

information sharing and networking. The introduction and use of local airborne observations is a high value tool. Considering multiple data from different time-space locations and altitudes around the world airspace will perform the obtaining of an accurate 4d map about the next and future weather conditions in different earth domains. Challenge is very accessible in terms of technology; Modern aircraft are equipped with navigation capabilities that allow them to accurately sense and all interesting atmosphere parameters along their flight path. Having an air-ground datalink in place, the local airborne observations made by all aircraft operating within the airspace of interest could be taken advantage of to enhance the accuracy of atmospheric predictions, especially at those altitude levels where the aircrafts operate. Tests had been made receiving airborne data from simulated ATM scenarios. Thus, the DMET service traits the aircraft capable of sensing atmospheric parameters as mobile meteo stations and considers the data provided by them within the computation processes in the same way as it does with the ground sensors. Preliminary results show further benefits in the accuracy of parameters. The downlink of aircraft met data may be future based on the introduction of new surveillance systems as well as by the use of ADS-B applications. Integration requirements, standardization needs and the sum of benefits are facing hard in WP 11. Considering the majority of aircrafts operating within European airspace will be required to be equipped with some form of the surveillance technology, this may be the way to satisfy the required information for the weather forecast accuracy improvement.

Finally, other applicable detectors like infrared cameras for land way temperature or modern LIDAR (Light Detection and Ranging) have been considered in simulations, although no specific development has been included in experimental activities so far.

2) *Local Data Assimilation:*

A non-trivial problem arises associated with the acquisition and treatment of local observations coming from heterogeneous sources within the undergoing processes in the remote model computation cluster. In effect, in addition to the disparity in format, location, timestamps, and communication protocols, each data source has different inherent accuracy and must be given a different level of confidence accordingly. Three steps are necessary, i) first guess from global models, ii) external data harmonisation and iii) data assimilation in the model. Official global weather data from Met Agencies and local observations coming from ground-based and airborne sensors are collected and channelled to a common database where the data remains stored until the appropriate process makes use of it. Timestamp, data source, location and meteo variables are homogenised in units and scales, and appended to the table as soon as there are received from the different

external engines (local or remote). This way, the data storage is asynchronous with respect to the model execution, minimising latency in the use of the information.

For data assimilation, a mature time-static variational scheme has been used [7], where correlation background files are obtained from hourly model outputs processed during 30 contiguous days. The process tries to minimize a quadratic cost function providing the best compromise (minimum variance) between the a-priori estimate (or first guess) from the model and the available observations, the fit of which are weighted by their corresponding errors.

Extending this approach to time-dynamic schemes or more complex ensembles that transform the Kalman filter is foreseen in the future, once these techniques have proved an improved accuracy with the available throughput.

C. *The Atmospheric Model Structure*

The basic model structure is a 4D Grid of spatial temporal cells. Size of cells is function of the propagation stamp and the acceptable accuracy for ATM. The structure of the 4D grid that represents a particular weather scenario is divided into the following elements (from less to more complex): "LAYER", "BOX", "OBJECT" and finally the "SCENARIO".

For each specific time instant, a "Layer" is a 2D grid of values of a certain atmospheric property at equally spaced points located over a surface of equal pseudoaltitude (an internal dimensionless vertical coordinate based on pressure levels). The complete set of layers that covers the range in altitude is called a "Box". Each time instant is associated with five boxes, which correspond to pressure, temperature, the two horizontal wind components and the geopotential altitude. The set of these five boxes is called DMET "Object". The time dimension is achieved by queuing objects into a so-called DMET "Scenario".

D. *Computational Process:*

DMET Computational process uses the WRF (Weather Research and Forecasting) architecture. The WRF model is a fluid computational dynamics code for atmospheric simulation and weather prediction that implements a full-physic non-hydrostatic equation model. WRF is referred as a multi-agency effort to build a next-generation mesoscale forecast model and data assimilation system to advance the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations [8]. Thus, WRF meets all the requirements for the present application, being rigorous in its formulation [9], but flexible and efficient in parallel computers.

The modular architecture of WRF can be summarised as follows:

- Geogrid: domain definition, boundaries and digital elevation model setup; this module needs only to be run once per simulation site, generating the working mesh. Three domains are nested, to deal with large

mesoscale, regional and local domains (typically 10000, 1000 and 100km in width).

- Ungrib: in charge of global data decoding to generate the first meteorological fields to initialize the model.
- Metgrid: performing the horizontal interpolation of meteorological data to the domain grid.
- Real: same for vertical interpolation to pressure levels.
- WrfVar: this module is in charge of the external data assimilation, inserting observations through variation techniques. In DMET model, the observations are all stored in a common database from which data is transferred to the simulator every time this is executed.
- Wrf: propagation module able to produce forecasts using fluid mechanics equations.

Every time an object is generated, the publisher module is activated; again, time to publish a full box should not exceed the processing time for the next box, although this can happen if the network is saturated and the system has to survive that by implementing FIFO queues). In a single run, the model produces enough predictions to support trajectory propagations during TMA (Terminal Manoeuvring Area) operation.

One hour later, the process repeats. Some of the forecasts are then redundant, since that point in time had already been calculated in the former run. New datasets, however, embed more recent observations and possibly, after three hours, updates of the global model. The timestamps and other control identifiers allow subscribers to compose a coherent 4D scenario with a good understanding of the accuracy expected at every future time.

Current implementation of WRF produces 4D scenarios every hour, each one including a 2.5 hour forecast at intervals of 10 min (15 time samples). Domain size is configurable; the default being 150km x 150km, compatible with the TMAs allocated to the test airports. Vertical dimension comprises from ground/sea level to 20km high (top of atmosphere level) with a resolution of 27 layers.

IV. DMET IN THE FUTURE INFORMATION MANAGEMENT SYSTEM

A. ATM Service Requirements

ANS (Air Navigation Services) in future ATM contexts demand the fulfilment of higher requirements in terms of amount, availability, real-time updating and accessibility of information .WP8 (Information Management) and WP 14 (SWIM Technical Architecture) set the ideas for the developments of the properly communication and dissemination architecture: future services must be implemented in the "Service Oriented Architecture" in order to get the "Aviation Intranet Concept" [10]. The infrastructure supporting such data distribution requirements has been paid much attention in the past years, the research efforts leading to a service-oriented concept called System Wide Information

Management (SWIM) [11], which is envisaged as the medium-long term effective solution for data management and services in multiple-user net-centric environments. SWIM will be the enabler for the information sharing in the required time, quality and security. In Eurocontrol terms relating to the future ATM system, SWIM is focused as being "the tool for the establishment of a network centric information environment". The bases are the provision of air traffic services living in a middleware in which the data distribution must be done in a common digital format and under a standardized management system.

B. Communication and Dissemination

The weather Data modelling and the building of the required infrastructure to make possible the forecast distribution by SWIM have been developed by two ways: firstly, the selection of the communications paradigm and secondly by the outputs modelling. The terms are right defined here:

1) *Technologies*: the DMET approach to the dissemination of atmospheric 4D models is based on a Publish/Subscribe paradigm. In effect, users subscribed to the DMET service will receive periodical information with the latest forecast available. Thus, DMET provides a widespread, periodic and automated service. The technology used for its implementation is based on the OMG Data Distribution Service (DDS) for real-time systems [12]. DDS is the first open international middleware standard addressing publish-subscribe communications for real-time and embedded systems.

2) *Datapacket modeling*: process outputs had to be modelled to fit to the aforementioned dissemination standard. Data packages making up the MET scenario should satisfy both: user and technical requirements for an optimal publication, specifically; i) multiple user support; ii) regular and real-time updating, iii) compliance with DDS technology specifications, iv) acceptable bandwidth usage and v) provision of user- understandable data or decoding support. User multiplicity, data updating and data flow management are addressed by means of the features provided by the of DDS technology. DDS creates a globally-accessible shared data space in which components and interfaces can be decoupled from each other and from the underlying platforms their location in the network. In turn, delivery time is dependent on the particular resources and the control of data flow can be managed to certain extent through customization of QoS (Quality of Service) configuration parameters.

DDS operation lies with the reading and writing of data-objects defined as "topics". Topics are the basic units of information or data packets. Thus, all data to be distributed over the network must be contained in a fixed structure previously agreed among the end-parts that can be expressed in IDL (Interface Definition Language). To accomplish with

DDS, DMET service outputs are required to be locked in fixed data structures.

The size of 4D meteo models instances is so large that, if put in single data packet, their transmission would monopolize all the network communications resources in a typical infrastructure. Thus, in order to avoid conflicts with other information flowing through the network that can be more time-critical, an approach for splitting the 4D meteo model has been developed. The approach defines 2 topics:

- The “MetaData” Topic, that identifies data for the generation of the new met scenario, and
- The “DMET Scenario”, which itself splits into layer instances of the overall atmospheric model.

The MetaData topic includes the data header that provides the necessary information for the assembly of the new updated model structure at the end-user side. The second topic hosts the meteorological information following the compositional structure settled by the former. Metadata topic is a layer instance of the atmospheric model.

V. DMET PERFORMANCE ESTIMATIONS

In order to estimate the feasibility of the proposed service, a miniature test has been performed in a Beowulf cluster composed of four computers (seven slave nodes and one master). The system is homogeneous in hardware and software: Intel Core 2 Quad CPU Q6600@2Ghz, 2GB RAM, OpenSuse 11.2 OS. Besides this, there is a data collecting computer in a hangar by the local airport (León – Spain) runway, where local meteo stations (two of them) delivers their readouts. Finally, a dedicated computer offers a model viewer linked to the SWIM network, where products can be checked for quality, navigated in altitude and time, compared cell-to-cell and prepared for fast access to support real operations. All the products received are stored in a general archive that can be used for off-line validation.

Performance is always a critical issue [13] in meteorological simulations. Each model run takes a lot of time and the requirements often recommend better resolution, shorter refreshing times, longer forecasts and even ensemble products. Thus, it is important to improve every simulation step in order to get outputs as fast as possible. Some DMET modules can be compiled with parallel support so that global process can be divided into smaller tasks, executed in different processor cores in the machine or in the network. Operation timeline is of paramount importance, since real time, processing time and simulated/forecast time are involved in the process. Besides these, communication time can be relevant if datasets are large and refresh time short.

But all this is only possible if the geographic domain is limited. On the other hand, very limited territory leads to few readouts from official stations, and the poorer forecast. A compromise solution could be to use a 150 x 150 x 20 km domain, which can be successfully contained in a 100 x 100 x 27 cell grid. Time domain is atomised in 10 min forecast time

steps, producing 15 files in each simulation (2.5h). A proper performance index is the processing time spent on producing one hour forecasts per square kilometre. For the first case, in the small cluster of 20 cores total, simulation takes 20 min, resulting in 21.33 ms/km²/h. The transmission speed currently reaches 140s/object, fully compatible with the cluster performance. The same simulation in 32 8-core machines of the supercomputing centre takes 2.13 ms/km²/h, one tenth of the former figure. Scaling with number of nodes has a limit, determined by the size of the chopped domain. With the above numbers, coverage of whole Europe would need to multiply by 30 the computer throughput if 1500 m resolution needs to be maintained. That is not impossible nowadays, since there are various supercomputing centres in Europe that clearly overcome the figure of 1024 4-core computers. The explained model has been tested for accuracy using two kinds of references, both from AEMET: meteorological forecast service and atmospheric sounding data. Preliminary results obtained from data corresponding to August 2010 at Santander airport (North coast of Spain), show excellent matching with AEMET-HIRLAM forecasts and less than 10% mean error in wind speed modules within the operational range below tropopause. Obviously, this analysis needs to be extended in space and time to certify an acceptable quality of service for future operational use.

Illustrations provided on Figure 2. show a comparative among DMET and HIRLAM forecasts with AEMET observations. The root mean square errors of the forecasts are represented for different heights in order to get some conclusions about the performance of DMET and HIRLAM models. It should be highlighted that DMET was working without any external data assimilation.

The main conclusions are

- Pressure: considering the atmospheric truth given by AEMET sounding, DMET model is as good as HIRLAM or even better in most of the altitude range, with the only exception of ground level; the availability of ground truth in the airport at the time the simulation was conducted would have clearly removed this small error. In any case, the pressure error is below the margin that could affect flight performance.
- Temperature: DMET model is more accurate than HIRLAM over 2000 m high; below, a typical shift of less than 0.5 K is present; again, ground truth is the key point for this behaviour.
- Wind velocity: both the official HIRLAM and DMET present quite similar errors in wind speed estimations. Typical error figures of 2/3 m/s in the range of interest for aviation are obtained. This performance can be improved with the inclusion of more external wind data in real time, specifically those taken in altitude. The fact that both models behave similarly with respect to the balloon sounding may reflect the difference between spatially/temporally averaged wind data versus instantaneous readouts.

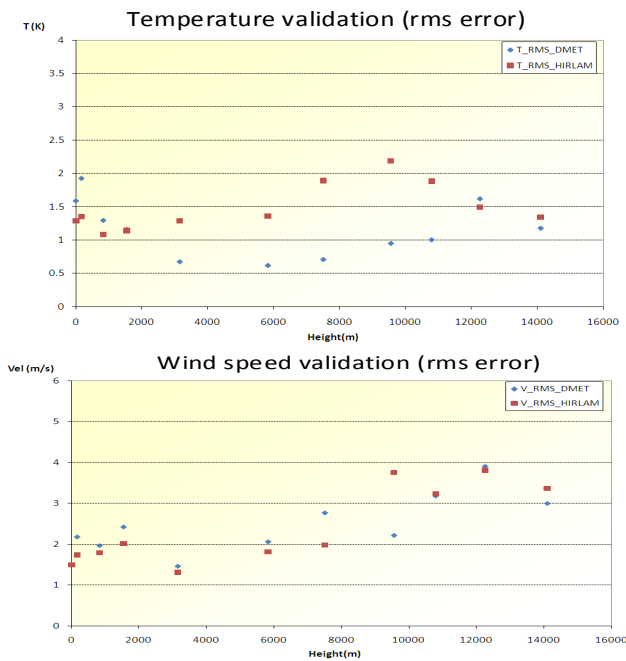


Figure 2. Temperature and Wind Speed errors estimated from wind validation campaigns

VI. TOWARDS THE ATM AUTOMATION SUPPORT: DMET FOR THE OPTIMIZATION OF FLIGHT TRAJECTORIES

Presently, there are efforts worldwide to automate the air traffic management, compressing from seasonal route programming to the development of decision-helping tools for air controllers. In all cases, meteorology is a key issue both for security and effectiveness reasons. When dealing with light aircrafts, atmospheric conditions such as rain or wind fields can become critical. Moreover, should the flight manager (or pilot) be autonomous enough, the real-time decisions on the optimum trajectory to the final destination may sensitively improve the performance.

Apart from safety issues, one of the most relevant applications of a DMET service is the optimization of flight trajectories. In order to check the validity of the developed model for this particular job, some numerical and analytic methods for airplane trajectory optimization have been designed and tested, initially for cruise phase. In this paper, only a brief overview of these studies is presented.

The algorithms implemented are twofold:

- Constrained programming methods (Dijkstra algorithm [14]): developed for structured and unstructured meshes, demonstrate good performance when state vector dimension is very limited (minimum 2D-flight time at constant velocity, minimum consumption at 2D-flight constant throttle and vertical wind, etc.)
- Analytical methods: direct or indirect, these methods solve differential equation systems meeting Pontryagin's minimum principle [15][16], a necessary

condition to reach the optimum path. Pseudospectral algorithms are currently under assessment.

In all the above techniques, atmospheric parameters play a relevant role. Dynamic pressure is proportional to air density, impacting heavily on engine and propeller performance and aerodynamic actions. Wind velocity adds to ground speed to modify aerodynamic speed, with quadratic impact on aerodynamic actions. Besides, most of the optimisation algorithms explicitly include wind speed components and their spatial derivatives in the resulting trajectory equations. The availability of DMET products, with high spatial and temporal resolutions, allows a comparison between conventional trajectory prediction simulations and a more sophisticated scheme where non-uniform atmospheric conditions are used.

In order to provide clarifying examples, tests developed until now have included the utilization of cinematic models for several cases of level flight: cruise at constant air speed, constant propulsion power, air speed constrained within certain range, flight in thermal ascending winds and obstacle negotiation. The most common cost functions include minimum time and minimum consumption. The importance of wind field knowledge, especially when the desired (or available) aircraft speed is comparable with present winds is demonstrated. Should the aircraft be very fast, the influence of winds on best path design is lesser.

Even in that case, a common meteorological reference is of paramount importance to proceed with automatic conflict resolution and hence safe optimization of the airspace usage.

Next steps in the demonstration of these concepts shall include dynamic aircraft models, ascending and descending paths and other more complex optimization functions. Besides, spatial resolution is more and more demanded in today's trajectory prediction systems, specifically in the surrounding of airports. The combination of coarse meteorological models and detailed CFD (Computational Fluid Dynamics) computing provide useful information at the expense of computer throughput requirements and complex interface decisions. Modern supercomputer centers and advances in the state of the art of terrestrial boundary layer studies envisage a promising perspective in the operational use of these techniques, which are currently under implementation in DMET.

CONCLUSIONS

The long term support tools for ATM automation shall necessarily rely on consolidated, reliable, available and fully accepted meteorological models. The nature of the atmosphere and the fluid dynamics laws make this goal a challenge for current developers of technical and legal frameworks of operations, as SESAR or NextGen. In the current work, main technical difficulties are reviewed and some concepts proposed to better estimate the capabilities of current systems and the needs for the future.

A step ahead in the integration of modern meteorological models in the process has been proposed, simulated and tested. The effort consisted of the development of a digital meteo

model (DMET) that combines atmospheric data from several sources into a 4D predictive scenario that is made available to subscribers through periodic updates.

Atmospheric data sources include forecasts from global and mesoscale weather models as well as live observations provided by ground stations and aircraft in the scene. The final product consists of a 4D grid of pressure, temperature and wind data fields valid over an airspace cube of about $150 \times 150 \times 20$ km, within a time interval of 2.5 hours. Preliminary validation is very encouraging, so more effort is currently being dedicated to move the concept closer to operational requirements.

On top of this model, minimum time, minimum consumption and other interesting trajectories are simulated and shown to check impact of wind. The service has also been used for trajectory propagation and conflict resolution by other Spanish research partners, with promising results.

Now, apart from accuracy and processing requirements, efforts should be also allocated to the paradigms of management of meteorological maps, in order to ensure all the actors involved in ATM perform operations using compatible data (dates of generation of predictions, formats and data involved, etc.). This is a huge work that would need a lot of coordination within SESAR.

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