AIAA AFM/ASE 2010, TORONTO, MANAGING WVE SESSIONS – REVIEW

A P Brown, NRC, and Authors' Inclusions

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1. INTRODUCTION

1.1.1 A contingent of the Wake Turbulence research and operational community met in Toronto, at the AIAA GNC/AFM/ASE/MST/AS Conference at the Sheraton.

1.1.2 Two joint AFM/ASE Conferences' Invited Sessions were held: Managing Wake Vortex Encounter I, and Managing Wake Vortex Encounter II, Wake Vortex Transport and Decay. In addition, on Thursday, a small number of visitors toured the FRL research aircraft facilities at the FRL, and the T33's instrumentation in particular.

1.1.3 To some in Toronto, I expressed my intent to summarise my views of our presentations in Toronto – this was conducted at the beginning of September. The circulation of the synopsis was intended to provide attendees to discuss, correct, rejoin, disagree, or amplify the synopsis, with your own views. This has been undertaken by the authors' and co-authors over the intervening months of September through October. Their comments, amplifications and corrections to my *précis* have been compiled herein, and are now circulated for archiving – including posting on the WN3E and WakeNet USA websites.

1.2 Purpose

1.2.1 The synopsis summaries the presentations made at the two WVE Sessions.

1.2.2 As such, the synopsis is presented in the following format:-

- Draft of circular email, 1st September 2010, suitably corrected by individual author respondents; and
- Individual author respondents' amplifying text and views presented, under individual author notation.

1.2.3 With reference to the draft issue of this text, circulated 1st September 2010, corrections have been made and incorporated in the present Issue 1, as advised by individual author responses. Insertions to Section 4 have been made, and author credited, in the temporal order that they have been received – thus, reading sections top-to-bottom retains the flow of the discussion', such as it has been injected by individual author responses.

1.3 Session Agenda

1.3.1 The agenda for the Sessions is included as Appendix A.

1.3.2 Session I consisted of seven presentations: six written and one, oral. Session II consisted of the first seven presentations in the Agenda for Tuesday.

2. MONDAY AFTERNOON, MANAGING WAKE VORTEX ENCOUNTER I

2.1.1 A number of current WVE applied research efforts, and elements there from, were reported upon in the First Session. Included was an update on the DLR Institute of Flight Systems Aerodynamic Interaction Modelling (AIM),)/ validation and wake encounter severity assessment including an application example (wake vortex advisory system "WSVBS" [Hahn] by Schwarz *et al*. The Simplified Hazard Area Prediction (SHAPe) is an engineering solution outcome. Although SHAPe hazard areas are based upon Roll Control Ratio (RCR), it was stated that the RCR limit value applied within the concept covers any WVE flightpath upset parameter, such as Cn, Az or Ay, for example. The SHAPe hazard areas are defined according to a non-hazard approach to ensure not only safe but undisturbed flight operations, i.e. to avoid go-arounds. Covering all relevant aircraft parameters is an important broadening of definition, given that flight data and actual WVE accidents or incidents highlight the multi-axis nature of WVE loading. Just as such a broadening of the definition of aircraft response is useful, broadening of the vortex velocity profile domain (to include bounding limits of possible profiles – e.g. the potential, or Rankine, profile might be an upper bound, B-H might be a lower bound in velocity magnitude) is arguably also warranted – perhaps, initially by undertaking an AIM/SHAPe sensitivity analysis to a range of profiles and associated peak induced velocities, from the 'standard profile' which is typically applied to such research, namely the Burnham-Hallock (B-H) profile. [inserted by Hahn].

2.1.2 The same comment can be applied to the research of Hahn *et al*, which applies, essentially, Forward-Looking Measurements to Gust Alleviation augmentation, *via* O-ID or On-Line Identification – overall, termed the Integrated Loads and Ride Improvement System (IRLIS). It is a very clever usage of LIDAR detection of wake vortex, at the level of *existing* LIDAR range technology, *i.e.* short range. Hahn *et* al conducted sensitivity analysis of the number of LIDAR spheroid detection points and the accuracy of a parallel-pair of B-H vortex profiles, to show that a limited number, 4, of detection points at a minimum update rate of 10Hz could identify a vortex pair, and provide anticipation to a gust-alleviation system, one which includes direct lift control. Perhaps velocity-profile sensitivity analysis has been conducted for IRLIS – because the Inflight IRLIS Simulation, using the VFW-614 in bootstrap mode (*i.e.* driving itself to the WVE upset accelerations), used both the B-H profile and the output from LES (Hennemann) – but if so, there is no distinction in results, and the LES profile shapess are not itemized. Also, it would be beneficial to itemize and correlate flightpath disturbance parameters which drive pilots' ratings of WVE severity and improvement. I look forward to the author'publishing further details on this research. [inserted by Hahn].

2.1.3 Brown presented NRC flight data of wake vortex core traverses, and attendant near-core-edge velocity profiles, from 1 x A380, 2 x B744 and 1 x B772 wake vortex surveys. Although the traverses are essentially co-axial (taking 1 sec to traverse upwards 10 m across the core, in this time 200 m along the vortex line), the overlay of CPA 'approaching' and 'receding' flightpath segments showed that useful core profile shape data was obtainable. The 25 core profiles suggested the existence of solely a primary vortex in a minority of cases (to which a Burnham-Hallock profile fitted well), but rather primary plus secondary vortex elements in a majority of cases (to which a potential vortex profile fitted well), and primary, secondary and tertiary vortex elements in other cases (exceeding potential profile velocity peaks, but of small scale). The NRC flight technique has been developed, to the point of undertaking oblique vortex crossings. This shall be conducted in the future, in order to more clearly identify the PRI, SEC and TER constituents. For now, the occurrence of TER vortex elements outside and inside the core edges has been determined, from the flight data.

2.1.4 Guerreiro *et al* presented the wake-free zone characterization behind the FAA-proposed Simplified Aircraft-based Paired Approach (SAPA), using Monte Carlo simulation. Whilst based upon WV avoidance, this work is a good example of the early application of applied Operational Research, at a fundamental level, at an early stage in the consideration of new procedures, in this case that may have application within the realm of Dynamic Spacing. The early dissemination of such research is beneficial, so that fluid mechanicians, flight dynamicists, control and instrumentation engineers and meteorologists can align their research, to particular applications.

2.1.5 Similar, by way of Flight Procedural Research, Lang *et al* presented the status on RECAT. Consideration of minimum in-trail separation distances is a reminder that there is a level of WVE acceptance inherent in any set of WV separation standards. RECAT has the implementation benefit of overlaying the ICAO HEAVY/MEDIUM/LIGHT categorizations. However, it will not necessarily overlay individual Member States' standards, and this is a reminder that separation standards development has been idiosyncratic – reactive to particular environments or realms where incidents and accidents have occurred, but the statistical significance of which is uncertain, due to lack of comprehensive reporting upon WVE.

2.1.6 Whether flown autopilot or manual, WVE acceptability research requires the application of models of pilot acceptability, 'logic-gate' decision-making and, finally, behavior. The simulator-based research of Luckner and Reinke addressed this question, for WVE in cruise. Firstly, they conducted a comprehensive analysis of cruise WVE scenarios, with particular reference to RVSM airspace. Generated circulation in cruise is of similar magnitude to that on departure or approach – however the TAS of the WVE aircraft is much greater, resulting in the generation of greater aerodynamic forces on the WVE aircraft. The simulator study is, likewise, comprehensive. For an A330, the >6 nm/1000ft a_Z load maxima, which occurred after the vortex-induced upset during manual recovery, from an A380 order of circulation are impressive, of the order of limit loads, +2.5g/-1g. However, due to the limitations of flight simulators' motion systems, it can be expected that in real-life encounters pilot reactions would be less aggressive, which would result in larger altitude deviations (separation violations, TCAS alerts). Although the pilot set of 3 limits statistical inferences (and none is claimed); it is a useful pilot set, as it would appear to contain a wide range of pilot psychological decision-making paradigms, therein termed 'AP-trusting' (believes AP-engaged is the best WVE strategy), 'static' (disengages AP if static Euler angular displacements are exceeded) and 'dynamic' (disengages AP often, for concern of AFCS failure or aggravated response, very much a pilot-in-the-loop paradigm). Nevertheless, the results highlight issues:- *e.g.*, pilot's unawareness of the magnitude of linear accelerations in the flight simulator

and possibly, a primary concern on uncommanded bank-angle induced spiral departure (notably, height-above-ground for a recovery from banked-flight to wings-level); Structural engineers would have different concerns (perhaps fuselage bending) and cabin crew, high sensitivity to negative-g (the latter is observed here at the NRC on microgravity flights, all manually flown in the Falcon 20, with a target tolerance of $\pm$0.025g. An exceedance to -0.05g usually raises comment from the cabin crew. Nevertheless, all such parameters of concern are included in the Airbus VESA too. [insertions by Luckner].

First, let me comment on your synopsis of the Luckner / Reinke paper. I agree with Robert's comments: maximum aircraft state deviations seen in the simulator – especially those developing during recovery - must be interpreted with care since the accelerations of the simulator cabin can be far from realistic, especially for large amplitudes. Concerning the encounter strength at altitude, please be aware that while circulation levels in cruise are of the same order of magnitude as during approach, the same applies for direct aerodynamic effects on the encountering aircraft and they are not necessarily greater. [inserted by Reinke].

2.1.7 Lelaie provided an Oral Presentation on further details from the A380 Wake Vortex Flight Test program. It has been the most comprehensive WVE program ever, and is on-going, at least for analysis. Although proprietary data, Airbus have been able to progressively release to the technical community, more details from the flight testing – details which highlight the variability of such testing, and the difficulties of trend analysis within data-sets that contain relatively high standard deviations. Nevertheless, the Airbus philosophy arguably uses the correct parametric analysis that must be applied to eventual WVE design requirements – it is after all, the product of vortex-induced wind speed and air density, that provides aerodynamic force generation – the response to which, for the WVE aircraft, is acceleration, whether angular, such as roll, or linear such as a_Z or a_Y. On the latter, the developed sideslip angles during the Airbus WVE test points, albeit in Direct law, were impressive, in the range of 10-13 degrees.

2.1.8 The industries' military tactical aircraft engineers and test pilots were unable to join the Session. Brown gave a brief run-down on the WVE experience of military aviation, such as it may benefit civil aircraft WVE, which have always been designed and operated on a philosophy of wake avoidance. On the other hand, military tactical aircraft, whether transport or fighters, have had to operate with WVE probabilities of one: yet, without any formal design requirements. The result, for agile neg-stab FBW fighters has typically been problematic responses to WVE during OT&E, requiring FCS modification. Tactical transport have had to be cleared for minimum time takeoffs, an example being the OT&E clearance for C-17s, requiring takeoffs through the wingtip vortex of the preceding aircraft.

3. TUESDAY AFTERNOON, MANAGING WAKE VORTEX ENCOUNTER II – WAKE VORTEX TRANSPORT AND DECAY

3.1.1 Whereas ameliorating aircraft response to WVE is the ultimate design goal (to which Monday's presentations were directed), understanding the operational scenarios wherein WVE probabilities are significant and the nature of the vortex flowfields involved in such WVE, will ultimately provide the gust-field specification for design and then, for Type Design Certification or Qualification. After all, atmospheric turbulence design requirements have long been based upon (a) a discrete gust size, speed and shape, and (b) a continuous-turbulence gust spectra. Thus it will be for WVE Design, as it is now for *ad hoc* WVE design for fighter aircraft. On

Tuesday, we were treated to a number of first-class presentations, which demonstrated advancements and new approaches in computational understanding, particularly in relation to WV deformations, sensing technology, and dataset analysis.

3.1.2 Lai *et al* of NWRA presented upon usage of a LIDAR simulator, for the estimation of LIDAR positional-sensing accuracy. In engineering measurement technology, there are few instruments which are not, at first, calibrated before undertaking measurements. Unfortunately, WV LIDAR is one such sensor – the inference of Doppler velocities relies upon laser behavioural theory. Thus although the simulator is arguably 'bootstrap' and is tied to a non-turbulent B-H WV velocity profile. Nevertheless, it has provided insight into theoretical positional accuracy that might be applicable when vortex centre locations are derived from LIDAR measurements. Further insight might be available, if vortex profile sensitivity analysis were to be conducted – such as examining tool performance against a potential vortex profile, and against turbulent vortices, particularly where the turbulence is coherent, in the form of superimposed vortex elements outside the vortex cores.

3.1.3 Kato *et al* presented on the topic of Data mining of WV data-sets from terminal area LIDAR measurements, for correlating WV transport. In this case, the LIDAR data is from approaches and departures at Sendai Airport, Japan. Correlation identification techniques, including rough set theory, were used against an expanded set of atmospheric parameters, which included Richardson Number and the vertical gradient of potential temperature – parameters used to characterize the stability of the atmosphere. Although these are still bulk quantity parameters (as opposed to spectrally-discrete parameters – which have never been used for correlation), nevertheless, to expand the parameter-set in such a way is lateral thinking, no less. For example, the authors found that that humidity correlated with 'updraft' vertical advection, which might be an enlightening finding. Hopefully, such correlative work can continue. On other fronts, such techniques might find application, in the correlation of flight data, such as the large datasets of Airbus.

3.1.4 Wassaf and Wang also presented upon terminal area WV dataset analysis, from the perspective of the association between vortex circulation and survival probability, in forward and reverse analysis processes. These are statistical treatments, applicable to ensemble WV datasets, by way of PDF(Γ,t). The reverse process of inferring circulation is illustrated by Monte Carlo simulation, using, for closure, a selected Γ decay model. Resultant 10^{th} and 90^{th} percentiles covered a broad range of Γ - such that, in the future, examples of the technique in supporting operational procedures research would be beneficial to the community.

3.1.5 Proctor *et al* presented upon 3-phased decay modeling of wake vortex decay, within the atmospheric variables of turbulence and stratification. It is an exciting example of the progress in the computational analysis of WV behaviour – LES OGE solutions, using TASS, being developed to the point of detailing and classifying an additional phase of WV decay, namely that associated with the ring vortex stage, following vortex linking – characterized by a relatively slow rate of circulation decay, and initiating at circulations within the range of Γ/Γ_O=0.4 to 0.5. This finding can be incorporated into the TDAWP model. Vortex core radius is covered by 3 cells. In vorticity iso-surfaces format, the solutions depict vortex ring connector filaments, which appear to emanate from helical vorticity which is shown to develop in the downstream direction, over the second half of sequential vortex rings. As such, these flow-field solutions contain secondary vortex elements of significance – which might also be of significance in their velocity and scale-size content. Hopefully velocity field information could at some point be extracted from the solutions.

3.1.6 For this work, an improved WV tracking algorithm has been developed, the work of which was presented by Switzer *et al*. Tracking multiple vortex positions and calculating the associated circulations is accomplished by defining Regions of Interest around each vortex. Examples of ROI tracking were presented for single and multiple aircraft, in terms of vorticity iso-surfaces. In relation to the above comment on velocity field information, it should be possible that ROIs would also provide a mechanism to facilitate the extraction of Velocities and Scale-Sizes of Interest, VSOI!

3.1.7 Holzäpfel et al. presented new aspects of WV decay behavioural processes, as implied by computational analysis, using two different LES codes. It is another example of the contemporary extension of LES computational sophistication, to the point of supporting hypotheses on decay processes. As above, the solutions exclude any internal core deformation dynamics, because core radii are approximately 3 cells,making the Nyquist cell-size 1 x r_C . Lamb-Oseen profiles were used – which have velocity defect some way between potential and B-H. A vortex-centre identification technique was applied in post-processing. Three-phase circulation decay characteristics are reported in neutral to weak stratification. The third phase corresponding to long-lived vortex rings. These findings are very similarly to the description given by Proctor in the previous talk. It is further found that the integral turbulence length scale (as long as it is smaller than the initial vortex separation b0) may have a quite pronounced effect on the circulation decay rates in the diffusion phase. During this first phase vortex decay is related to stretching of environmental vorticity. Depending on the environmental conditions all possible decay characteristics like one-phase, two-phase, and three phase decay are observed. Particular solution phenomena the paper addresses are secondary vortex rings and axial 'bursting'. For the latter, reference is made to the earlier work and observations of Spalart, which, it is fair to say, have not yet been understood. This is an example of the importance of maintaining a tradition of hindsight of historical aeronautical research – time will tell if it is significant, only if it is addressed (at the NRC, this is the case for the smaller-scale vortex elements of greater velocity that have been disclosed by the contemporary flight measurements, and yet were discovered outside vortex cores in the earlier 1969 NRC research and rationalized to have a helical character, there – similar to the solutions of Proctor, Holzapfel and others, with the vortices in non-linked and quite undeformed states.) Therefore, what is interesting in the Holzapfel solutions, being decoupled from vortex core dynamics, are the apparent presence of axial cellular flow, causing 'bursting' concentrations of mass-less tracers at 'collision' points of secondary vortices – interesting because on the one occasion where contemporary NRC flights experienced these condensation patterns (26^th May 2006, A310), the discs were in-phase with apparent vortex funnel condensation features within the cores. [incorporating additional sentences by Holzäpfel]

3.1.8 Furthermore, similar as in the NRC research, the vortex bursting phenomenon was observed in the LES prior to vortex linking [Holzäpfel].

3.1.9 As to secondary rings, is this an example (from YouTube!)?

http://www.youtube.com/watch?v=ppMyI5xcVpg

3.1.10 De Visscher *et al*. presented a global overview of the WAKE4D platform and its sub-models DVM and PVM. The platform is an operational tool, deterministic or probabilistic, that uses the DVM or PVM models in multiple computational gates to forecast the wake vortex behaviour (transport and decay), also for complex scenario. Those models have been calibrated and validated using results of LIDAR measurements and LES results. An example of WAKE4D-DVM was presented which is a simulation of the Marseille STAR trajectory with turns and finally precision approach segments. Some examples of past and future potential applications of such platform were shown with an accent towards WVE studies. First, in the same way as it was used for the TBS and WIDAO studies, it can be used for off-line fast-time comparative risk analyses of potential WVE studies. The simulated 3-D wake vortices can also be used for WVE analysis in a flight simulator. Two post-processing routines were shown that enables the real-time evaluation (e.g., 10 times per second) of the 3-D induced velocity field at arbitrary points in 3-D space (e.g., typically 100 points for aircraft dynamics in a flight simulator). The first routine enables the simulation of complex trajectory (with turns, take-off, etc.); the second takes into account the wake deformation (Crow instability) . The computed velocity fields are similar to those obtained by LES, yet of course they constitute a RANS view of the velocity field. De Visscher et al. also performed LES of vortices evolving in a turbulent and/or stably stratified atmosphere. The results of a fine grain LES (512^3 LES on (8 b_0)^3 box, pseudo-spectral non-dissipative code, very high Re vortices with multiscale SGS model, 6 points across the vortex core diameter) of wake vortices evolving in a weakly turbulent atmosphere and with Crow instability development, reconnection and further decay were also presented (although not put in the paper which focused on WAKE4D). An example of velocity field as extracted from this LES was also shown: it too can be used efficiently in a flight simulator, eventually with some filtering (e.g., to 128^3 field) so as to be able to access the required evaluation points in real-time. One also observed the bursting of the vortices at reconnection and also after, with the propagation of a helical waves from the reconnection point through the whole vortex ring. [replacement paragraph by Winckelmans, Chatelain & De Visscher].

4. WHERE TO NOW?

4.1.1 I feel that we should endeavour to continue to take steps to design and qualify, then certificate, aircraft for an acceptable level of WVE. In those steps, I offer the following suggestions to the continued necessary elements of research of (1) AIM and WVE Management Systems, (2) Simulator Experiments, (3) remote-sensing, LIDAR, (4) WV behavior, and (5) flight data, in-situ:-

(1) AIM & WVE Management Systems, such as IRLIS

- Conduct velocity profile sensitivity analyses, potential and B-H might be two limit cases;
- Conduct deformed vortex sensitivity analyses, namely simultaneous tri-axial profiles;

(2) Simulator Experiments

- Simulator studies are an important effort, but limitations are WV model and mechanical response;
- Apply to the development of pilot-behavioural models, for both 'surprise' and 'anticipated' WVE (arguably, AA587 was in the latter category);
    - Simulator studies are the only option (a) for systematic parameter variations, i.e. sensitivity analysis (e.g. to study the impact of variations in core radius, tangential velocity profile, vortex strength etc) or worst-case search, (b) for risk assessments (e.g. for modified separation minima, RECAT) that are required in the "Safety Case"
    - Effort is needed (a) to validate the simulation models (aerodynamic interaction model (AIM) and vortex models that are used in the flight simulator, (b) to validate the pilot models (behavioral models and severity assessment models) that are developed from flight simulator results.
    - A comparison of pilot behavior in a flight simulator WVE with his behavior in an identical WVE in an aircraft (artificially generated in bootstrap mode, e.g. DLR's VFW614-ATTAS) is recommended as a potential option for pilot model validation. [inserted by Luckner].
    - We support the comments of Luckner [inserted by Hahn, Schwarz *et al*].
    - Luckner's additions above are correct and necessary. Note in this context that data to validate aerodynamic interaction and vortex models can only be gathered from WVE F/T. [inserted by Reinke].

(3) Remote-sensing LIDAR

- Apply velocity profile sensitivity analysis to the LIDAR simulator tool (some reductions have used the potential profile for vortex positioning);
- Apply closed path integral analysis to circulation identification, rather than assumed B-H profile fits [a 5-15m velocity profile identification might be typically applied to a particular profile shape, generally a B-H profile, for circulation identification; *in lieu* of a profile-fit, a closed-path integration of LIDAR-sensed Doppler velocity could be undertaken, as it has been, for flight data];
- Develop a Lab calibration procedure;
    - On the usage of remote-sensing LIDAR, generally:- Lidar does not require a calibration procedure, the sensed velocities are basically very accurate. The challenge lies in the small volume of air where the maximum tangential velocities (in particular close to the vortex core) prevail compared to the range gate (sensing volume) of the pulsed lidar beam. The difficulty is to set the signal to noise ratio that differentiates between physical velocities and noise. For this

some kind of calibration is necessary but I do not see how this could be done in a Lab – [inserted by Holzäpfel].

- Inter-compare in flight, using simultaneously, an airborne LIDAR platform (such as the DLR Falcon FA20) and an in-situ platform (such as the NRC T33);
    - Airbus F/T results indicate that vortex circulation alone falls short of predicting wake-induced upsets. F/T results and model calculations indicate that the vortex core radius plays a relevant role. Hence more focus on measuring and modeling of vortex core radii is required (e.g. simulation of LiDAR accuracy in measuring vortex core size, improved reproduction of vortex core size in numerical analyses). [inserted by Reinke].
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(4) WV behaviour, in temporal order

- Extract velocity field information! (compare to flight data)
    - Usually, vorticity is shown because this is more intuitive in order to understand the different phenomena. Field velocity data is the basis of the vorticity calculations and is directly available. What could be done is to mimic the flight path of the aircraft in the simulation domain and to extract the velocities along the aircraft track. These could be compared to velocity profiles extracted from planes perpendicular to the vortex axis– [inserted by Holzäpfel].
    - The 3-D velocity fields are indeed directly available from the LES. Some filtering of the database would obviously be needed to enable a real-time evaluation (for flight simulator studies for instance). The LES databases are thus certainly very helpful in that respect, as they contain all the required detailed information on the velocity field (also the turbulence); yet as they are expensive in computational time, they are not available for many configurations. Notice also that the case of combined “weak turbulence and weak stratification (N*=0.35)” was also done by UCL : it also leads to a Crow instability yet with more turbulence than without stratification and more destructions of the vortices by the stratification effects. The use the induced velocity fields computed from the WAKE4D model results, also with Crow up to the time of reconnection (see above) are also an alternative for flight simulator studies. It also provides a fast-time tool to investigate various scenarios. [inserted by Winckelmans, Chatelain & De Visscher]
    - I agree that what is really needed are velocity data since only these have a relevant impact on the encountering aircraft. Still, some sort of parameterization is required and to me a set of (1) circulation, (2) core radius, (3) vortex spacing and (4) tangential velocity model function forms the right level of detail while remaining sufficiently general. We may anyhow have to add parameters to evaluate encounters with older, curved or ring-state wakes. [inserted by Reinke].
- Look for dynamic-coupling atmospheric parameters (i.e. dynamic field characteristics, whose spatial or temporal frequencies might resonate with vortex dynamics, resulting in growth of particular instabilities), not just EDR & BV (EDR is a bulk scalar quantity; the above LES solutions output $8b_V$ linking, yet flight data have a range of Crow wavelengths, with 4 and 6 b_V being more prevalent);
    - I am not sure what you mean with dynamic-coupling atmospheric parameters. Note that in the simulations the Crow wavelengths are largely controlled by the size of the simulation domain. Different domain sizes lead to different wavelengths. Once the domain is larger than several Crow wavelengths (which is extremely challenging) the wavelengths for linking may develop freely. [inserted by Holzäpfel].
    - LES of wake vortices in a (4 b_0)^3 domain were also been performed at UCL, with the same conditions as mentioned above: weak turbulence and various

stratification level: form none to very high (N*=0, 0.35, 0.75, 1.0, 1.4). Even for the case without stratification there is no Crow instability developing. The vortices generate their own turbulence and then decay slowly, yet no reconnection of the vortices occurs. The size of the computational domain thus influences the development of the long wave instabilities but those instabilities do not necessarily grow up when the box is (4 b_0)^3. We have not tested the case (6 b_0)^3. [inserted by Winckelmans, Chatelain & De Visscher.

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- Core grid scale down-sizing, to capture & couple vortex core dynamics (funnel vortex features not explained); can this be done with LES? even the immense DNS solutions of Chatelain *et al* fixed the core profiles as Gaussian; separate non-linear vortex stability studies?
  - It looks like the global wake evolution (radii averaged circulation and trajectories) does not depend too much on the vortex core size and its resolution (see very similar results of Protor's and Holzaepfel's simulations). It appears not feasible to simulate simultaneously highly resolved vortex cores and realistic ambient atmosphere. With dedicated studies it could be feasible to simulate the generation of funnel vortex features. But this would certainly not be easy and is of rather academic interest for the general wake vortex research. On the other hand, it could prove the high maturity and capabilities of our tools and our understanding of the problem. [inserted by Holzäpfel].
    - It is important to distinguish three major parameters in wake vortex simulation setup:- the chosen circulation distribution profile (e.g., Gaussian, Burnham-Hallock, Proctor-Winckelmans), the size of the effective core (typically taken in simulations as 5% of b0),and the resolution of the simulation.
    - In the DNS of Chatelain et al. (Chatelain recently joined UCL by the way), they were interested in DNS of a low Reynolds number case (Re=5000), and for a 4-vortex counter-rotating system (not realistic aircraft wake, yet interesting from the academic point of view and also investigate in AWIATOR and FAR-Wake). Hence, as is a usual choice for low Re, they initialised the simulation with a Gaussian vortex, yet with a realistic 5% core size. The instabilities in the 4-vortex counter-rotating system lead to the creation of very small structures. As this simulation is a DNS, those structures must be properly captured. The grid size is then determined by the size of the small structures, not by the core size, and certainly not by the chosen circulation distribution profile. In that simulation, the core was discretized using 22 grid cells (thus very well resolved initially). The generation of fine structures and high vorticity reduce this "over-resolution" somewhat later in the simulation; this can be seen in the plot of the dissipation error (Fig. 4 of the paper). It must be stressed that this simulation was at Re=5000, which is far below reality.
    - In LES of very high Re wake vortices, with multiscale SGS modelling and with high accuracy codes (also negligible numerical dissipation) it has been shown, also by UCL, that a typical resolution of 3 grid points within the effective radius r_c (thus 6 within the effective core of size 2*r_c) is indeed sufficient to properly capture both the vortex global dynamics and also a significant part of the inner core dynamics (inertial waves, vortex bursting events at least to some extent (e.g., well seen in the LES by UCL of wake vortices with Crow mentioned above). Of course, not all details are captured. Obviously, if one wants to capture even smaller scales than those already captured, the grid must be refined.

- It is important to stress that a quality SGS model is essential for those kinds of applications, together with a quality numerical method. Even with a good numerical method and a fine grid, a too dissipative SGS model (e.g., Smagorinsky without vortex correction) artificially diffuses not only the vortex core size r_c itself, but also the small and important structures generated by the vortex dynamics and reconnection, leading to an artificial wake vortex decay.
- Now, as to the issue of the choice of the core size: we too use r_c/b0=0.05; which, by the way, is actually quite good as this corresponds to r_c/b = 0.04, a value close to what is “believed” to be the effective core size of a well-developed and turbulent wake vortex system, at least in the far wake. Of course, this is still an open issue, and it could be that the effective core size of aircraft vortices from a clean wing configuration (e.g., cruise) is twice smaller, even in the far wake: r_c/b = 0.02 ?
- It would indeed be quite difficult to perform simulations with say r_c/b=0.02; yet this is not impossible: for our (8 b_0)^3 simulation, this corresponds to going from a 512^3 to a 1024^3 simulation: something we have already done in another context of a Ph.D. (study of the Taylor Green vortex). [inserted by Winckelmans, Chatelain & De Visscher].

(5) Flight data, in-situ

- Undertake oblique traverses, to discretise (rather than horizontal-ensemble) core profiles [NRC vortex core flight data has been obtained essentially *in-trail*, wherefore vortex core traverses have been commenced bottom-centre below the cores, and flown upwards, in the axial direction – obtaining 600 data points, approximately, for the 1-second traverse – in which time the aircraft flies about 210 m in the axial direction – so the core traverse ‘ensembles’ axially-dependent variations in core characteristics, over this axial distance; oblique, or ‘cross-track’ traverses will be much quicker, therefore have fewer data points – 30 to 60 – but not the axial variations – a loss of resolution, but more a ‘slice’ of core rather than an axial ensemble of core];
- Inter-compare simultaneously with LIDAR (possibly ground based LIDAR for approach situations and airborne LIDAR for cruise). [inserted by Hahn *et al*].

4.1.2 **WHILST** these suggestions might refine WVE research, they do not provide a clear path to implementation; the following path is proposed as an example of implementation:-

- use an effort that parallels the long-standing design requirements for turbulent atmospheres;
- by necessity, designers require velocity data – definitions of velocity data reqts come from closing (4) above with (5)-(3) – therefore, make this the research emphasis;
- let industry drive – in particular, an airframe OEM; **HOW:-**
  - use an incremental approach;
  - design a Full-Authority, Full-Time Gust Alleviation System, FAFTGAS! (this has been done by our tactical fighter designers, e.g. Eurofighter Typhoon WVE fix)
  - prove the FAFTGAS, by analysis and flight (incremental)
  - the proven FAFTGAS provides credit – permits the aircraft to move up in category, i.e. a Medium with FAFTGAS is treated as a HEAVY, for it as the follower-aircraft;
  - Concerning FAFTGAS: of course, good idea. But I am not yet convinced that one alleviation method to fit all sorts of gusts or turbulence is the optimum.

- I do not support the idea of “certifying” aircraft for an acceptable level of WVE. Still, reducing aircraft vulnerability to wake encounters may be feasible and could qualify for reduced separation requirements in the context of pair-wise separation schemes. Modern flight control laws as used in Airbus aircraft already provide improved aircraft stabilization but today there is no agreed metric taking this into account. Circulation alone is certainly a bad choice in this regard. [inserted by Reinke].
- Finally, Airbus - given several years of activities and a unique data base of measurements – is certainly a suitable candidate to drive research efforts. Still, since our activities are driven by the needs of our customers and occur in a competitive environment, there are limits to what can be shared. [inserted by Reinke].

4.1.3 **Which OEM and aircraft?** Possibly, Airbus, retroactively – the A320 gust alleviation system does seem high-authority, from accident analyses conducted by Airbus, by myself, and from Claude’s observations that Normal Law strongly suppresses WVE responses. Possibly Bombardier, the C-Series might be ripe for the timing.

4.1.4 **Co-ordination and Collaboration?** We have increasing concerns expressed on RVSM WVE; we have continuing needs to increase terminal area aircraft density. On research, we have DLR imminently undertaking Medium Category WVE flight tests with its Falcon FA20; we have the NRC continuing flight profile development and WV/emissions research flights; we have Holzapfel, Proctor, Winckelmans and others continuing WV modeling efforts. All such research efforts are expensive and bespeak a desire to collaborate, in order to value-add and maximize the benefit of such research – e.g. one example, by organizing an experiment which combines LIDAR, in-situ, WVE response, WV modeling, to provide a closed-loop of research, (4)-(3)-(5).

4.2 APPENDIX A – SESSION AGENDA

Monday, 2 August 2010

37-ASE-2 — **Ice Accretion Physics and Modeling**

Chaired by: J. TSAO, Ohio Aerospace Institute, Cleveland, OH — **Conference Room C**

1400 hrs	1430 hrs	1500 hrs	1530 hrs	1600 hrs	1630 hrs	1700 hrs	1730 hrs
AIAA-2010-7670 **Experimental Observations on the Deformation of Water Droplets Near the Leading Edge of an Airfoil** M. Vargas, NASA Glenn Research Center, Cleveland, OH; A. Feo, National Institute of Aerospace Technology (INTA), Madrid, Spain	AIAA-2010-7671 **Comparison of Experimental and Computational Ice Shapes for an Engine Inlet** M. Papadakis, Wichita State University, Wichita, KS	AIAA-2010-7672 **Heat Transfer on Iced Cylinders** L. Stefanini, O. Silvares, University of São Paulo, São Paulo, Brazil; G. da Silva, Ats4i Aero-Thermal Solutions for Industry, São Paulo, Brazil	AIAA-2010-7673 **Ice Accretion Model on Multi-Element Airfoil** F. Petrosino, G. Mingione, A. Carozza, Italian Aerospace Research Center (CIRA), Capua, Italy; T. Gilardoni, Piaggio Aero Industries s.p.a., Genoa, Italy	AIAA-2010-7674 **Mixed Phase Modeling in GlennICE with Application to Engine Icing** W. Wright, ASRC Aerospace Corporation, Cleveland, OH; P. Jorgenson, NASA Glenn Research Center, Cleveland, OH	AIAA-2010-7675 **Super Cooled Large Droplet Analysis for Several Geometries Using LEWICE3D Version 3** C. Bidwell, NASA Glenn Research Center, Cleveland, OH	AIAA-2010-7676 **Eulerian Modeling of SLD Physics Towards More Realistic Aircraft Icing Simulation** E. Iuliano, G. Mingione, Italian Aerospace Research Center (CIRA), Capua, Italy; C. de Nicola, University of Naples "Federico II", Naples, Italy	AIAA-2010-7677 **An Eulerian Approach to Three-Dimensional Droplet Impingement Simulation in Icing Environment** E. Iuliano, Italian Aerospace Research Center (CIRA), Capua, Italy; F. De Domenico, C. de Nicola, University of Naples "Federico II", Naples, Italy; G. Mingione, Italian Aerospace Research Center (CIRA), Capua, Italy

Monday, 2 August 2010

38-ASE-3/AFM-6 — **Managing Wake Vortex Encounter I (Invited)**

Chaired by: A. BROWN, National Research Council, Gloucester, Canada and F. PROCTOR, NASA Langley Research Center, Hampton, VA — **Conference Room B**

1400 hrs	1430 hrs	1500 hrs	1530 hrs	1600 hrs	1630 hrs	1700 hrs	
AIAA-2010-7678 **On the Specification of Wake Vortex Encounter Gust-Fields from Flight Data** A. Brown, National Research Council, Gloucester, Canada	AIAA-2010-7679 **Wake Encounter Severity Assessment Based on Validated Aerodynamic Interaction Models** C. Schwarz, K. Hahn, D. Fischenberg, German Aerospace Center (DLR), Braunschweig, Germany	AIAA-2010-7680 **Wake Encounter Flight Control Assistance Based on Forward-Looking Measurement Processing** K. Hahn, German Aerospace Center (DLR), Braunschweig, Germany VRLIS	AIAA-2010-7681 **Characterizing a Wake-Free Safe Zone for the Simplified Aircraft-Based Paired Approach Concept** N. Guerreiro, ATK, Hampton, VA; K. Neitzke, S. Johnson, H. Stough, B. McKissick, H. Syed, NASA Langley Research Center, Hampton, VA	AIAA-2010-7682 **Progress on Joint FAA/Eurocontrol Efforts to Develop an ICAO Wake Turbulence Re-Categorization** S. Lang, J. Tittsworth, W. Bryant, Federal Aviation Administration, Washington, DC; C. Lepadatu, Eurocontrol, Brussels, Belgium; D. Delisi, D. Lai, NorthWest Research Associates, Redmond, WA; G. Greene, Consultant, Hampton, VA	AIAA-2010-7683 **Pilot Models for Simulation of Wake Vortex Encounters in Cruise** R. Luckner, A. Reinke, Technical University of Berlin, Berlin, Germany	AIAA-2010-7684 **Airbus Encounters Flight Tests and Analysis Methods** C. Lelaie, Airbus, Toulouse, France	

Monday, 2 August 2010

39-GNC-14 — **Adaptive Control Theory II**

Chaired by: F. MORA-CAMINO, National Center for Scientific Research (CNRS), Toulouse, France and E. LAVRETSKY, The Boeing Company, Los Angeles, CA — **Peel**

1400 hrs	1430 hrs	1500 hrs	1530 hrs	1600 hrs	1630 hrs		
AIAA-2010-7686 **An Output Feedback Model Reference Adaptive Control Law** K. Kim, T. Yucelen, A. Calise, Georgia Institute of Technology, Atlanta, GA; B. Yang, Guided Systems Technologies Inc., Stockbridge, GA	AIAA-2010-7687 **L1 Adaptive Control Augmentation System with Application to the X-29 Lateral/Directional Dynamics: A Multi-Input Multi-Output Approach** B. Griffin, J. Burken, NASA Dryden Flight Research Center, Edwards, CA	AIAA-2010-7688 **Input and Output Performance of M-MRAC in the Presence of Bounded Disturbances** V. Stepanyan, K. Kalmanje, NASA Ames Research Center, Moffett Field, CA	AIAA-2010-7689 **An Adaptive LQ-Based Control Design with Parameter Projection Applied to the NASA GTM** J. Guo, S. Narkhede, G. Tao, University of Virginia, Charlottesville, VA	AIAA-2010-7690 **Immersion and Invariance Based Nonlinear Adaptive Flight Control** L. Sonneveldt, E. van Oort, Q. Chu, J. Mulder, Delft University of Technology, Delft, The Netherlands	AIAA-2010-7691 **Development of Verification and Validation Approaches for L1 Adaptive Control: Multi-Criteria Optimization for Filter Design** N. Hovakimyan, K. Kim, University of Illinois, Urbana, IL		

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Tuesday, 3 August 2010

92-ASE-6 — **Icing Effects Evaluation and Simulation** — Conference Room C

Chaired by: D. MARCOTTE, Ottawa, Canada and P. STRUK, NASA Glenn Research Center, Cleveland, OH

1400 hrs	1430 hrs	1500 hrs	1530 hrs	1600 hrs			
AIAA-2010-7983 **Computational Prediction of Propeller Performance in Icing Conditions** G. Busch, M. Bragg, University of Illinois, Urbana-Champaign, Urbana, IL	AIAA-2010-7984 **Simulation of Ice Shedding Around an Airfoil** H. Beaugendre, University of Bordeaux, Bordeaux, France; F. Morency, École de Technologie Supérieure, Montréal, Canada; F. Gallizio, Optimad Engineering, Turin, Italy	AIAA-2010-7985 **Prediction of Rotor Blade Ice Shedding Using Empirical Methods** J. Cajigas, J. Bain, L. Sankar, Georgia Institute of Technology, Atlanta, GA; R. Flemming, Sikorsky Aircraft Company, Stratford, CT; R. Aubert, Bell Helicopter Textron, Fort Worth, TX	AIAA-2010-7986 **Dynamic Wind-Tunnel Testing of a Sub-Scale Iced S-3B Viking** S. Lee, ASRC Aerospace, Cleveland, OH; B. Barnhart, Bihrle Applied Research, Hampton, VA; T. Ratvasky, NASA Glenn Research Center, Cleveland, OH	AIAA-2010-7987 **Piloted Simulation to Evaluate a Real-Time Envelope Protection System for Mitigating In-Flight Icing Hazards** R. Ranaudo, B. Martos, B. Norton, University of Tennessee Space Institute, Tullahoma, TN; B. Barnhart, D. Gingras, Bihrle Applied Research, Inc., Newport News, VA; T. Ratvasky, NASA Glenn Research Center, Cleveland, OH			

Tuesday, 3 August 2010

112-ASE-9 — **In-Flight Icing Weather Forecasting** — Conference Room C

Chaired by: M. POLITOVICH, National Center for Atmospheric Research, Boulder, CO and T. BOND, Federal Aviation Administration, Washington, DC

					1630 hrs	1700 hrs	1730 hrs
					AIAA-2010-8109 **Potential Upgrades to the Current and Forecast Icing Algorithms** M. Politovich, C. Wolff, F. McDonough, J. Haggerty, National Center for Atmospheric Research, Boulder, CO; H. Kenneth, National Severe Storms Laboratory, Norman, OK	AIAA-2010-8110 **Using Icing Algorithm Output to Create AIRMETs** C. Wolff, P. Prestopnik, M. Politovich, F. McDonough, National Center for Atmospheric Research, Boulder, CO; C. Wallace, J. Levit, Aviation Weather Center, Kansas City, MO	AIAA-2010-8111 **The Global Forecast Icing Product** F. McDonough, C. Wolff, M. Politovich, National Center for Atmospheric Research, Boulder, CO

Tuesday, 3 August 2010

93-ASE-7/AFM-16 — **Managing Wake Vortex Encounter II - Wake Vortex Transport and Decay (Invited)** — Conference Room B

Chaired by: F. PROCTOR, NASA Langley Research Center, Hampton, VA and A. BROWN, National Research Council, Gloucester, Canada

1400 hrs	1430 hrs	1500 hrs	1530 hrs	1600 hrs	1630 hrs	1700 hrs	1730 hrs
AIAA-2010-7988 **Assessment of Pulsed Lidar Measurements of Aircraft Wake Vortex Positions Using a Lidar Simulator** D. Lai, NorthWest Research Associates, Redmond, WA; D. Jacob, Lockheed Martin Corporation, Louisville, CO; D. Delisi, NorthWest Research Associates, Redmond, WA	AIAA-2010-7989 **Data Mining for the Advection Database of Wake Vortices** H. Kato, K. Shimoyama, S. Obayashi, Institute of Fluid Science Tohoku University, Sendai, Japan; M. Kudo, Electronic Navigation Research Institute, Chofu, Tokyo, Japan	AIAA-2010-7990 **Inferring Aircraft Wake Vortex Circulation from Survival Probability Using a Data-Driven Probabilistic Inverse Model** H. Wassaf, F. Wang, U.S. Department of Transportation, Cambridge, MA	AIAA-2010-7991 **Three-Phased Wake Vortex Decay** F. Proctor, N. Ahmad, NASA Langley Research Center, Hampton, VA; G. Switzer, AS&M, Inc., Hampton, VA	AIAA-2010-7992 **Wake-Vortex Topology, Circulation, and Turbulent Exchange Processes** F. Holzäpfel, I. Hennemann, T. Misaka, T. Gerz, German Aerospace Center (DLR), Wessling, Germany	AIAA-2010-7993 **An Improved Wake Vortex Tracking Algorithm for Multiple Aircraft** G. Switzer, Analytical Services & Materials, Inc., Hampton, VA; F. Proctor, NASA Langley Research Center, Hampton, VA; F. Limon Duparcmeur, Eagle Aeronautics, Inc., Hampton, VA	AIAA-2010-7994 **The WAKE4D Simulation Platform for Predicting Aircraft Wake Vortex Transport and Decay: Description and Examples of Application** I. De Visscher, G. Winckelmans, T. Lonfils, L. Bricteux, M. Duponcheel, N. Bourgeois, Catholic University of Louvain, Louvain-la-Neuve, Belgium	AIAA-2010-7995 **Calculation of Parameters for the Near Area of the Aircraft Far Wake by the Method of Discrete Vortices** L. Turchak, A. Belotserkovskiy, Dorodnitsyn Computing Center, Moscow, Russian Federation