is the i-th node, the following greedy algorithm is applied in order to prune *noisy* position reports:

```
(A) E = total_error(T)
(B) for i in T
      remove node i from T
      E_i = total_error(T)
(C) if (min(E_j) < E)
      permanently delete node j from T
      E = E_j
      goto (B)
```

Figure 8 shows for 9 trajectories the evolution of the error with respect the number of point removed (without stopping at the local minimum.)

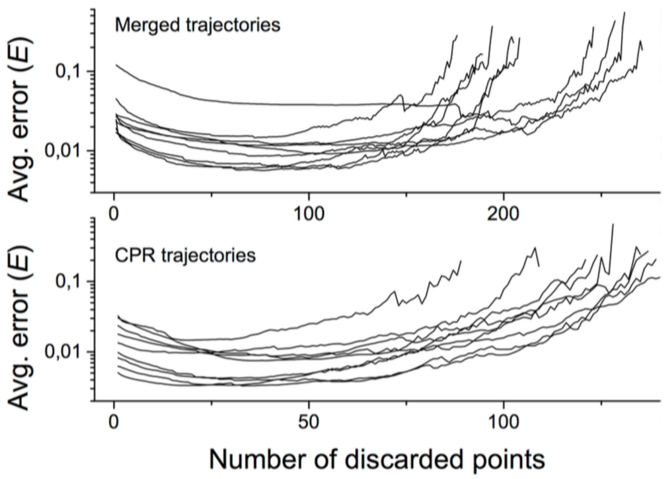

Figure 8. Average error, E, vs. number of discarded point for 9 representative trajectories. Note: node removal NOT stopped at local minimum

The error, E, for a trajectory is calculated as

$$E = \frac{1}{|t|}\sum_t (\hat{e}_{\Theta_{+1}(t)} - \hat{e}_{\Theta_{-1}(t)}) \frac{t - t_{\Theta_{+1}(t)}}{t_{\Theta_{-1}(t)} - t_{\Theta_{+1}(t)}}$$

where t represents the time, and spans between the time stamps of the first and last trajectory points; $\Theta_{-1}(t)$ and $\Theta_{+1}(t)$ are two functions respectively yielding the offset of the trajectory points defining the segment in which t is contained; $\hat{e}$ is the vector of the error at each point of the trajectory.

The error $\hat{e}_i$ at each point i in the trajectory is calculated as follows:

$$\hat{e}_i = \min(e_i - \frac{\gamma}{2}(e_{i-1} + e_{e+1}), 0)$$

where γ, in the range $[0, 1]$, modulates the error propagation from the two neighboring points; with $\gamma = 0$ adjacent points' errors have no influence.

Procedurally $\hat{e}_i$ is calculated as follows:

1. sort all points by e_i
2. calculate $\hat{e}_i$
3. (if $\gamma \neq 0$) repeat step 2. until $\hat{e}_i$ converges.

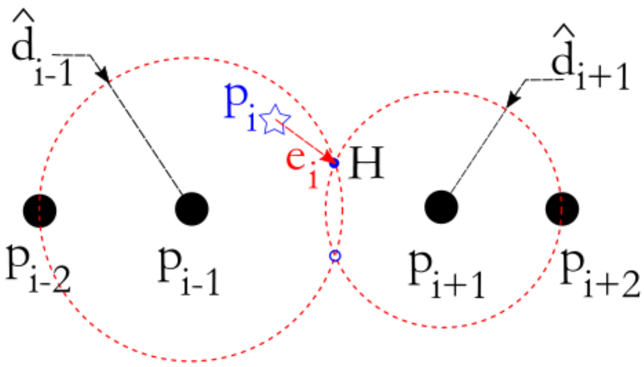

Figure 9. Error analysis.

Figure 9 shows how is computed the estimation of the error e_i between the position report p_i and probable position H when it is assumed that $v_{i-1} = v_{i-2}$ and $v_{i+1} = v_{i+2}$, i.e. that the aircraft has maintained a constant dynamic in the *short* time windows $[t_{i-2}, t_i]$ and $[t_i, t_{i+2}]$ respectively.

The depicted case is for the when the two circles of radius $\hat{d}_{i-1} = \hat{v}_{i-1}(t_i - t_{i-1})$ and $\hat{d}_{i+1} = \hat{v}_{i+1}(t_{i-1} - t_i)$ intersect in H, otherwise the intersection point is assumed to lie somewhere in between p_{i-1} and p_{i+1} at:

$$x_H = x_{i-1} + \frac{t_i - t_{i-1}}{t_{i+1} - t_{i-1}}(x_{i+1} - x_{i-1})$$

$$y_H = y_{i-1} + \frac{t_i - t_{i-1}}{t_{i+1} - t_{i-1}}(y_{i+1} - y_{i-1})$$

The proposed procedure has been studied with synthetic trajectories (with addition of noise both in lon/lat/elevation and time) to validate its soundness and theoretical characteristics.

Observations

The whole pruning procedure is nicely filtering out noisy points and able to reconstruct real trajectories, but it can be quite computationally onerous given it has a cost proportional to $O(n^2)$ for n points in the trajectory: every point has to be checked for possible deletion via calculating E which has a linear cost in n.

B. Additional uses and cross-fertilisation

The availability of RTD, still at an early stage of inception, is an essential and useful starting point for governmental, industrial and academic groups. An open data set of reference trajectories makes it possible to reproduce analyses, e.g. to review ANS performance by PRU, to research new solution on a consistent foundation of aviation data, to assess different solutions proposed in different research project, etc.

Future developments will research alternative fusion and reconstruction procedures in order to reduce the computational cost.

Further investigation would also consider the use of trajectory predictive models (for example SESAR[19]-funded DART[20] project) to fill the inevitable gaps after the fusion of the various input data feeds described above. For example, the (predictive) model built from machine learning from past flight trajectories from/to the same aerodrome could be able to contribute the missing portions of the trajectory that needs to be reconstructed.

V. Conclusions

The need within PRU for reference trajectories stems from the intention to better characterize performance at European scale especially in the terminal area for topics such as vertical flight efficiency or the effect of holdings on additional ASMA time whereby existing trajectories do not support finer granularity analysis.

But the usefulness of a reference trajectory dataset goes beyond the needs of PRU: just looking at SESAR projects the same task of collecting, cleaning and validating flown flights data is repeated over and over again for each project, with all the limitations of having access to a limited temporal and/or geographical area (typically only the one covered by the partner ANSP) and with the difficulty of not being able to share such data as soon as the project partners' composition changes in the followup or subsequent phase of the research. Another example of application of a reference trajectory dataset is the possibility to compare and evaluate different (research, industrial, operational) solutions given the same *traffic*.

This paper reports on conceptual and initial work of the PRU in developing a data analytical process chain for the production of a reference trajectory data set. The production of such a trajectory dataset is based on the augmentation of air traffic management data with open source and crowd-sourced data. The resulting data set shall be made available to Member States, stakeholders, academia and the public.

To adhere to the goals of transparency and openness the input data sets will be referenced and made available when the data provider's licence allows for it.

This paper reflects the design and specification stage of a project within PRU. Work is on-going to implement and refine the described processing infrastructure. Additionally, PRU is establishing contact with a variety of open/crowd sourced projects to investigate the modalities of data fusion and sharing through the described RTD framework. Next to this fundamental capability building steps, there is a need to provide documentation for the generation of the synthesized trajectory, the respective data cleaning and verification steps. The overall goal is to make the reference data sets openly available and to maintain the underlying infrastructure and sharing processes.

[19]the **S**ingle **E**uropean **S**ky **ATM** **R**esearch (SESAR) project was launched in 2004 as the technological pillar of the SES. It is the mechanism which coordinates and concentrates all EU research and development (R&D) activities in ATM.

[20]Data-Driven Aircraft Trajectory Prediction Research (DART) aims to present to the ATM community an understanding on what can be achieved today in trajectory prediction by using data-driven models, also accounting for network complexity effects. For more details see http://dart-research.eu/the-project/.

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