A TARGET WINDOWS MODEL FOR MANAGING 4-D TRAJECTORY-BASED OPERATIONS

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Abstract

The Contract of Objectives (CoO), which is based on Target Windows (TWs), constitutes a new concept of operations for Air Traffic Management. TWs are represented by 4-D windows to be respected during the flight execution. They are negotiated and formally agreed by all the different actors involved in the execution of a flight and are located at the transfer of responsibility areas between them. This paper focuses on the TW modelling process which is at the base of the operational assessment carried on in the framework of the CATS project to investigate the impact of this concept on Air Traffic Controllers and pilots’ working methods. In particular in this paper we focus on the TW model which has been developed for the first Human In the Loop (HIL) experiment, a real time simulation carried on to assess the impact of the concept on air traffic controllers working methods. A different work by CATS project elaborates instead on the specific indicators measured during this experiment, regarding both system performances and human performances observed during the HIL.

Introduction

The European CATS (Contract-based Air Transportation System) project, carried out by a consortium consisting of major stakeholders in Air Traffic Management (ATM) (Frequentis, EUROCONTROL, Air France Consulting, ENAV SpA, SkySoft ATM, Unique, the Universities of Leiden, Trieste and the Zurich Institute of Technology) and co-founded by the European Commission through the Sixth Framework Program, has been launched in November 2007 to develop and assess in accordance with the E-OCVM [1], a new concept of operation in ATM: the Contract of Objectives (CoO).

CATS Project proposes, through the CoO, one of the possible implementations of the SESAR business trajectory, in which trajectory objectives are assigned and negotiated through collaborative decision-making (CDM) processes. These objectives represent the commitment of each actor to deliver a particular aircraft inside temporal and spatial 4-D intervals, called target windows (TWs). The CoO thus consists of a collection of agreed TWs, one at each transfer of responsibility area between different actors (e.g. between two Area Control Centres - ACCs), whose sizes reflect the objectives resulting from downstream constraints, such as arrival punctuality, runway capacity, en-route congestion and aircraft performances. The concept is intended to introduce a stronger and more reliable plan of operations for the European ATM system than today. In fact under the current system, the Flight Plans (FPLs) filed by airspace users constitute a mere intention to flight and there is not formal commitment by stakeholders to adhere to them. Moreover the different actors interacting during the execution of a flight are not fully aware of the objectives and priorities of each other, this fact leading in general to a sub-optimal management of operations [2]. The CoO should instead provide a formal description of those objectives, as well as a mutual commitment to respect them, thus leading to improved planning and earlier detection of unplanned disruptions, such as delays.

At the same time the TWs represent an operational tool that allows the deployment of the Demand and Capacity Balancing (DCB) process. According to SESAR [3] this process starts with the long-term planning phase and finishes during the flight execution phase, through the medium and short term planning phases. It is Airspace User oriented meaning that the new ATFM process shall endeavour to offer as much as required en-route capacity so that Airspace Users can meet their business objective.
Target Windows within the SESAR Business Trajectory concept

The TW generation is an iterative process which is carried on along three main phases, corresponding to the layered (CDM) planning at the base of the of the SESAR business trajectory life cycle:

- Long Term Planning phase;
- Medium Term Planning phase;
- Short Term Planning phase.

During the Long Term Planning phase the TWs are defined in accordance with the Business Development Trajectory (BDT), which is not yet shared outside the Airspace User organisation. This phase requires a negotiation process between airports and airspace users due to the airports constraints and allows Airport staff to assign long term traffic demand to various airport resources (runways, taxiways, stands, de-icing pads). Airport Slot Requests are balanced with available airport slots through slot allocation and the corresponding TWs are defined. During the Long Term Planning phase, coordination between users and airports is required for establishing the first set of TWs, related to departure and arrival airports, which are defined consistently with the airport slots.

The BDT and its associated TWs are progressively enhanced and refined on a bi-lateral basis by the airlines and airports, but they are not yet shared by all the actors, mainly for business reasons. The transition between this phase and the second one occurs when airspace user’s flight intentions are stable enough to be published to all other involved actors. From the airport side, the main advantage represented by CoO is that it is built through a consistent collaborative planning procedure for all the stakeholders. This will allow the reduction of inconsistencies between airport slots, Estimated Off-Block Times (EOBTs) and short term departure slots.

The Medium Term Planning phase encompasses the period from the end of the Long Term Planning phase until the day of operations. During this time, the CoOs and TWs are refined, enhanced, and updated in relation with new information coming from traffic and operational conditions forecasts (airports, users, and ANSPs). The medium Term Planning phase can be mapped onto the SESAR negotiation phase, during which the Shared Business Trajectories (SBT) are available to all stakeholders allowing to build a consistent plan for network operations. During this phase potential discrepancies between the SBT and network constraints might already be detected and the Airspace Users will be notified with the request to adjust their Business Trajectory. This process is iterative until the optimum result for the users is achieved taking account of the need to ensure an optimum overall network performance.

If there are mismatches between capacity and demand, a negotiation process is engaged between airports and users until satisfactory solutions are found. If an agreement cannot be found between airspace users and airports, the ATM Network Management Function (ATM-NMF) plays its role of moderator, facilitator or decision maker. In all cases, the CoO drafting is running at the regional or sub-regional levels under the supervision of the ATM-NMF.

The Short Term Planning phase: during this last phase the process of TW refinement responds to the balance of demand with capacity, which mainly proceeds through:

- Capacity adjustments: more accurate weather forecast becomes available, and more and more flight intentions are defined in the form of SBTs and related TWs, with a high level of detail. Some users’ intentions will still not be known (e.g. business aviation, etc.) so that predicting traffic demand is still relevant. These are the main Network Management Functions, both as regional and sub-regional levels, that collaborate closely to assure the best possible capacity plan is offered to airspace users;
- Traffic and airspace demand adjustments: final plans are made for airspace configurations and TWs are negotiated and agreed. The Airspace Users, working together with the Network Managers agree on the solutions to be applied in the cases in which demand exceeds the available capacity: airspace re-configurations, TW adjustments, queue management. In the case of a severe capacity drop, a specific queue management process called UDP (User Driven Prioritisation Process) will be triggered by the Regional Network Manager. It will be the responsibility of the concerned Airspace Users to respond in a collaborative...
manner to the ATM-NMF with a demand that best matches the available capacity, as a consequence of the shift to user trajectory ownership.

The Short Term Planning Phase finally leads to the formal commitments of all actors involved in the flight execution, represented by a CoO. Each CoO defines the volume of traffic to be handled (number of TWs) and the maximal delay (width of TWs). As a consequence an agreement on the quality of service based on SESAR Key Performance Areas and Indicators (KPAs/KPIs) can be established among stakeholders. The final result of this process is the CoO, which is signed just before off-block determining the instantiation of Reference Business Trajectory, which the Airspace User agrees to fly and the ANSP and Airport agrees to facilitate. The TWs included in the CoO can still be modified if a disruption occurs, by triggering a specific decision making process called renegotiation. Figure 1 below illustrates the business trajectory development during the different planning phases along with the correspondent lifecycle of the related TWs.

Global approach for TW modelling

The CATS concept is not limited to a simple management of constraints provided by all actors, but it is rather a complete concept that provides tools and methodologies to support and organize cooperation among different organizations of stakeholders. According to the CATS concept [4], each actor has a central role in the definition and organization of its area of responsibility. This means that each actor is able to evaluate its constraints and capabilities and thus to know which TW values are manageable for him. These feasible values, after negotiation and agreement with all concerned actors, become valid and constitute a global consolidation of local constraints formally represented by the individual Contract of Objectives, one for each flight.

The TW values included in each CoO constitute the best trade-off between flexibility and predictability. This trade-off is mainly represented by the TW width, since larger TWs will allow more flexibility during the execution of the flight but less predictability at the same time, while narrower TWs will allow a more precise prediction of the future positions of the aircraft, only permitting minor changes when the plan is executed.

**TW generic characteristics**

Each TW is univocally described by the following characteristics, schematically represented in Figure 2:

- Flight ID (CALLSIGN);
- Named point: it is the name of the nearest waypoint before the TW along flight trajectory;
- TW type: it can be adjacent (ADJ) if the TW is located on the lateral border of the transfer of responsibility area or super-imposed (SUP) if it is located on the vertical border;
- Times: TW is delimited in time by T_MIN and T_MAX;
- Level: TW is delimited in altitude by FL_MIN and FL_MAX;
- Coordinates: if TW is of type ADJ it can be described by the coordinates of its extreme points P1 and P2. Otherwise if it is of type ADJ also a third point P3 is necessary to define a TW rectangular area.
Basic principles for TW calculation

The TW calculation is based on the following steps:

- Forward-propagation of the uncertainty from the departure to all the transfer of responsibility areas along the trajectory.

The uncertainty on each crossing point increases with the distance between the crossing point itself and the departure airport (ADEP) and is calculated as a function of the specific Origin/Destination pair, of the distance from the departure airport, of the Flight Level and specific time on the point. Uncertainty can be qualitatively represented as in Figure 3 below:

![Figure 3. Uncertainty on the position is growing with the distance from ADEP](image)

Aircraft performance and airspace topology data must be known in order to calculate, through a trajectory prediction, the 4D coordinates of the crossing points located at the intersection between each transfer of responsibility area and the flight trajectory. Once these points have been identified, the uncertainty zone around them is defined by projecting them over the uncertainty cone, specifically defined for the flight.

The rationale for this calculation step is that each flight has a first part of its trajectory, starting from the ADEP, where all the deviations from the original plan (i.e. delays or changes in the flight path) can still be absorbed without impacting the arrival punctuality, represented by the last TW at the Destination Airport (ADES).

- Definition of the accepted tolerances by retro-propagation of the accepted tolerances at the arrival airport on the transfer of responsibility areas.

In order to guarantee punctuality at destination, the last TW should be limited in width, the accepted tolerances varying in accordance with the specific destination airport. This tolerance is defined in SESAR [5] as the Target Time of Arrival (TTA) window at the destination. In order to respect the last TW, the set of possible points (in space and time) in which the aircraft should be, constitute a tube whose section is increasing with the distance to the destination (see Figure 4 for a graphic representation). It is calculated as a function of the specific destination airport, its distance from the point, the Flight Level and the flight envelope. The latter is described in terms of maximal and minimal Climb and Descent Rates as well as maximal and minimal speeds at the given Flight Level.

![Figure 4. Tolerance on the position is growing with the distance from ADES](image)

- Integration of individual specific constraints.
Those constraints can result from negotiation, as in some cases some specific intervals might have been negotiated for TWs. In those cases the agreed values are imposed. In some cases the sectors’ geographical boundaries and shapes might constrain a TW to assume specific bounds, because of one or both the limits of the TW, which might fall outside the sector itself. This could occur either on the horizontal plane or on the FL as sectors are limited volumes of Airspace. In those cases the limits of the sector are imposed. Also there could be some limits in capacity that prevent a part of traffic to enter a specific airspace or there could be airspaces which are temporarily closed, due for example to military exercises, and thus cannot be crossed. Additionally aircraft travelling in different directions in level flight (i.e. not climbing or descending) are required to adopt flight levels according to their direction: eastbound flights (with a magnetic track from 0° to 179°) have to maintain odd thousands (FL 250, 270, etc.), while westbound flights (with a magnetic track from 180° to 359°) have to maintain even thousands (FL 260, 280, etc.). This rule (later referred as parity/imparity rule) constrains the allowable flight levels in each TW and in particular the extreme values FL_MIN and FL_MAX, describing the TW in its altitude component. Besides, the performances of each type of aircraft are constrained within feasible limits as described in the envelope tables extracted from the Base of Aircraft Data (BADA) [6]. In particular, the aircraft maximal speed as well as its limiting Climb and Descend Rates are imposed according to the Flight Level.

- Final refinement of all TWs in the system.

This is achieved, once all the TWs have been calculated according to the previous steps, by integration of specific systemic constraints (e.g. mutual interaction between TWs) and consolidation by negotiation among concerned actors. For example if two different TWs established for different flights partially overlap they have to be separated either through time separation, vertical separation, horizontal separation or a combined time-vertical-lateral separation.

The exposed process is flexible enough to include any possible constraints imposed by new regulations, business models or system requirements (e.g. environmental).

### Target Windows calculation for the first Human in the Loop (HIL) experiment

From this global TW generation design we developed a specific model which was applied for the first HIL experiment, carried out during October 2008 in Geneva [7]. This experiment consisted of a real-time simulation on the airspace composed by two en-route sectors at the border of two European ACCs (Milan and Geneva). The aim was to evaluate the acceptability, efficiency and impact (task sharing, changes in working methods, etc.) of the CoO on the work of controllers. Following two HIL experiments are planned in order to evaluate the impact of the concept also on pilots and operational staff of airports and airlines. In particular, the second HIL experiment will focus on the impact of the concept between ATCOs and aircrew, while the third HIL will focus on the renegotiation process, involving airlines, airports and ANSPs. In fact in the first 2 experiments the CoO is negotiated and signed prior to the execution of the flight and not altered during the execution of the experiment. For the third HIL instead the main goal is to assess the impact of renegotiation among actors, in the case one or more TWs cannot be fulfilled for whatever reason. These operational assessments are supported by rapid prototyping, off-the-shelf platform adaptation and a TW generator based on a model especially developed for the experiments by Air France Consulting.

The TW model employed in the first HIL simulation implemented a fixed threshold in order to determine the intersection between the uncertainty and flexibility tubes for each flight. This implies that the tubes depend only on the distance from ADEP and ADES and not on other factors (for example the time of the day, the specific trajectory profile, the weather) that might influence both uncertainty and flexibility in real world operations. This allowed to simplify the model and was justified by the lack of the necessary data in the traffic samples employed for the first experiment (in particular arrival and departure times and flight trajectories outside the simulated sectors). Instead, the model calculates for each flight the minimal value of uncertainty at departure and its maximum level at a certain point during the trajectory called “PRAG”, located at 100NM from ADEP, according to Air France Consulting experts. For all the points in the interval [ADEP, PRAG], the uncertainty is calculated as linear interpolation between the limit...
values. The same principle is applied for the calculation of the tolerance tube (minimal value in ADES, maximal in PRAG and linear interpolation in the interval [PRAG, ADES]). The PRAG distance univocally demarks the intersection between the two tubes, representing uncertainty and flexibility for the TW generator, which coincide at PRAG.

According to this characterization of uncertainty and flexibility tubes, for the HIL 1 simulation environment, we can distinguish 3 different cases for the PRAG to be with respect to the area simulated, as depicted in Figure 5: completely before the PRAG, completely after the PRAG or in part before and in part after.

**Figure 5. Location of the HIL1 simulation area with respect to the PRAG**

The TWs on the entry and exit point in the HIL simulated are defined accordance to the specific case in which the flight is: TW are determined by the intersection of the Uncertainty and/or Flexibility tubes with the HIL area of simulation, and are thus only function of the distances from ADEP and ADES.

Once the entry and exit TWs are determined, the other TW between these 2 (at most one) are determined by adding to the tubes a series of other constraints in the following hierarchy:

- Individual specific constraints resulted from negotiation: in some cases some specific intervals might have been negotiated for TWs, in those cases the agreed values are imposed.
- Sectors geographical boundaries: in some cases the sector shape might not allow a TW to assume the entire values imposed by the tube, because one or both the limits of the TW might fall outside the sector itself. This could occur either on the 2D surface or on the FL as sectors are limited volumes of Airspace. In those cases the limits of the sector are imposed.
- Parity/Imparity rule: as described in the previous section.

**Global de-conflicting among TWs**

After a first hierarchical level in which TWs are individually calculated as described in the previous section, a second one is triggered. This is necessary in order to ensure the global TW plan built after the first calculation phase is globally acceptable, meaning that by producing TWs which do not overlap, ATCOs workload is not increased to perform this task during the execution phase.

Starting from the TWs values previously calculated, all the TW pairs are checked to ensure their separation in time, that must be greater than a pre-fixed $\Delta t$ minimum for all those TW overlapping totally or in part on the other 2 dimensions (i.e. vertical and horizontal). Thus, to check this last condition the model calculates for each pair of TW their spatial intersection, with different algorithms according to the specific TW types.

**Figure 6. ADJ TWs overlapping – constraint violation (same « odd » or « even » TWs levels)**

For ADJ TWs with time separation less than $\Delta t$ we calculate the area of intersection onto the vertical boundary, representing the transfer of responsibility area between adjacent actors. If this area is greater than a minimum acceptable $\Delta S$, then TWs are potentially in conflict. Figure 6 represents such a case. In this case 2
main procedures can be employed by the model to de-conflict them:

- Time separation
- Vertical separation
- Lateral separation
- A combination of time-vertical and lateral separations

Time separation is applied by assigning new $T_{\text{MIN}}$ and $T_{\text{MAX}}$ values to both involved TWs $(i,j)$, such that the following constraint is respected:

$$\text{Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme.}$$

The new time values for the TWs are the result of a negotiation between involved actors, according to their business priorities. For the HIL experiments the TW model assign the same priority to all concerned flights, thus the time shift required to satisfy constraint on $\Delta t$ minimum is equally shared between flights. This is done according to their respective flight envelopes to ensure that the new assigned times are feasible for aircraft.

The TW model adopts a similar approach for vertical separation, i.e. new levels are assigned in order to ensure that a minimum separation is guaranteed. This is done by the model by equally sharing the deviation between involved flights, always ensuring that the new levels assigned are feasible for flights both in term of aircraft envelope, parity/imparity rules and sectors vertical limits.

For lateral separation we impose that segments $(P1-P2)$, and $(P1-P2)$, are sufficiently separated by assigning adequate new coordinates to those points. This is done minimizing the deviation with the previously assigned values and equally shifting the conflicting TWs in opposite directions with respect to the center of the intersection segment. At the same time the respect of aircraft envelopes is always guaranteed as well as the respect sectors lateral limits.

A combination of those three separation strategies can be employed to ensure TWs de-conflicting.

For TWs of type SUP, as the ones represented in Figure 7, the same constraints apply on the separation but the procedures employed by the model to implement separation are different, due to the different topology of the horizontal SUP TWs. This implies that the lateral separation adopted for ADJ separation becomes a horizontal separation which involve the tuples $(P1-P2-P3)_i$ and $(P1-P2-P3)_j$. Point $P4$ is automatically determined by the other 3 points since we assume a rectangular shape for all SUP TWs. The resulting deconflicted TWs delimited by $(P1-P2-P3)_i$ and $(P1-P2-P3)_j$ are obtained through a negotiation among concerned actors in a real environment, while the model applies an algorithm that equally shift TWs in opposite directions until the horizontal separation constraint is respected.

![Figure 7. “SUP” TWs overlapping – constraint violation](image)

**Target Windows values generated for the first HIL experiment**

A TW generator was developed for the first HIL experiment, based on the concepts illustrated so far. It was then run on 9 different traffic data samples, one for each session of simulations, and it produced TW values for each flight in the samples. There were a total number of 1284 TWs of ADJ type calculated during the 9 sessions of simulation and assigned to 616 different flights. The main statistics on the ADJ type of TW values obtained are shown in Figure 8 below.
The lower bound on the spatial width of ADJ TWs was 4 Nautical Miles, while 50% of the ADJ TWs were narrower than 7 NM. In 25% of the cases this distance was between 8 and 18 NM, this maximum value obtained just in 2 cases. The temporal part of the ADJ TWs had the same extreme values in minutes, but the 1st and 3rd quartile were closer to each other, meaning that 50% of ADJ TWs were distributed between 4’52” and 5’44”.

The vertical dimensions of TW (FL_max, FL_min) can take only discrete pair values, according to the parity rules described before. In 34 cases there was only 1 FL allowed by the ADJ TW, i.e. FL_min and FL_max coincided. A total number of 141 ADJ TWs had 2 admissible FLs (i.e. FL_max-FL_min=20), while the remaining 75% of ADJ TW had a FL window consisting of 3 admissible levels.

During the different sessions for the first HIL experiment Air Traffic Controllers (ATCOs) were able to manage traffic respecting the TWs associated without any impact on safety. This was observed for both 2008 and 2020-predicted levels of traffic [7]. Moreover efficiency and predictability showed a slight improvement according to a series of performance indicators defined in accordance with [8], even if a major improved is expected at system level rather than at sector level. The new concept did not introduce substantial modification to the ATCOs working methods and the additional information provided by TWs was considered in general as enhanced situation awareness.

**Conclusions**

The CATS project investigates a new concept of operations for managing 4-D trajectories, which represents a possible implementation of the SESAR Business Trajectory concept. It is based on 4-D Target Windows (TWs), which are mutually agreed by all concerned actors and constitute the object of a formal Contract of Objectives (CoO) among them. A first model has been developed to generate TWs and the results have been validated through a Human in the Loop (HIL) experiment. Our paper focuses on the description of the model, while another work from the CATS project elaborates on the specific indicators measured during the experiment [9]. The model takes in input the aircraft characteristics, provided by the BADA database and a set of constraints and rules which can be expressed as forbidden space or time regions. It then integrates typical uncertainty and tolerance values arising in real operations, to calculate a set of TWs for each flight individually. The values generated separately for each flight are then de-conflicted by a global algorithm which may employ different strategies in order to produce acceptable TW values. After the positive feedbacks obtained by Air Traffic Controllers (ATCOs) during a first HIL simulation, whose objective were to assess the acceptability of the concept by ATCOs, we are currently preparing a second one which will assess its impact also on the aircrew and the task sharing between ATCO and pilot. A more sophisticated model integrating also safety and cost-benefit criteria will be integrated in the next future in the TW generator, in order to analyze systemic issues resulting from the adoption of the concept, which cannot be catch by HIL experiments.
References


Acknowledgments

This research work is supported by the European Commission under the project Contract-based Air Transportation System (CATS), TREN/07/FP6AE/S07.75348/036889.

28th Digital Avionics Systems Conference
October 25-29, 2009