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ERASMUS Strategic Deconfliction to Benefit SESAR

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Abstract— **This paper summarizes the methods and results from our analyses of the ERASMUS [1] autonomous strategic deconfliction concept. An international team of researchers from R&D labs and universities across Europe and the US generated conclusive performance results via real-time and fast time simulations and human-in-the-loop experiments during a 30-month study of the impact that machine-generated, subliminal speed modifications of an aircraft trajectory have on controllers and pilots. A new means of separation assurance was investigated using autonomous strategic conflict management and tactical separation via RTA speed adjustments. Our main findings are organized according to the research questions raised in the ERASMUS validation strategy [1]. The ERASMUS solver described in this paper provides a potential "quick win" for insertion into the Single European Sky ATM Research (SESAR) deployment program, starting in mid 2009.**

Keywords- ***controller workload; aircraft separation managment; strategic airspace deconfliction; ATC automation; subliminal control; trajectory prediction accuracy.***

I. INTRODUCTION

The future Air Traffic Management (ATM) system described by SESAR is expected to manage up to three times the current traffic demand by the year 2025. In order to handle this expected increase in traffic, SESAR will introduce key transformations in ATM. These transformations are based on performance-based services, net-enabled information access, and four dimensional (4D) aircraft business trajectory operations. Access to airspace in SESAR relies on performance-based services that depend on aircraft equipage and capability. 4D Reference Business Trajectory (4D RBT) based operations will require aircraft to precisely follow user-preferred 4D trajectories, which will consist of clearly specified lateral and vertical flight trajectories and time conformance requirements along these flight paths. These precisely described trajectories will enable aircraft separation and optimised traffic flow management across several different time horizons.

The ERASMUS project has investigated the impact on the controller and flight crew when traditional controller practices in traffic management are replaced by autonomous, strategic deconfliction and separation management operations using 4D business trajectory operations in the en-route flight phase.

II. ERASMUS PRINCIPLES

ERASMUS aims to improve the SESAR performance framework by augmenting the strategic deconfliction and separation management functions. Strategic deconfliction is a service designed to reduce the number of conflicts in the airspace and refers to actions that can be taken 20 to 30 minutes before a potential conflict to ensure that conflicts do not occur. The separation management service provides separation assurance to traffic flying in controlled airspace. This service is more tactical in nature and deals with traffic in real-time operations.

The first objective of ERASMUS is to improve the strategic deconfliction of the airspace via in-flight adjustments of the 4D RBT to reduce the number of conflicts, i.e. to generate a conflict free trajectory for the next 15 minutes of flight. The ERASMUS concept considers airspace complexity as

1) *a factor of the number of conflicts in a portion of the airspace*
2) *a factor of the level of doubt on the situations encountered by the controller [7].*

The concept of "doubt" is defined by the separation margins and specific reasoning controllers apply today during conflict management, using flight data that is not precise. ERASMUS asserts that when 4D trajectory-based automation reduces doubt, the traffic complexity and residual number of conflicts left for controllers to handle can be significantly reduced.

The ERASMUS strategic deconfliction function proposes three main services:

1) *Conflict-free trajectory generation*
2) *Guaranteed measurement of aircraft separation distance*
3) *Performance monitoring & automation recovery*

Conflict-free flight trajectory generation aims to reduce the number of aircraft in conflict by calculating the constraints on the aircraft flight path needed to ensure a 15-minute conflict-free trajectory. This is achieved by adjusting, in real-time, the

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[1] [1] En Route Air Traffic Soft Management Ultimate System (ERASMUS) is a European Commission-funded sixth framework programme.

4D RBT. The 4D RBT has been negotiated between all stakeholders (airline, Air Navigation Service Provider (ANSP), etc.) and ideally should not be changed. If this agreed-upon trajectory has to be modified to avoid potential conflicts, then this has to be done within a pre-defined time/speed buffer. The trajectory adjustments will be done accordingly to rules and constraints, taking into account that changes should be kept to a minimum.

The conflict-free trajectory generation service is expected to generate a significant decrease in conflicts and provide the Tactical Controller (TC) with only a limited number of conflicts to handle amidst 2020 traffic.

The second service is the “Guaranteed measurement of aircraft separation distance” service which provides accurate and reliable information on the separation distance between two aircraft from the time that the flights enter the sector. The predicted separation distance between aircraft, generated by the conflict detection service, is computed using the highly accurate FMS trajectory prediction data that is periodically downlinked to the ground. Aircraft are classified by the underlying ERASMUS conflict detection function as “aircraft in conflict” and “aircraft not in conflict” according to their predicted. The user of this separation distance information is the tactical controller, who is provided with more accurate trajectory information, particularly regarding the predicted minimum distance between aircraft, and thus is be able create smaller separation buffers compared to the separation buffers generated today when working with less accurate radar generated trajectory information.

The last service for strategic deconfliction is “performance monitoring & automation recovery.” This service identifies when the conflict-free trajectory generation service is no longer delivering traffic with a sufficient reduction of conflicts. This service effectively alerts the user that there is an abnormal situation. The user of this service is a new actor in air traffic management: the Multi Sector Planner (MSP).

The second ERASMUS objective is to increase sector capacity. This is accomplished via separation management improvements based on conflict-free trajectory generation that reduce the need for tactical interventions by the controller. The performance of controller decision aids can be increased when these tools utilize highly accurate 4D RBT’s. The separation management function will be used by the tactical controller.

Increased predictability of traffic due to the use of 4D RBT’s and target driven processes will permit through-sector entry and exit planning tasks to be accomplished well in advance of the aircraft’s entry into the sector. This provides the tactical controller with a more organized and conflict-free inbound traffic, and thus fewer interventions will be necessary per flight. In our Human In the Loop (HIL) experiments conducted at the Aix en Provence Air Traffic Control Center (ATCC), Air Traffic Controllers (ATCo) indicated that they required well spaced aircraft traffic at 8 minutes before sector entry.

Furthermore, the reduced uncertainty in the aircraft position along its predicted trajectory results in an improved performance of controller support tools. Thus the conflicts highlighted to the controller by the conflict detection tools will indeed result in conflicts if no action is taken. This certainty, with respect to the precision of the information, will allow controllers to work more traffic, and thus increase capacity.

The ERASMUS project mainly focuses on the ground side of ATM. However, the airborne side is directly affected by ERASMUS actions, and cooperation between the airborne and the ground side is required for successful ERASMUS operations.

III. THE 4D REFERENCE BUSINESS TRAJCTORY

ERASMUS is based on a 4D trajectory negotiated between ATCo and the aircrew. The Flight Management System (FMS) downlinks its 4D business trajectory to the ground where ERASMUS performs Conflict Detection and Resolution (CD&R) on all the aircraft within the sector(s), and uplinks trajectory Required Time of Arrival (RTA) clearances to the aircraft. If feasible, the FMS generates a clearance-compliant trajectory and periodically (e.g., every 3 minutes) downlinks this predicted 4D trajectory. The FMS then uses feedback control to track the negotiated trajectory. The pilot is free to request a new clearance if the trajectory is no longer optimal or feasible. Thus the trajectory prediction functionality is required in the airborne system to assure that the trajectory is feasible within the aircraft performance limits (speed envelope, passenger comfort…), and optimal for the flight business objective (e.g., minimize fuel cost, minimize time to destination…).

The trajectory prediction capability is also required on the ground where the automation tools need to generate a predicted trajectory for unequipped aircraft and iterate on conflict resolution solutions on equipped and unequipped aircraft trajectories during “what if analysis.”

Aircraft state, weather and trajectory data exchanged via ADS-B/C & CPDLC messages increase the accuracy of both ground and airborne trajectory prediction computations. Weather (i.e., wind and temperature data) forecast uplinks as well as aircraft-sensed weather data downlinks have been shown in ERASMUS experiments to increase trajectory prediction accuracy during enroute flights [15].

IV. CONCEPT VALIDATION STRATEGY

The ERASMUS validation strategy includes different techniques to validate the ERASMUS concept. These techniques range from simple monitoring to lab studies to real-time simulations. Simple testing and lab studies were planned as initial steps to validate the background hypothesis and ensure relevant material for the ERASMUS research questions we needed to answer. The main technique used to validate the concept and provide quantified results of potential benefit were fast time simulations and real time simulations.

For human factors assessments, the ERASMUS project initially planned to address controller and pilot interactions and impacts simultaneously. However, the final validation strategy directed us to assess the ground and airborne human factors aspects in two separate steps, with each point of view evaluating the air-ground interactions.

We chose to test the potential impacts of the ERASMUS solver in a 2007 ATC environment that was easy to simulate and where operational controllers could apply their expertise. In this 2007 environment, the effects of the ERASMUS (background) automation solutions were not noticeable by controllers. Therefore, the initial potential assessment of ERASMUS was focused on its first application, namely "Subliminal Tactical Control by Speed Adjustment (TCSA)". As part of this first application, Honeywell and DSNA/DTI investigated the potential use of autonomous speed variations [8] [10] for strategic deconfliction. This initial phase of technical testing and validation required definitions of different parameters as input to the ERASMUS solver [9].

Once parameters for the most appropriate values for efficient strategic deconfliction were set in the solver, the next validation step was to test the solver with real traffic. Two series of Fast Time Simulations (FTS) were conducted to test efficiency and robustness to strategically solve the potential conflicts with baseline and 2020 traffic levels. These FTS were also used to test the parameters of the solver, including separation distance targeted in conflict resolution, length of computation cycle, processing power, etc. The solver performance was compared when varying these parameters. Real traffic across all sectors controlled by the Aix en Province ACC was used to build these simulations.

Once the solver performance was optimized, we were able to initiate a series of experiments to validate the ERASMUS concept. In experiment 1, our aim was to demonstrate that controllers did not notice speed variations initiated by ERASMUS-actions and that the concept of subliminal control without controller awareness was realistic. Many studies have been performed on detection and resolution processes, but very few give information on this specific question. ATCo was not expected to monitor speed changes specifically, since these rarely vary as long as aircraft maintain their cruising altitude in en-route airspace. Such changes usually only occur in a specific instances such as significant head or tail winds, or turbulence encounters.

Experiment 2 was conducted as a small scale laboratory study to demonstrate the hypothesis that doubt situations demand increased controllers' cognitive resources. This study aimed to test a second hypothesis: proposed subjective indicators are sensitive to the controllers' behaviour in situation of doubt. Doubt situations were introduced in the scenarios and a correlation of the different subjective scales was expected.

Two Real-Time Simulations (RTS), namely Experiment 3 and Experiment X, were executed to assess the performance impact on the ground controllers' operational performance. Certified controllers were asked to manage realistic working positions, using the Radio Telephony (R/T) to communicate with the pilots and the telephone to communicate with their colleagues involved in the simulation.

A RTS Experiment 4 was used to assess the impact of ERASMUS on the airborne side. The pilots were asked to fly different scenarios with a highly adjustable cockpit simulator. The pilots were tasked to apply standard operating procedures and existing business trajectory optimizations. The focus of this experiment was on assessing the pilots' response to ERASMUS issued datalink clearances. Table 1 summarizes the experiments used to prove the ERASMUS concept and to initially demonstrate the ERASMUS potential for strategic deconfliction of the airspace.

For 2020, the objective was to evaluate how ERASMUS can improve the future air traffic management system's capacity and efficiency with regards to air-ground communications. The ERASMUS project team generated a high-level description of new and changed tasks that air traffic controllers would need to perform when interacting with the ERASMUS solver. For the second application, we subsequently integrated these ERASMUS services into the futuristic 2020 environment which included other potential controllers' tools available in 2020. Experiment 5 relied on gaming, and was created to demonstrate and evaluate the results of these future services.

TABLE I. LIST OF VALIDATION EXERCIZES

Exercise name	Type of method	Environment	Aim
FTS1	Fast-time simulation	Baseline	Test solver efficiency and robustness on baseline traffic
Experiment 1	Test study	Baseline	Test detection of speed variation
Experiment 2	Lab study	Baseline	Determine impact of traffic configuration on strategic deconfliction.
Experiment 3	Controller Real-Time Simulation (RTS)	Baseline	evaluate potential operational performance impact of TCSA on ATCOs
Experiment X	Controller RTS	Baseline	Refine operational conditions of TCSA performance
Experiment 4	Cockpit RTS	Baseline	Evaluate TCSA impact on pilots
FTS2	Fast-time simulation	2020	Test solver efficiency and robustness on 2020 traffic
Experiment 5	Gaming	2020	Initial assessment of expert judgment of potential impact of ERASMUS services to SESAR 2020

With gaming techniques, the potential for measurements are limited and the extraneous variables too numerous to be rigorous in experimental design. Gaming techniques are often referred to as hypothetical exercises. Nonetheless, gaming exercises can be used to demonstrate in practice the main roots of potential behaviors of an agent in a complex, large and futuristic environment. The storyboard of our gaming exercise was built to highlight the ERASMUS 2020 scenario's main features. It was structured in 4 parts:

1) Demonstrate and compare the meaning of today's traffic and a 70% traffic increase in terms of number of aircraft and in term of objectives and perceived conflicts (~25 instantaneous aircrafts, ~6 instantaneous conflicts).

2) Demonstrate and compare the meaning of 'unreliable' and 'reliable' information according to the list of conflicts displayed to the Tactical Controller (~3 conflicts detected by the machine).

3) Demonstrate and compare the meaning of ERASMUS actions resolving 80% of conflicts at the 15 minutes time horizon (~1 conflict to manage each 20 minutes)

4) Demonstrate and compare the actions needed to manage the residual conflicts (i.e., Multi Sector Planner actions to manage a threshold of residual conflicts delivered to the Tactical Controller and Tactical Controller action to manage residual conflicts).

V. RESULTS

A. *Solver configuration testing*

The initial tests in Experiment 1 concluded that within a range of 10%, Aircraft Speed Modifications (ASM) could be applied without being noticed by the controllers [11]. On the one hand, as depicted in Table 2, this experiment showed that significant changes in speed (±6%) went mostly unnoticed by controllers even though the experiment instructions had informed them of the existence of these covert changes and they were challenged to point them out. Only 25% of these changes were identified. In additional, half of more considerable changes (-12%) also went unnoticed. This confirmed that absolute values of speed are only sporadically considered (and memorized) by controllers in en-route ATC. Meteorological conditions (winds) and substantial differences in instructions from airlines to their crew, for example, induce enough permanent speed variability in a given aircraft type for controllers to accepts airspeed within a certain interval of values as "normal". Therefore, once the order of magnitude (mainly related to the nominal speed of the aircraft type) is stored in their working memory, controllers seem to accept it as starting data for extrapolating conflict risks, which is their essential task. These first results give interesting clues for optimizing ATCOs' cognitive resource savings, which is central to ERASMUS performance objectives, although no evidence of ASM perception thresholds is shown for controllers (see Table 2). At the same time, a significant number of false positives (identified speeds modifications) were also reported by the participants.

Therefore, the combined effects of the false positives and the unnoticed speed changes clearly lead us to think that controllers cannot rely on such an uncertain/incomplete perception. Thus, neither a strategy for improving resolutions nor any disruption of the current plan of actions has to be expected or feared for the controllers. In other words, since the number of false detection is high, the ability to globally supervise ERASMUS actions seems to be beyond reach for ATCOs. The few cases where low to moderate speed changes were initiated by ERASMUS and perceived by the controllers are well within the range of speed changes caused by local variations in wind direction or strength.

TABLE II. GLOBAL PERCEPTION OF ASM'S

Magnitude	**Perceived**	**Not Perceived**	**Total**
(# of speed-modified aircraft)			
-12%	296	260	556
-6%	159	345	504
+6%	113	495	608
(# of unmodified aircraft)			
No ASM	207	2298	2505

In the solver, the magnitude of the speed adjustments are tightly bounded and designed to minimize controllers' attention. In this way, ERASMUS will minimize any disruption to the tactical controller [11]. Honeywell assessed that the optimum speed variation range to facilitate aircraft engine performance is within -6% and + 3% (see Table 3) and thus this range was used for speed adjustments initiated by the solver. The ERASMUS range is very close to the plus or minus 5 percent range of speed variation allowed to be applied by pilots' discretion by ICAO without the need to notify ATC [13] and thus harmonization with existing regulation will not be an issue.

TABLE III. HONEYWELL SPEED VARIATION RANGE RESULTS.

separation values (nm)	**[0-5]**	**[5-10]**	**[10-15]**
initial number of conflicts	45	75	68
resolved conflicts for $\Delta V \in \{-6\%, +3\%\}$	30 *(67%)*	52 *(69%)*	35 *(51%)*
resolved conflicts for $\Delta V \in \{-3\%, +3\%\}$	19 *(42%)*	25 *(33%)*	23 *(34%)*

B. *Initial TP precision technical study*

Honeywell used their Aircraft Simulator and FMS software for the Airbus A380/A340 aircraft to study the impact of wind forecast uncertainty on the FMS trajectory prediction (TP) accuracy for look-ahead times of 15 to 20 minutes. Analysis results showed worse-case ΔETA errors of 10 seconds and cross-track errors of 0.01nm from 19 test scenarios. For level flight, with wide ranging wind forecast errors, the FMS demonstrated an overall CTA/CTO Performance (longitudinal) of 0.5 Nm (5 sec) open-loop accuracy, 15 min ahead of the current aircraft position (see Figure 1).

In the FMS, sensed local wind is blended with the available wind forecast data. Our analysis indicated that inaccurate forecasts generated worse results than no forecast for trajectory predictions for a 15 to 20 minute time window and level flight. Random (Gaussian) gusts only slightly decreased TP accuracy. Timely wind forecasts are especially essential for accurate trajectory predictions during climb & descent. Thus greater weight is given to forecast winds for the rapidly changing wind at altitude for descend and climb calculations.

As a result of these experiments, the FMS TP precision was set to 5 second accuracy for a trajectory calculated 15 minutes out. The first RTS was executed based on the TP precision values delivered by this study [12]. At the time of issue of this article, Honeywell and ETH Zurich have just been completed a series of enhanced TP studies, which analyzed the influence of weather on TP accuracy on a larger scale. The studies propose the way forward to upgrade the TP accuracy management under specific weather conditions [14].

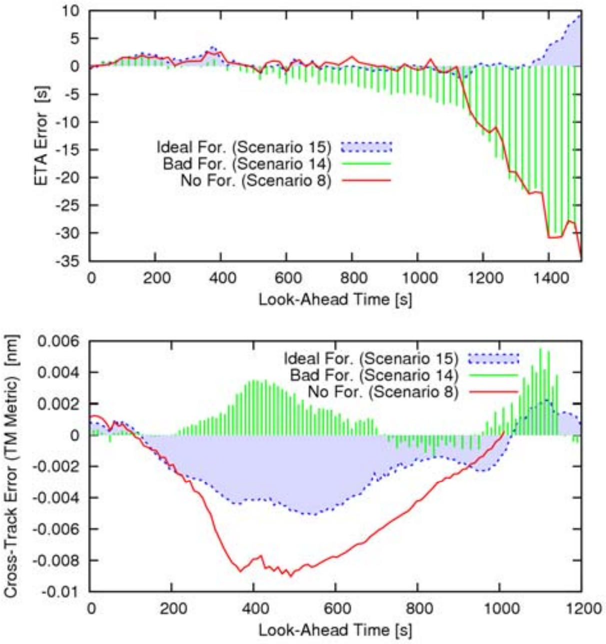

Figure 1. FMS precision according to look-ahead time

C. Baseline fast time solver efficiency

The performance of the ground automation system was measured by the percentage of conflicts solved [6]. We observed that the ground system performance depended mainly on three factors: the TP error, the CTO guidance error and the cyclical update of the conflict detection & resolution algorithm computations (i.e. the comparison of exe1 and exe2 shown in Table 4). Overall the FTS demonstrated that ERASMUS has the potential to meet the target of 80% conflicts solved.

TABLE IV. FTS 1 MAIN RESULTS

Exercise name	Exe1	Exe2
TP error	5s	5s
CTO error	5s	5s
Global error[2]	2.7 Nm	2.7 Nm
Algorithm update cycle	**3 minutes**	**5 minutes**
Speed variation	[-6%, +3%]	[-6%, +3%]
Nb of conflicts	4031	4031
Nb of residual conflicts	570	882
Percentage conflicts solved	**85.7%**	**78.1%**

D. Ground assessment: acceptability, performance for the controllers

Experiment 2 confirmed that diagnosis of *certain* conflicts is easier than detection of *potential* conflicts. Experiment 2 also refined the concept of doubt. From the controllers point of view, doubt concerns various factors that range from the nature of the problem-situation (conflict or not), the solution to achieve, the traffic load evolution, to the data available (at the time of aircraft integration) and the lapse of memory concerning an action (see Table 5).

Doubt is a pre-categorization activity, when the controller decides if an aircraft will be in conflict or not. Traffic pre-categorization is fast because it prevents a detailed analysis and it is sustained by an expert's intuition. Strictly cognitive reasoning is used to refine this pre-categorization.

TABLE V. DOUBT VARIABLES

Internal Variables	External Variables
✓ Sector size, inferior, terminal	✓ Expertise level
✓ Traffic load	✓ Self-confidence level
✓ Temporal Horizon	✓ The events encountered during the activity
✓ Conflict geometry	✓ The punctual individual state
✓ Actions load	✓ Etc.
✓ Panel of possible solutions	

The hypothesis that doubt situations require more resources than conflict situations was not confirmed. However, the concept of doubt is not essential in the demonstration of the potential benefit of ERASMUS. What is important is to demonstrate reduced demands for cognitive resources, whether they come from doubt relief or not.

For Experiment 3 and Experiment X, the demonstrations were centered on the assessment of reduced demand for

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[2] The global error is calculated from the following formula : FMS 5s error + CTO 5s error * 2 aircrafts = 20s error with 2 flight at 480kts head to head (worst case), error will be 480/3600*20=2.7Nm

cognitive resources due to ERASMUS actions, not only from the reduction of doubt but also from the reduction of conflicts and the reduction of tactical interventions.

Various subjective ratings of workload (AIM, NASA TLX, Workload feelings…) situation awareness (SASHA, SAGAT), complexity (dynamic density, complexity feeling…), effort (effort required to maintain picture, effort to resolve conflict…) as well as objective data from the simulator (number of clearances, number of conflicting aircraft, and closest point of approach…) were collected.

E. Workload

There was a significant difference in workload between low and high density traffic, indicating the importance of taking these different traffic loads into account in these results.
When traffic situations were rated as relatively complex, subjective workload assessment techniques showed an effect for lower workload with ERASMUS (see Figure 2 for an example). This may demonstrate that there is a required minimum traffic density and controller workload in order to be able to assess an effect due to ERASMUS actions. i.e., be able to show that when workload is high, ERASMUS actions lower the controller's workload.

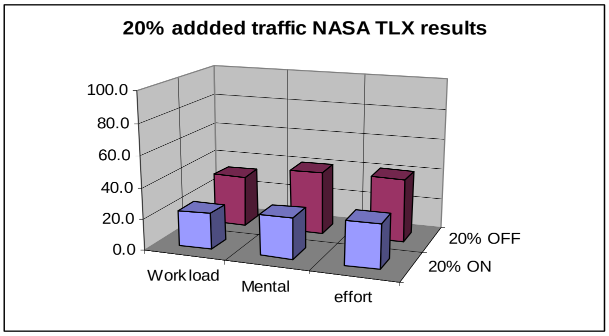

Figure 2. ERASMUS workload impact with NASA TLX

F. Situation awareness

Although it appears that ERASMUS did not have a statistically significant effect on the effort required by the subjects to construct an adequate mental representation of the traffic (within a 0.05 confidence rating, where P = 0.059), there does seem to be a correlation (Figure 3). This could indicate that ERASMUS helps the controller to acquire a better representation for traffic situations that are complex and when the development of a mental model of the traffic is not easy. The reported effort dedicated to survey the radar information contrast this result with a clear tendency to increase with ERASMUS, especially for the higher traffic sample.

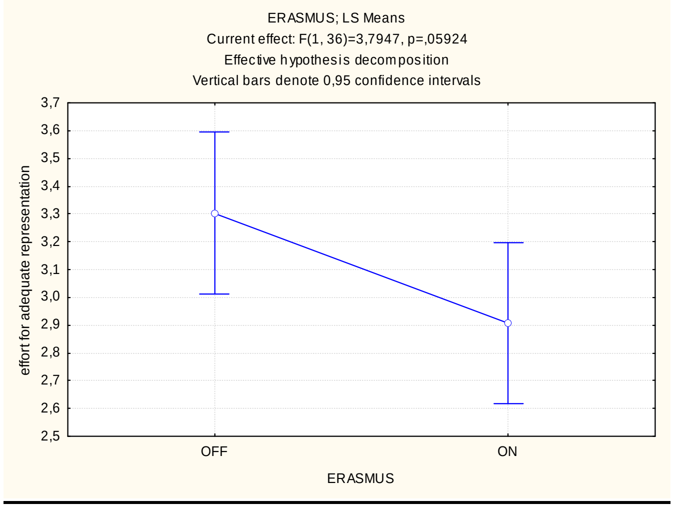

Figure 3. Effort for adequate representations

G. Capacity

ERASMUS enables controllers to manage a slightly greater number of aircraft in the same time period. Thus even though no effect on the global level of workload was noticed, ERASMUS did demonstrate a potential benefit when we considered the workload per aircraft.

In terms of saving in the number of tactical interventions, ERASMUS demonstrated a clear effect. The number of clearances was reduced with ERASMUS in all conditions. (Figure 4 depicts one example).

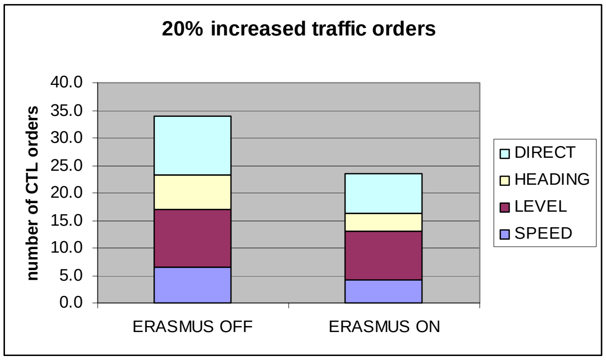

Figure 4. Number of controller's orders with and without ERASMUS

Also, Experiment 2 previously demonstrated that the controller's ratings of subjective state and perception of comfort are a relevant indicator for ERASMUS and the changes implied. The results obtained on those indicators during the experiment suggest that ERASMUS may provide some benefit to controller resource conservation that was not captured with more classical methods of workload.

H. *Safety impact*

ERASMUS' effect on airspace safety is another important area of consideration. Safety improvements can be correlated to the numbers of conflicts as well as to the separation that is achieved between aircraft. Separation in that case reflects both the efficiency of the solution that is computed by ERASMUS as well as a measurement of human/system performance. The data analysis of separation considers all pairs of aircraft where at least one aircraft was in the evaluated sector Y. Table 6 presents the minimum separation achieved distributed between 3 categories.

TABLE VI. CATEGORIES OF PROBABILITY OF CONFLICT

Category (CAT)	**Distance (Nm)**	**Probability of conflict and controller intervention**
A	**0 - 7**	**Very probable**
B	**7 - 15**	**Less probable**
C	**> 15**	**Very improbable**

The data collected during the real time simulations are statistically significant ($p < 0.05$) for the reduction of the probability of conflict. As shown in Table 7, ERASMUS removed most aircraft from CAT A by provision of greater separation distances. ERASMUS also reduced the number of aircraft in CAT B by reducing the number of aircraft that would have been classified as being in conflict.

TABLE VII. REDUCTION OF PROBABILITY OF CONFLICT IN RTS

	ERASMUS OFF Ref traffic	**ERASMUS ON ref traffic**	**ERASMUS OFF traffic+20%**	**ERASMUS ON traffic +20%**
Number of aircraft in CAT A	**9.4%**	**4.3%**	**4.3%**	**1.2%**
Number of aircraft in CAT B	**53.6%**	**22.0%**	**52.8%**	**33.7%**
Number of aircraft in CAT C	**36.9%**	**73.6%**	**42.9%**	**65.1%**

I. *Complexity results*

Objective complexity, measured with the dynamic density metric, was significantly reduced with ERASMUS. However, subjective difficulty results showed a tendency to increase with ERASMUS in high traffic settings and decrease with ERASMUS in low traffic settings. This suggests that ERASMUS does not reduce demand for resources but that instead there is a change in controllers' strategy when ERASMUS is used in a high traffic setting (depending on the specifics of the traffic sample used). ERASMUS also demonstrated significant subjective comfort improvements suggesting that strategic deconfliction provided by ERASMUS is compatible with controllers' activities and strategies.

J. *Airborne assessment: pilot acceptability and compatibility with actual working methods*

There were four scenarios used in the airborne experiment to reflect different flight conditions, as shown in Table 8.

TABLE VIII. EXPERIMENT 4 SCENARIO DESCRIPTIONS

Exercise	**Speed change**	**Type of conflict**	**Number of RTA's**
1	**Increase**	**Crossing**	**2**
2	**Decrease**	**Crossing**	**1**
3	**Decrease**	**Overtaking**	**2**
4	**Decrease**	**Overtaking**	**1**

The mean airborne transaction time was ~104 seconds as shown in Figure 5. This experiment showed that clearances originating from a machine are acceptable to the airborne crew as long as the clearances are in line with the pilot's expectations. Data showed that pilots are perfectly comfortable with the concept of RTA's sent by an automated system rather than a human controller. However, it is problematic that the pilot is unable to negotiate another solution with the air traffic controller, since the human ATCo is not aware of the specific clearance that ERASMUS has sent to the aircraft. Some pilots would like to negotiate a more optimal solution especially in the case of a 6% speed decrease.

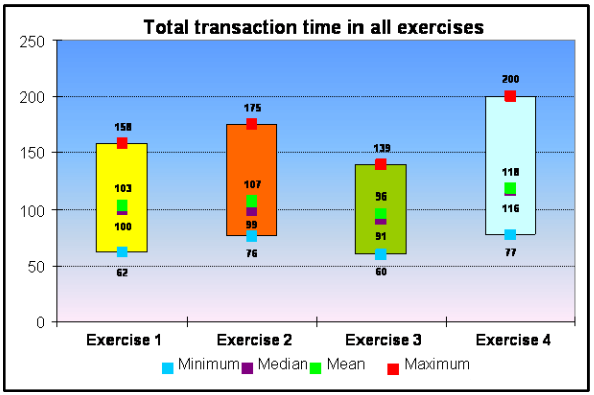

Figure 5. Transaction time to execute RTA

The tasks required to process the ERASMUS clearances were perceived by the pilots as straightforward and easy. Pilots were comfortable with the ERASMUS clearances and most (i.e., 79%) of the ERASMUS clearances were accepted. Differences were identified amongst the subcategories of comfort; two problematic areas were identified:

1) *Not being able to negotiate an aspect of the clearance with ATCo, and*
2) *The magnitude of the requested speed change.*

Pilots were comfortable with the concept of RTA clearances having been generated by automation: there was no difference detected in pilot comfort levels before or after the experience with ERASMUS-generated clearances. Instead, the most important factors in evaluating an ERASMUS clearance as acceptable or not acceptable were speed, fuel usage and Estimated Time of Arrival (ETA) impacts.

To conclude the baseline environment assessment, a summary of the main findings in the analysis of performance benefits (per SESAR KPA) attributable to ERASMUS is provided in Table 9.

TABLE IX. BASELINE PERFORMANCE TO SESAR KPA'S

KPA	
Capacity	Management of 30% traffic increase gives potential capacity gain 35% Complexity reduction for the higher traffic sample in RTS
Flexibility	Human : unchanged performance, potential saving of resources to be allocated to other tasks Algorithms : robust enough for all conditions tested
Safety	35% conflicts diluted in RTS Safety margins are increased : for aircraft 7-15 more than 10% separation increase Less conflict resolution to be done: about 30 % less in RTS
Cost effectiveness	Maneuvers cost reduction: potential for 8340 k€ savings per year
Flight-efficiency	Minor trajectory modifications (± 1 minute) Improved traffic flow (RFL, less deviations) Average processing time (i.e. the time the pilots required to make a decision about the ERASMUS clearance) ~83s
Environment	Estimated CO_2 reduction: 22850 tons per year

K. *2020 Fast Time Simulation results*

The fast time simulations conducted with increased traffic levels demonstrated algorithm robustness and resistance to parameter variations (TP accuracy level, number of equipped aircraft…) shown in Table 10 as the percentage of conflicts solved according to TP precision and in Figure 6 as the ratio of solved conflicts according to the level of equipped aircraft.

TABLE X. PERCENTAGE OF CONFLICT SOLVED ACCORDING TO VARIATION OF TP PRECISION

TP error	Percentage of solved conflicts
1 Nm	90,22%
2 Nm	88,44%
3 Nm	87,84%
6 Nm	81,59%

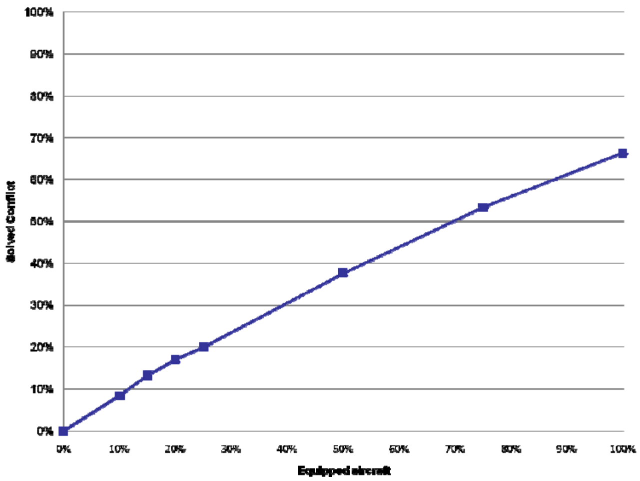

Figure 6. Equipped aircraft Vs conflicts solved

L. *Gaming results*

The Gaming exercise enabled us to address systemic aspects of the ERASMUS application in terms of controller practices and controller tasks with a minimum setting.

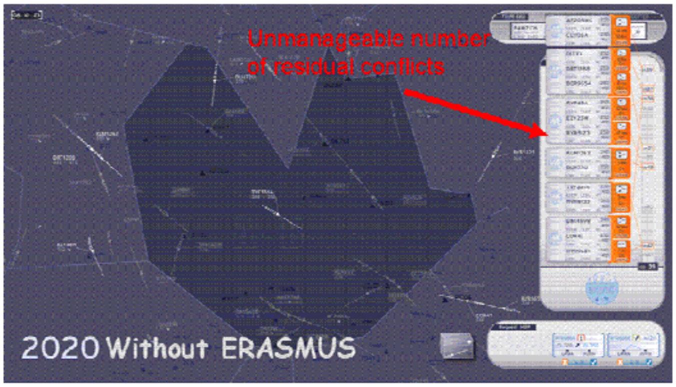

Figure 7. MSP potential visualisation of strategic conflicts to manage in 2020

The results demonstrated the need for ERAMSUS-like services to manage 2020 traffic levels. Without these automation aids controllers will not be able to handle the traffic levels expected for the 2020 in the European airspace (See Figure 7). The anticipated number of conflicts to manage will be too great and the traffic situations will be too complex.

VI. DISCUSSION

It is widely accepted that advance TP capabilities and improved datalink technology will reduce aircraft position uncertainty and improve aircraft trajectory predictability. Strong resistance in the ATC community remains against automated conflict resolution tools when this automation is seen as a substitute for the controller. However, the concept where automation supports the controllers instead of replacing them was well received by ATC experts, even if such a solution induces a change in controller teams and roles (as is the case with the new role of MSP and the increasing importance given to strategic management versus tactical management of traffic). Experts accept these kinds of solutions as a way forward to face the challenges in future air traffic management. ERASMUS demonstrates a potential to strategically solve 80 percent of conflict and minimize the residual conflicts to a value of 3 per hour (i.e., one every 20 minutes on average, as shown in Figure 8).

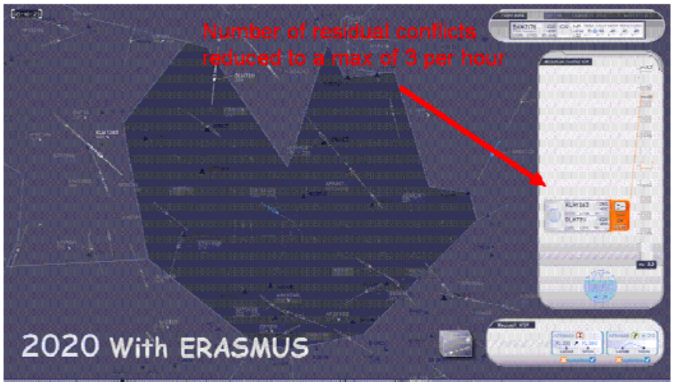

Figure 8. MSP potential visualisation of residual conflicts with ERASMUS in 2020

The level of aid that ERASMUS can provide is foreseen as a means to provide the controller with a sufficient level of situation awareness (SA) to be able to act strategically. A commonly shared concern by controller is that the increased traffic levels and strategic actions potentially can interfere with their ability to maintain full SA and full control of the aircraft in their area of responsibility. How to address this concern and ensure a safe and efficient flow of traffic is not yet clear.

In the baseline scenario, experiments demonstrated the risk that tactical intervention by controllers interfered with ongoing ERAMUS CD&R actions. In our demonstrations we chose to tag those aircraft under ERASMUS autonomous control and highlight those aircraft managed via MSP strategic resolution guidance. Experts were not able to reach an agreement on the desire to tag aircraft under ERASMUS control. Some advantages and disadvantages have been raised and further assessments will be required.

In the gaming exercise, controllers feared the reduction of tactical solutions they could execute when only a limited number of aircraft were untouched by ERASMUS, and thus remained available for controller intervention. This concern also raised the question of responsibility: in the end, who is responsible when a mid-air collision or near miss occurs?

In the future, the use of 4D RBT, improvements in TP accuracy, and the systematic exchange of trajectory information will provide controllers with a better understanding of aircraft flight intentions. Thus, controllers will not have to infer information and routine behavior and aspect of "doubt reasoning" or "doubt removal" [5] regarding potential conflicts will no longer be required. However, controllers will still have to handle exceptions (degraded mode, unexpected situations) and residual conflicts using tactical interventions. The anticipation and situational awareness concerns associated with today's modus operandi will be reduced. A more reactive mode closer to anti-collision working methods will arise. However, will this mode be sufficient to cope with situations of exception, knowing that the level of control situation is usually linked to the level of anticipation in dynamic environments? More generally, if controller contributions consist of very punctual adjustments, they will not rehearse their skills sufficiently and these skills will progressively erode. ATCo will be in a paradoxical satiation where they are being pulled out of the global management of the situation, leading to loss of practical skill of de-confliction and yet still be in charge of the most difficult problems that cannot be handled by the automation.

The evolution of the controller function from tactical interventions to controlling trajectory conformity assumes, by nature, a highly monitored activity. As a consequence, the expected gain in terms of attention resources will probably not be fulfilled. To cope with those concerns, SESAR proposes to maintain the current expertise of controllers, i.e. the current reasoning modes. However, the cohabitation of two very different control logic methods does not seem to be cognitively consistent for the same operator: Exception handling puts the controller in a passive position. Inaction makes it easier for controllers to lose concentration. Thus, some mental resources are necessary to maintain controller attention.

Due to the aim of separation delegation, the transfer of responsibility will probably occur in the form of target transmission (i.e. the operator hands off a target to fulfill) and not by means transmission (i.e. the operator dictates detailed actions or means). This process may suppose additional effort to recognize the executive strategy of the separator on the one hand, and to memorize it on the other hand. To decide actions and means facilitates working memory, which contributes to the situation awareness.

VII. CONCLUSION

The results obtained from the experiments conducted to date have indicated that ERASMUS has the potential to impact ATM performance based in a number of SESAR KPA's. The key success of ERASMUS lies in the autonomous support of strategic deconfliction. The solver abilities and philosophy in support of controller activity is the added value of ERAMUS. Some investigations remain to further the scope of separation management and answer additional open questions that our experiments have raised regarding strategic deconfliction. Questions regarding the quality and reliability of the downlinked and ground computed trajectory information also remain to be explored. This follow-on work is planned as part of the SESAR Work Package 4 deployment program starting in mid 2009.

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