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Analysis of the wake vortex encounter risk under reduced vertical separation enabled by geometric altimetry

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Abstract. As the current requirements of at least 1000 ft vertical separation between aircraft in en-route airspace are mainly determined by the limited accuracy of barometric altimetry, a study has been performed whether these separation minima might be reduced to 500 ft with usage of geometric altimetry. Thus, allowing smaller nominal vertical distances between flight paths, it is to be expected that the risk (in frequency of occurrence and severity) of wake vortex encounters increases. The present study, using a comparative fast-time simulation of traffic at European level for two full-day scenarios, indeed confirms a relative encounter risk increase by a factor of 3 to 4 across all severities (as expressed by the magnitude of the circulation encountered), with this factor being largely independent of the wind situation. Consequently, the exploration of mitigation means such as conditional application of reduced vertical separation or tactical wake conflict prediction tools should be undertaken as part of further development of the concept.

Motivation

In order to increase capacity in en-route airspace and therefore reduce the need for detours, thus contributing to a more environmentally friendly aviation, a reduction of the vertical separation minima has been considered as a part of the research project *Green-GEAR* (Green Operations with Geometric Altitude, Advanced Separation & Route Charging Solutions). Currently, within the so-called RVSM (Reduced Vertical Separation Minima) airspace between flight levels (FLs) 290 to 410 inclusive, a minimum vertical separation of 1000 ft between aircraft is applied. The new RVSM 2 concept [1] aims to reduce this separation minimum to 500 ft while at the same time increasing the upper applicability limit to FL 600, enabled by the usage of geometric altimetry, i.e. usage of GNSS vertical positions, instead of barometric altimetry. In view of the fact that the main contributor to the current value for the minimum vertical separation is the comparatively large allowance for the barometric altimetry system error (ASE), its decrease should be feasible when geometric altimetry is employed.

Geometric altitude reference in cruise implies no longer following the isobaric altitudes that are consistent with aircraft performance, resulting on average in penalties in fuel use as expectable [2,3]. On the other hand, besides the capacity increase reducing the need for detours, the finer granularity of available flight levels could allow flights to operate closer to their optimum altitudes than today, counteracting and possibly outweighing the penalties [4].

A reduction of aircraft separation minima would obviously impact flight safety so that a safety case including consideration of the risks of aircraft collisions under nominal and non-nominal conditions and of wake turbulence encounters is required. The Green-GEAR project has conducted a preliminary safety study for the RVSM 2 concept [5,6]; the results of the wake turbulence risk assessment are presented in this paper. While out of scope here, we note that the aircraft collision risk for RVSM 2 is acceptable under certain conditions [5].

Background and Prior Work

A wake turbulence encounter is a possibly hazardous situation for an aircraft, but such encounters cannot be completely avoided by procedural means alone if any airspace capacity is to be maintained. Existing (procedural) separation minima have been initially defined at ICAO level using expert judgement more than 50 years ago [7], and the only modifications for en-route airspace implemented so far have been the increased horizontal separation from the Boeing B757-300 and the new SUPER wake vortex class (currently only populated by the Airbus A380) and the introduction of RVSM between FLs 290 and 410. Studies for wake vortex risk in the en-route flight phase are scarce (e.g. [8-10] for North American airspace, [11,12] for European airspace) and with the exception of [10] concern the status quo. Due to limited monitoring and reporting of wake vortex encounters, it is difficult to quantify whether the studies correctly estimate their frequency and severity. Especially concerning the latter, it can be observed that the crossing of a wake where forces or moments beyond the aircraft's control capabilities could be generated needs to be regarded as hazardous from a safety point of view *in the absence of further information*, but these effects may only persist for a fraction of a second and need not lead to relevant consequences on practical operations [6].

Method

The analysis is based on a fast-time simulation using a software toolbox [13,14] that had been previously developed and now has been improved. The fast-time simulation uses trajectory data generated from submitted flight plans and meteorological data, in this case from the German COSMO-EU numerical weather prediction model, as input. As there is no (planned) traffic yet adhering to the new flight levels, a corresponding modification of altitudes has been employed for the RVSM 2 scenario, cf. Fig.°1, that also serves to concentrate the traffic around the most popular flight levels, effectively locally increasing traffic density. ASE, different for barometric and geometric altimetry, and flight technical error (FTE) are modelled to obtain actual flight altitudes from nominal ones [6]. The simulation calculates probabilistic corridors with an elliptical shape that contain the wake vortices with a high probability using the well-established P2P model [15,16] that also models the evolution of these wake corridors over time. A semi-deterministic approach (the initial conditions for aircraft trajectories and meteorological parameters are assumed as known in the simulation, while uncertainties in atmospheric effects and consequently wake evolution are modelled) ensures realistic corridor sizes with the proper probability distribution of parameters. The traffic scenario is then evaluated with respect to crossings of the aircraft trajectories with these wake corridors. The final step is a hazard assessment based on the SHAPe model [17-19], which uses the roll control ratio (RCR) as the most relevant parameter and has been integrated into the simulation as part of this work.

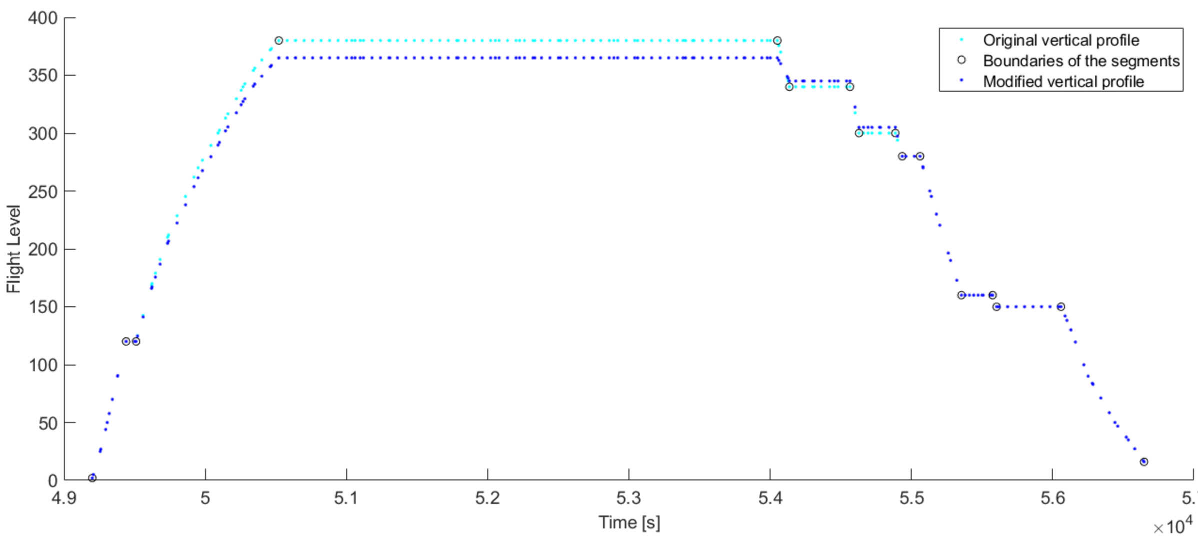

Fig.°1: sample of adapted fight profile, moving horizontal segments to new flight levels

Two full-day scenarios with traffic samples for the whole European airspace (more than 20000 trajectories each) have been analysed in this study: one day with relatively low wind speeds and one day with relatively high wind speeds at the relevant altitudes, as the wind situation strongly influences the horizontal movement of wake vortices and therefore the probability of wake encounters. Both scenarios have been analysed in a baseline version using barometric altimetry and 1000 ft minimum vertical separation in the RVSM airspace as it is used today and in a modified version using geometric altimetry and 500 ft minimum vertical separation as it might be used in the RVSM 2 airspace in the (far) future. Due to limitations of the meteorological data input driver, scenarios from 2014 (14^{th} Feb and 3^{rd} June) were used. The observed increase of traffic densities since then, or even until a possible introduction of RVSM 2, is not modelled, which is believed acceptable as the relevant question is the relative change of encounter risk.

Results

The results show that a reduction of the vertical separation to 500 ft leads to an increase of the number of wake encounters approximately by a factor of 3 to 4 over the full range of encountered circulation values, as shown in Fig.°2 for both scenarios. The figure only contains encounters where the magnitude of the encountered circulation in relation to the respective aircraft's capability to deal with it (as assessed by the SHAPe method) is high enough that the situation cannot be *guaranteed* to be safe. The high-wind-speed scenarios show a smaller overall number of encounters, which can be explained with the higher wind speeds moving the wake vortices away from the generator aircraft's trajectories in many situations so that other aircraft on the same trajectory do not encounter them. Aircraft on adjacent trajectories can encounter wake vortices as a result of strong crosswinds, but overall, the reduction of the number of wake encounters on same trajectory outweighs this effect. Despite the overall number of encounters being very different in the two wind scenarios, the relative increase between baseline and modified separations is approximately the same.

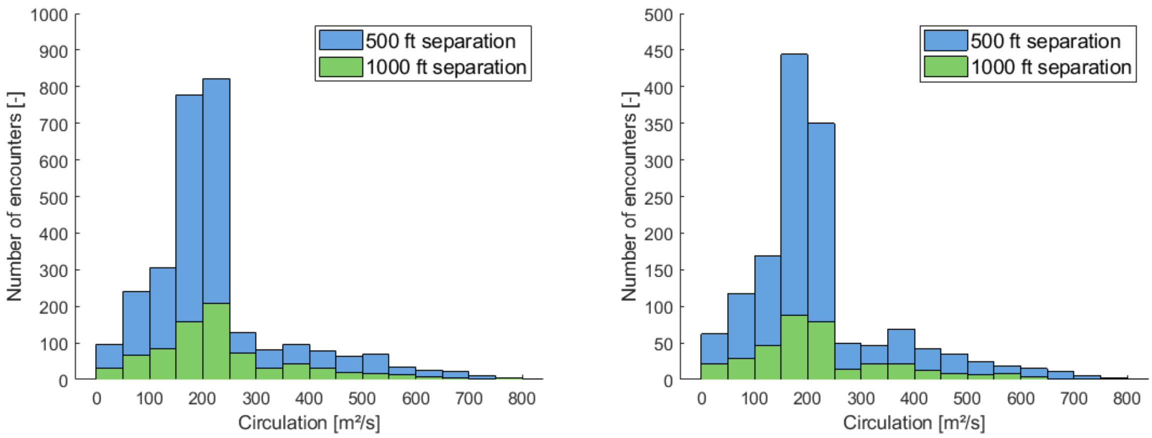

Fig.°2: Distribution of the encountered circulation in the low-wind-speed (left) and high-wind-speed scenario (right). Note the different vertical scaling.

An analysis of the aircraft separations at the start times of the wake encounters revealed that in the scenario with 500 ft vertical separation, most encounters happen 500 ft below the wake generating aircraft at a horizontal separation between 5 and 20 NM. In the scenario with 1000 ft vertical separation, far less encounters happen 1000 ft below the wake generating aircraft at a similar horizontal separation. Therefore, it can be concluded that the wake encounters 500 ft below the wake generating aircraft are not shifted from 1000 ft below to 500 ft below when changing the vertical separation, but instead, these are nearly exclusively additional encounters that would not happen with 1000 ft separation as used today. This is plausible because, even though wake vortices can descend more than 1000 ft (in some cases even 2000 ft [20]), they descend less than 1000 ft most of the time.

Conclusions and Further Work

As *Green-GEAR* is an exploratory research project with a relatively low TRL (Technology Readiness Level), some limitations of the fidelity of the results have to be accepted, notably due to restrictions in traffic flow modelling. Nevertheless, as many additional effects with respect to prior work have been modelled in relatively high detail, and large-scale scenarios have been used for the simulations, at least the relative results can be considered as representative.

With that caveat in mind, we find a substantial increase in the number of wake encounter occurrences with no significant change in average severity as expressed by the magnitude of the circulation encountered. In fact, there is an increase of the number of encounters in all ranges of circulation values, with a comparatively higher increase for lower circulation values (see again Fig.°2) so that the average is, if only slightly, decreased. The overall result means an increase in wake encounter risk (substantially increased frequency of occurrence at virtually unchanged average severity) and as such is not unexpected considering the nature of wake vortex transport and evolution. We therefore note a substantial relative decrease in wake turbulence safety.

Prior activities modifying separation standards have adopted a comparative approach, demonstrating no (unfavourable) change of risk through a new concept of operation – this is not the case here. However, with no official definition of a target level of safety (TLS) for the wake encounter risk, nor any means of quantification for the encounter severity defined by regulation, a formal statement that the new situation would be unsafe cannot be made at this point. It is reasonable to assume though that it would not be acceptable without modifications. Remedies can be mitigation means and/or limiting conditions for its application. Indeed, further analysis of the results especially regarding particular aircraft (category) pairings, relative flight path geometries or weather situations is desirable, so as to possibly identify criteria when or where the new separation standards could be applied safely, or should not be applied. An alternative approach could be the introduction of a safety net: analogous to the Airborne Collision Avoidance System (ACAS) and Air Traffic Control's short-term conflict alert (STCA), a ground-based or airborne predictive tool to identify and prevent potentially hazardous wake encounters [21] could be employed, potentially rendering large benefits as operational limits, and thus capacities, would no longer need to be dictated by the worst-case assumption. Such a tool could already contribute to increase the safety of operations under current separation rules.

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