The Second UK State Consultation on a Harmonised Transition Altitude (TA):

NVSM - Nominal Vertical Separation Minima Safety Report

CAP 1349 - 9

Civil Aviation Authority

UK State TA Project Safety Report

on

Nominal Vertical Separation Minima

20150724-Consultation Nominal VSM Final Safety Report

24 July 2015

NOMINAL VERTICAL SEPARATION MINIMA SAFETY REPORT

ISSUE

1 The implementation of a raised UK Transition Altitude generates challenges in the maintenance of an absolute 1 000ft separation at all times between interacting airport departures and arrivals operating on aerodrome QNH, and interactions with aircraft cruising on the Altimeter Setting Region QNH. It has been identified that the constrained application of a nominal Vertical Separation Minima[1] (VSM) would be of significant benefit.

2 The technical content of this paper was developed on a 'MOCOR 3'[2] basis within the joint project, and has been endorsed by the Transition Altitude (TA) Steering Group and independent specialists within the CAA's Safety and Airspace Regulation Group (SARG)[3] and subsequently approved by the CAA's SARG. It presents an overview of progress, consolidates all evidences gained, and outstanding issues related to the delivery of nominal Vertical Separation Minima (VSM). This concept is a core element of the TA project and is a safety significant change that impacts on the CAA and Air Navigation Service Providers (ANSP) alike and for which detailed and careful analysis is required to ensure an acceptably safe implementation of a raised TA.

BACKGROUND

3 Work conducted in January 2014 by the joint Project highlighted the challenges posed by the maintenance of 1 000 ft standard vertical separation between:

a. Interacting multiple airport departure and arrival procedures, which require the specific airport QNH to be set, whilst for separation purposes treating the differing QNH as being one and the same within a given tolerance band; hence the term 'QNH tolerance'.

b. Interaction of aircraft cruising on the ASR QNH with aircraft operating on specific airport QNH whilst flying arrival and departure procedures.

4 As a result of this work, a proposal was made of a conceptual safety argument on the viability of utilising VSM of a nominal 1 000 ft within controlled air space (CAS), caused by the use of a QNH tolerance of up to 6 hPa between aircraft altimeter settings. An endorsement in principle for this concept of nominal VSM was provided by CAA SARG in March 2014 to enable further development work to take place. This endorsement was given, subject to the completion of additional works to:

a. Model aircraft Airborne Collision Avoidance System (ACAS) interactions to determine the effects of operating with a QNH tolerance band on ACAS event susceptibility and to demonstrate that there would be no increase in ACAS events attributable to this change.

b. Conduct validation simulation of the aircraft interactions that demonstrate that the concept of operations and associated procedures are acceptably safe.

[1] A nominal VSM exists when aircraft are assigned cruising altitudes separated by 1000ft but where the aircraft are operating with a variance of up to 5 hPa between their respective altimeter settings. In this way, less than 1000ft of air exists between the two aircraft and thus the separation is 'nominally' 1000ft, based on the assigned cruising altitude.
[2] MOCOR being the Maturity Of Cross Organisational Relationships; a framework that describes the maturity of the working relationship required between the UK CAA and the organisations that it regulates.
[3] ISP Flight Ops Policy and Airspace/ATM Policy, AAA ATS Ops and Airspace Regulation, GA Unit and Flight Ops.

c. Assess the availability to Air Traffic Service (ATS) providers of advanced information relating to larger variations in pressure (i.e. rapidly moving low pressure systems) in order to mitigate their impact.

d. Assess issues regarding the operation of aircraft with failed Mode S transponders.

e. Assess issues regarding access to CAS by military aircraft, including formations.

f. Determine the impact on ANSPs who currently have access to controlled airspace but do not operate on a NATS surveillance platform.

5 Subsequent work completed by the joint Project, endorsed by the TA Steering Group and presented within this paper has:

a. collated and refined the evidence presented in January 2014;

b. addressed the requirements for further work placed identified by the CAA's SARG.

c. detailed the UK State TA Project's safety argument for the concept of a nominal VSM through the application of a QNH tolerance;

d. proposed the scope of the safety argument for the use of the nominal VSM concept and the generic contents of an ANSP safety case for its application.

e. proposed a maximum QNH tolerance value that may be applied by ANSPs; and,

f. proposed a number of applications of the nominal VSM principles.

SCOPE OF SAFETY ARGUMENT FOR THE USE OF NOMINAL VSM

6 Working under MOCOR principles, the project has and continues to take account of cross regulatory/industry roles and responsibilities in assessing and developing the safety argument for nominal VSM. However, the roles and responsibilities of the Regulator and ANSP must ultimately set the scope of the Regulatory Authority and ANSP's safety assurance requirements for the nominal VSM concept. In assessing the impact of the introduction of nominal VSM, generic safety issues (detailed at Annex A) were considered for further investigation and will be required to be addressed in the development of a nominal VSM safety argument; either by the Regulatory Authority or the ANSP.

7 The Regulatory Authority's role is to publish the VSM to be applied by ANSPs and to maintain oversight of that provision. Thus, the Authority must satisfy itself that those separation minima are, in principle, acceptably safe and that the effects on the ATM system are tolerable.

8 In accordance with normal safety assurance and oversight processes, it is the responsibility of the ANSP to demonstrate to the Regulatory Authority an acceptably safe means of delivering nominal VSM, through the application of a QNH tolerance. Thus, in order to gain approval from the Authority to provide nominal VSM, ANSPs will be required to satisfy the minimum requirements for a generic ANSP safety case identified by the joint Project; these being to:

a. Demonstrate that safety, workload, or other factors necessitate the use of a QNH tolerance. This may be in the form of documented workload assessments or hazard analysis and should provide a rationale for the selection of a QNH Tolerance concept over alternative mitigations and a clear scope of use for the concept, including how the concept will be applied and will be time-bound in its application.

b. Demonstrate that the concept will ensure safe and appropriate interactions with other ATC providers and for all airspace users.

c. Address and mitigate the risks associated with the ATCO HFs which include but are not limited to the effects of:

   (i) An increase in ACAS RA Events.

   (ii) An increase in STCA Events.

   (iii) The visual perception of nominal VSM on a surveillance display.

   (iv) The increased workload associated with altimetry calculations.

d. Explain fall-back procedures for use when ASRs are subject to significant weather fronts such that an out of tolerance gradient exists between the NASAS derived ASR QNH and the aerodrome QNH of surrounding aerodromes.

e. Address, where applicable, the integration of formation flights with other traffic in a nominal VSM environment.

f. Demonstrate how the ANSP's SMS will identify those incidents attributable to the use of a QNH tolerance.

g. Where there is reliance on such equipment, address issues regarding the operation of aircraft with failed Mode S transponders.

h. Where an ANSP determines that an exceptional requirement exists to utilise the maximum QNH tolerance value of 5 hPa, ANSPs should clearly articulate the justification for its use and the additional measures required to mitigate any consequent safety effects.

(i) Where utilised, demonstrate how the 2 hPa altimeter setting variance associated with the use of the altimeter setting update procedure will be contained within the overall use of a QNH tolerance whose maximum value should not exceed 4 hPa and shall not exceed 5 hPa.

9 The MOD, as a MOCOR 3 partner, have been fully involved in the development of the nominal VSM concept and the UK State TA Project's safety argument. Where this paper refers to a Regulatory Authority and ANSPs, it is envisaged that this will apply equally to the MAA and CAA and to civil and military ANSPs. However, this is subject to agreement by the MAA and the satisfactory completion of safety assurance and oversight processes by the military ANSPs in accordance with MAA requirements.

SAFETY ARGUMENT

10 The UK State TA Project believes that the utilisation of a nominal VSM is acceptably safe, based on the application of an altimeter setting variance between 2 aircraft that should not exceed 4 hPa and shall not exceed 5 hPa.

CONSTRAINING CRITERIA AND ASSUMPTIONS

11 The following constraining criteria and assumptions apply to the application of nominal VSM:

a. **Vertical Displacement per hPa.** Operationally, ATCOs and FISOs utilise a conservative, assumed, value of 30 ft per hPa to calculate aircraft separation. Calculations based on ISA values have determined that between the surface and

18 000 ft, 1 hPa equates to between 28.8 ft and 23.2 ft, dependent upon weather conditions. However, research has demonstrated that aircraft and ATM systems are programmed with an assumed value of 27.3 ft per hPa, irrespective of altitude; consequently, the separation values referred to hereafter will utilise the assumed value of 27.3 ft except where otherwise stated. That said, ATS personnel will continue to utilise the long accepted operational assumption of 30 ft per hPa in calculations. Table 1 below highlights the impact on VSM of utilising a QNH tolerance and the vertical difference between the absolute[4] and nominal separations.

Altimeter Setting Variance (hPa)	Vertical Separation (ft) (27.3 ft per hPa)	Vertical Difference (absolute vs nominal) (ft)
1	973	27
2	945	55
3	918	82
4	891	109
5	864	136
6	836	164

Table 1: Effect of QNH Tolerance upon VSM.

b. **Level Occupancy Criteria.** ICAO Doc 4444 Chapter 8 Para 8.5.5.2.1 states that 'The criterion which shall be used to determine that a specific level is occupied by an aircraft shall be +/- 60 m (+/-200 ft) in RVSM airspace. In other airspace, it shall be ±90 m (±300 ft), except that the appropriate ATS authority may specify a smaller criterion, but not less than ±60 m (±200 ft), if this is found to be more practical'. The mathematical underpinning for these figures is contained within ICAO Doc 9426 ATS Planning Manual and highlights that it is based upon both the correspondence error of SSR Mode C data and Assigned Altitude Deviation(AAD)[5] of an aircraft. The UK stipulates that ±200 ft will be used to assess level occupancy throughout its airspace[6] and this paper has been developed on the basis that the UK would not adopt the alternative criterion specified by ICAO.

c. **Rate of ACAS Events.** In order to determine a level of acceptability from which any impact of the use of 'nominal' VSM can be measured, it is reasonable to assume that the current incidence of ACAS events, both RA and TA, in UK airspace and thus the risks associated with them are considered to be Acceptable or Tolerable and As Low As Reasonably Practicable (ALARP) by both the Regulatory Authorities and operators.

d. **Current Exposure to Risk from Nominal VSM Derived from Altimeter Setting Variance.** In the work conducted in January 2014, it identified that a form of nominal VSM is currently utilised within the London TMA to mitigate the effects of the atmospheric pressure gradient[7] by 'deeming' certain aerodrome QNH values as being sufficiently similar to each other. Other than historic incident data or the lack thereof, we have limited means to prove, within a modern SMS construct, that current operations are acceptably safe. However, it is reasonable to argue that NATS, through their SMS, will have assessed that the risks associated with the current operation are

[4] An absolute VSM is defined as the separation of 2 aircraft by 1 000 ft with both aircraft being operated on the same altimeter subscale setting, or, the separation of 2 aircraft by 1 000 ft, correcting for a variance in altimeter subscale settings using the operational assumption of 1 hPa equating to 30 ft.

[5] AAD is the difference between the transponder Mode C altitude and the assigned altitude/flight level (ICAO Doc 9574).

[6] MATS Part 1 Section 1 Chapter 6 Paragraph 10B.

[7] A QNH Gradient refers to a stepped change in atmospheric pressure caused either by a weather front moving across an area, or by the difference in atmospheric pressure between a point at a distance from the pressure datum; for example the distance between EGSS and EGLL, the NASAS for the proposed London ASR.

at least tolerable and mitigated to ALARP. In turn, it is thus also reasonable to argue that the CAA, through their normal oversight activities, are content with the adequacy of NATS' current arrangements. However, the safety assurance from this legacy operation is not directly transferable to the significantly greater volume of airspace represented by a TA of 18 000ft.

e. **Future Airspace Strategy.** FAS requires that all changes are justified on the grounds that they will directly reduce the risk, and/or contribute, to the development of a fundamentally safer system or at the very least maintain current levels of safety whilst delivering benefits in other areas.

f. **Use Of VSM Within The ATM System.** A key task of the work conducted in January 2014 was to research the origins of the derivation of 1 000 ft VSM and its associated regulatory context; this is revisited at Annex B and includes additional material relating to aircraft formations within CAS.

g. **MOD Operations Inside CAS.** The UK MOD has stated that their aircraft will operate wholly on the ASR QNH for the purposes of crossing CAS[8] and as such will not utilise nominal VSM concepts in these circumstances, except for those procedures relating to the issuance of an updated altimeter setting – see paragraphs 25 to 27.

h. **SID and STAR Profiles.** In determining the separation between interacting instrument flight procedure profiles from adjacent aerodromes (SID/SID, SID/STAR and SID/arrival transitions), the CAA ensures that the profiles accommodate potential along track and cross track errors. This assessment assumes that an aircraft follows the vertical profile of the SID; however, this is within the constraints imposed by the vertical errors that already exist within the ATM system and are accounted for within the nominal VSM concept.

EVIDENCE

12 Significant, progress has been made to further develop and refine the information presented in January 2014, which has highlighted the complexity of the errors already in existence within the ATM system prior to the addition of a QNH tolerance, how those errors relate to the VSM and the varying approaches by airframers toward aircraft automation. Moreover, further work has seen the development of the evidences required to create this Regulatory Authority level safety argument for nominal VSM and to satisfy the requirement for ACAS interaction modelling described at paragraph 4a. Whilst the endorsement in principle from CAA SARG included a requirement to test the nominal VSM concept through the conduct of ATM validation simulations[9], due to the scope and maturity of the evidence presented herein, these simulations are no longer considered to be a pre-requisite for the CAA to approve the concept.

13 **Operational Effects of Nominal VSM.**

a. **ATM System Vertical Error.** As originally articulated in January 2014, there are a number of sources of vertical error that exist within the current ATM system which are independent from the introduction of a raised TA and a nominal VSM concept. These vertical errors within the ATM System are composed of aircraft Total Vertical Error (TVE) and those that are introduced by surveillance systems in transmitting and processing altitude related data. The findings and evidence have been further developed and are consolidated at Annex C.

[8] By which it is meant Airspace below FL 195, Airways, CTAs not associated with an aerodrome, for example Daventry, Clacton and Worthing CTAs, and TMAs.
[9] described at paragraph 4b.

b. **Effect of an Altimeter Setting Change on Aircraft Systems.** A raised TA increases the volume of airspace within which altitudes apply, and will thus increase the number of changes in altimeter setting required to be made by flight crews. However, research undertaken with aircraft operators and CAA SARG personnel has determined that the automated response by an aircraft to an altimeter setting instruction, i.e. whether it subsequently adjusts its vertical position to take account of the altimeter setting change, varies according to the automation ethos of the aircraft manufacturer (as shown at Annex D), the particular phase of flight (level flight, climbing/descending etc) and the automation mode utilised by the flight crew. This variation could create uncertainty as to whether aircraft will remain within the SSR verification and level occupancy criteria, which are the means of mitigating the accumulation of vertical errors within the current ATM system, and the key safety barrier in managing the addition of a QNH Tolerance. However, based upon evidence from CAA SARG Flight Operations personnel and through engagement with commercial aircraft operators[10] it is clear that flight crews are aware of the risk of departing a cleared level due to changes in altimeter settings. Where aircraft are known **not** to automatically re-capture the cleared level following an altimeter setting change, flight crew procedures require the manipulation of the aircraft automation in order to ensure compliance with the ATC cleared level. In terms of the conceptual safety argument for nominal VSM, the surety that an automated aircraft will correct to its cleared level following an altimeter setting change means that a QNH Tolerance may be applied from a known datum altitude and thus the effect of that QNH Tolerance on the separation between aircraft can be accurately assessed.

c. **Aircraft Formations.** SERA.3135 requires that for formation flights within controlled airspace, all aircraft within a formation shall be flown at 'a distance not exceeding… 30 m (100 ft) vertically from the flight leader'. As outlined in Annex B, the effect of SERA.3135 on the column of air that would exist around an aircraft formation is akin to the operation of an aircraft with an altimeter setting variance of 7.32 hPa (± 3.66 hPa); albeit that the elements of the formation would not be transponding and would thus have no impact on ACAS' onboard proximate aircraft. Given that SERA.3135 permits the operation of aircraft within CAS with as little as an 800 ft column of air between them, this figure should represent the extreme limit of the acceptable effect of a QNH tolerance on aircraft separation. Table 2 details the vertical separations derived from the interaction between aircraft formations and commercial air transport (CAT) flights and the use of an altimeter setting variance, before the effects of TVE are taken into account.

	Scenario			
	CAT vs Formation (Leader) ±2 hPa	CAT vs Formation (Leader) ±3 hPa	CAT vs Formation (Elements) ±2 hPa	CAT vs Formation (Elements) ±3 hPa
Vertical Separation	945 ft	918 ft	845 ft	818 ft

Table 2: Effect of SERA.3135 and QNH Tolerance upon VSM.

d. **Airborne Collision Avoidance System (ACAS) Effects.**

(i) Following a request from the HETA Rulemaking Group, Eurocontrol conducted an analysis of ACAS interactions in a nominal VSM environment, based upon a variance of up to 6 hPa between aircraft altimeter settings. The full results from this analysis are at Annex E with key findings below.

[10] NATS Safety Partnership Agreement.

(ii) ACAS' operate in accordance with a specific set of criteria that define the system's sensitivity levels and alarm thresholds. These thresholds vary according to the aircraft's altitude and are based upon the system measuring the 'time to go' to the closest point of approach between 2 aircraft, which should not infringe specific lateral and vertical criteria which vary with altitude. The Eurocontrol analysis utilised TCAS II, the sensitivity level definitions and alarm thresholds for which are at Annex F.

(iii) **ACAS RA.** Eurocontrol findings identified that no ACAS RA events would occur in level flight nominal VSM interactions utilising a QNH Tolerance of 6 hPa. Moreover, the Eurocontrol analysis identified minimum rates of climb/descent that would trigger an ACAS RA in nominal VSM interactions utilising a QNH tolerance of 6 hPa. However, it is acknowledged that ACAS RA occur in today's ATM system for climbing/descending interactions without the application of a nominal VSM; therefore, the challenge is in trying to quantify any potential increase in the rate of ACAS RA, as a direct result of utilising a nominal VSM.

(1) The level of detail contained within the CAA's MOR database relating to ACAS events was found to be insufficient to facilitate analysis. Consequently, it has not been possible to determine a baseline against which the Eurocontrol derived results can be compared.

(2) It can be stated that the use of a nominal VSM increases the likelihood of an ACAS RA event for climbing/descending interactions.

(3) Constraining the size of the QNH tolerance applied would have a direct influence on the likelihood of an ACAS RA.

(4) The likelihood of an ACAS RA occurring in climbing/descending aircraft interactions also relies on the lateral proximity and closure rate; therefore, it is not possible to quantify the increased likelihood of ACAS RA events.

(iv) **ACAS TA.** The Eurocontrol evidence proved that all level flight nominal VSM interactions above 5 000 ft within the lateral threshold criteria, utilising a QNH Tolerance of 6 hPa, would result in an ACAS TA event. A QNH tolerance value of 5 hPa would reduce the probability of occurrence; however, there is little leeway between the ACAS TA vertical alarm activation threshold of 850 ft and the nominal VSM of 863.5 ft. A QNH Tolerance value of 4 hPa or less would not result in an ACAS TA event in level flight.

(v) **ACAS Summary.** The results from the ACAS simulations highlight that the application of a QNH Tolerance may see an increase in ACAS RA events in climbing/descending scenarios between 10 000 ft and 20 000 ft, depending on the rate of climb applied in the final stage of closure and the magnitude of the QNH tolerance applied. In all other altitude bands and in level flight scenarios, the incidence of ACAS RA events is likely to remain similar to today's values. However, the critical result and, realistically, the result that has the most significant impact upon setting the magnitude of an acceptable QNH Tolerance, is that relating to ACAS TA events, due to the potential consequences of any increase in ACAS TA events on flight crews.

e. **Effects of Nominal VSM Upon Flight Crews.** In order to determine the effects of nominal VSM, and specifically any increase in ACAS TA events, on flight crews, the opportunity was taken to present the concept to a meeting of the NATS Safety Partnership Agreement in November 2014. In response, CAT operators stated that a nominal VSM of 836 ft to 890 ft would not be visually perceptible from the cockpit; however, it would be apparent on cockpit ACAS displays. Indicated vertical separations of 900 ft on ACAS displays were generally considered common; however, an indicated vertical separation of 800 ft was not considered to be common and would cause concern. Critically, the commercial operators did not consider a ACAS TA to be a common event and stated that it would cause concern on the flight deck; one operator reporting that they had mandated the reporting of ACAS TA events in order to identify geographic ‘threat areas’. Operators also expressed concern about any possible increased incidence of ACAS TA events, specifically the risk of flight crew de-sensitisation to such events. Putting the FAS requirements on safety into context, on the basis of the evidence provided by the CAT operators, an increased risk of incidence of ACAS events should be considered to be unacceptable.

f. **Meteorological Data.** Whilst not an element of the Regulatory Authority’s safety argument to support the concept of nominal VSM through the application of a QNH tolerance, a range of meteorological data is required for consideration by the State and for use by ANSPs in developing their safety assurance and ‘driving’ the magnitude of a QNH tolerance in operational use.

(i) **Intra-ASR QNH Gradient[11].** As stated earlier, given that through its normal oversight activities the CAA are content with the adequacy of the current arrangements within the London TMA, then by inference, they consider the variance between the disparate aerodrome QNH values within the London TMA to be acceptably safe for operations. Annex G provides a detailed comparison of the QNH of major aerodromes within the proposed ASRs to the QNH of the proposed ASR NASAS. Of specific interest is that it highlights that the QNH of all major aerodromes within the London TMA were within 2 hPa (ie ± 2 hPa) of the NASAS QNH on 99.22% of measured occasions between 1 Oct 06 to 30 Sep 11 and within 3 hPa (ie ± 3 hPa) on 99.99% of measured occasions during the same period. This data is supported by work conducted by NATS’ Operational Analysis team who analysed pressure data from aerodrome METARs during the period July 2013 to October 2014, in order to assess the impact of the significant low pressure systems that affected the UK during the period. However, in terms of the application of a QNH tolerance operationally, the key information is the ‘predictability’ of atmospheric pressure changes, the accuracy of pressure forecasting by the Meteorological Office and the difference between NASAS derived ASR QNH and, thus, the gradient that would exist at ASR boundaries.

(ii) **Inter-ASR QNH Gradient.** Annex H is duplicated from the State CONOP document[12] and depicts the variance of pressure between NASAS. Met Office data demonstrates that the variance between NASAS derived ASR QNH values was greater than 3 hPa on between 8.9% and 58.8% of occasions[13] during the measured period dependent upon location within the UK. This represents a significant variation across the UK and indicates the potential difficulty in applying a QNH tolerance concept at ASR boundaries.

(iii) **Predictability of Atmospheric Changes.** The UK Meteorological Authority has stated that “following a review of 9 locations in the UK (Ballykelly, Bridlington, Carlisle, Hurn, Kinloss, Langdon, Lerwick, St Mary’s, and Stornoway), it was noted that the hourly atmospheric pressure change within ± 1hPa occurs on 92-96% of occasions. Having reviewed the data and considered the location of the proposed NASAS, it is the view of the CAA that the hourly atmospheric pressure change within ± 1 hPa for locations within the UK FIRs would be 90-96 % of occasions”[14]. The CAA also recognises that a raised TA and the increased

[11] See footnote 7 on page 4 for a definition of a pressure gradient.
[12] CONOP V5.2 dated 2 November 2015.
[13] Data from the Met Office’s North Atlantic & Europe limited area forecast model were extracted from the archive for the 5-year study period from October 2006 to September 2011 inclusive. Met office reference document: ‘Variation of pressure between neighbouring ASRs’ dated 28th January 2014.
[14] Email from UK Meteorological Authority to State TA Project Safety Manager on 5 June 2014.

volume of airspace in which QNH will apply generates pressure management issues for all ANSPs. Consequently, benefits have been identified in the introduction of a UK-wide standard procedure for managing aircraft altimeter settings following an update; paragraphs 23 to 25 herein refer.

(iv) **Accuracy of Pressure Forecasting.** In support of ANSP activity and based upon 2 locations which the Meteorological Authority considered to be sufficiently representative of atmospheric conditions throughout the UK, forecasts for 1, 2 and 3 hours ahead were evaluated by the Meteorological Office and deemed by the Authority to be "extremely accurate…at this time range"[15]. 18 491 forecasts were reviewed at Charlwood (near Gatwick) and 17 945 were reviewed at Bishopton (near Glasgow) and the results from this analysis are in Table 3.

Charlwood	
Time	**% of occasions where forecast QNH is within ± 1 hPa of actual QNH**
T+1	99.95
T+2	99.88
T+3	99.69

Bishopton	
T+1	99.96
T+2	99.83
T+3	99.60

Table 3: Accuracy of Pressure Forecasting within the UK.

ANALYSIS OF NOMINAL VSM CONCEPT

14 Considered in combination with aircraft TVE, ICAO and EASA regulation relating to aircraft formation level keeping, and the relationship between feet and meters as units of measurement described by ICAO, it is clear that the concept of an absolute 1 000 ft of vertical separation between aircraft inside CAS is not sacrosanct. This view has been endorsed through informal coordination with ICAO's Air Navigation Bureau (ANB), who have verbally confirmed that these factors are the basis for the use of the term 'nominal' in ICAO documentation. Consequently, it is reasonable to argue that no 'legal' impediment exists to the concept of a nominal VSM. Thus, the challenge is to demonstrate that the application of a nominal VSM through the use of a QNH tolerance does not have additional, unintended consequences within the ATM System; specifically, the effect of the application of a QNH tolerance on ACAS and whether the TVE within the ATM system can be contained within the existing level occupancy criteria when combined with a QNH tolerance. In the context of this paper, we need to demonstrate that the concept of nominal VSM is acceptably safe.

15 The results from the Eurocontrol ACAS simulations highlighted the potentially safety significant effect of the application of a QNH tolerance of 6 hPa on the incidence of ACAS TA events. Moreover, it is clear from the results of the Project's engagement with CAT operators that an increase in ACAS TA events was considered to be unacceptable. Placing these into the context of the FAS directive on safety indicates that a tolerance of 6 hPa would be unacceptable. Setting the magnitude of an acceptable QNH Tolerance to below 6 hPa would move aircraft outside the vertical threshold activation minima for a ACAS TA event. In this way, the incidence of ACAS TA events would remain broadly similar to today's operation

[15] Email from UK Meteorological Authority to State TA Project Safety Manager on 20 May 2014.

and could thus be considered as being tolerable and ALARP by ANSPs and aircraft operators.

16 The surety that an automated aircraft, either automatically or through the intervention of the flight crew, would maintain its cleared level, represented a significant turning point in the concept's development. However, due to the lack of relevant quantitative evidence regarding the operational performance of aircraft altimetry systems beneath 18 000 ft, some uncertainty remains over the magnitude and cumulative nature of some vertical errors that are present within the ATM system. The magnitude of Altimetry System Error (ASE) that exists within the fleet of aircraft operating beneath 18 000 ft within the UK is, simply unknown and unquantifiable as it is not monitored. Moreover, ASE is undetectable to both the pilot and to the ATCO and can only be detected by ground testing of the altimetry system or, exceptionally, a pilot's visual assessment of aircraft separation. However, the requirements for altimetry system accuracy and aircraft maintenance are known, measures are in place to mitigate the risk of ASE amongst the commercial aircraft fleet operating within RVSM airspace and ASE, and thus the risks associated with it, reduces with decreasing height as a result of increased air pressure. Importantly, it should be borne in mind that ASE exists within today's ATM system and that the risks associated with it are considered to be tolerable and ALARP by both the international Regulatory Authorities and the operators themselves.

17 Regarding the other vertical errors that exist within the ATM system, it is not possible to state unequivocally what the cumulative effect of aircraft TVE and errors introduced by ground based surveillance equipment, combined with the effect of a QNH tolerance will be. However, we know, anecdotally, that, it is uncommon for aircraft to transpond a vertical position that is significantly different from the reported level[16]. Moreover, notwithstanding the effects of AAD, as described in Annex C, it has been determined that the application of a QNH tolerance of ≤ 6 hPa to an aircraft could be contained within the SSR level occupancy criteria. Consequently, given the maximum altimeter setting variance that each aircraft, and thus the ATM system, is exposed to would be exceptionally 3 hPa and, routinely, 2 hPa; there is an increase in the probability that an aircraft's pressure altitude report would remain within the SSR level occupancy criteria. Importantly, the maintenance of the UK's level occupancy criteria provides a key safety barrier to mitigate the risk posed by any accumulation of 'visible' errors. On the basis of the evidence, the UK State TA Project contends that the uncertainty regarding ASE and the possible cumulative nature of the other vertical errors within the ATM system should not preclude approval of the conceptual safety argument.

18 Notwithstanding that the Regulatory Authority's argument should consider only the overall concept of a nominal VSM, it must also have some consideration of the operational delivery of the concept. NATS have articulated that there are significant challenges in delivering a safety argument that is based upon an ATCO tactically managing a pressure 'allowance' of 4, 5 or 6 hPa; however, they believe that the concept could be delivered through an aircraft being permitted, under specific circumstances, to operate at ± 2 hPa or ± 3 hPa[17] of the published ASR QNH. Based upon the evidence received from the ACAS analysis and the engagement with commercial aircraft operators, this suggests a maximum altimeter setting variance of 4 hPa, delivered on a ± 2 hPa basis. However, considering the data presented on the meteorological environment presented in paragraph 13f(i) and Annex G, although the effects have yet to be fully determined, a maximum limit of 4 hPa could constrain aircraft departures from major aerodromes, specifically within the London TMA environment[18], on those occasions when the aerodrome QNH was > 2 hPa and ≤ 3 hPa from the ASR QNH. In order to address this, the balance of the risks involved in selecting a maximum QNH

[16] NERL Pressure Tolerance Safety Report V1.0 May 2015.
[17] I.E. where aircraft A operating with an altimeter setting +2 hPa from the ASR QNH was in level flight 1 000 ft above aircraft B operating with an altimeter setting -2 hPa from the ASR QNH. In this way, the aircraft pair would have a total variance of 4 hPa between their altimeter settings and a nominal VSM of 891 ft would exist.
[18] The operational challenges of variances between aerodrome QNH and ASR QNH of >2 hPa are lessened in other parts of UK airspace through the reduced complexity outside the LTMA.

tolerance value of 4 hPa or 5 hPa should be considered; specifically, the increased risk of a ACAS TA inherent to the use of a 5 hPa tolerance – rather than a 4 hPa tolerance – set against:

a. the relatively limited periods of time when the atmospheric pressure variance between the aerodrome QNH and ASR QNH exceeds 2 hPa;

b. the limited period of time where a flight will be conducted on the aerodrome QNH[19] within CAS and thus the limited opportunity for aircraft operating on disparate altimeter settings to interact.

c. the potential risk to ATM capacity of constraining departures from 'out of tolerance' aerodromes.

19 On the basis of the evidence presented and given that the requirement for a 5 hPa variance would be expected to be exercised by exception, a pragmatic solution would be to determine that the maximum altimeter setting variance between 2 aircraft should not exceed 4 hPa and shall not exceed 5 hPa. Later in this paper, we will discuss a number of the potential circumstances which may require the use of a 5 hPa variance.

20 With clarification on the maximum value of QNH tolerance that may be applied, the final issue that required resolution was the interaction between aircraft formations and other aircraft. As previously stated, the effect of SERA.3135 on the column of air that would exist around an aircraft formation is akin to the operation of an aircraft with an altimeter setting variance of 7.32 hPa. Analysis of these interactions combined with the use of a nominal VSM highlighted that the application of a QNH tolerance to both the formation and the interacting flight could reduce vertical separation between the formation elements and the other aircraft below 800 ft[20]. Whilst this reduction would not induce a ACAS event, it was considered to be unacceptable. As such, except for those procedures related to the issuance of an updated altimeter setting, no additional QNH tolerance shall be applied between aircraft formations operating in accordance with SERA.3135. Moreover, with regards to the coordination of an individual flight with an aircraft formation that is operating in accordance with SERA.3135[21], the QNH tolerance value applied by an ANSP should not exceed 2 hPa but shall not exceed 3 hPa and that no additional QNH tolerance may be applied.

CONCLUSION

21 Adherence to the scope of application articulated by CAA SARG for the QNH tolerance concept would limit the exposure of the ATM System to its use, in that it will be applied for 'time limited' periods to facilitate specific aircraft interactions. In that way, the risk associated with the cumulative effect of the limited exposure to significant QNH variance between affected aerodromes, aircraft TVE and surveillance system vertical errors may be mitigated. Consequently, the UK State TA Project believes that the utilisation of a nominal VSM is acceptably safe, based on the application of an altimeter setting variance between 2 aircraft that should not exceed 4 hPa but shall not exceed 5 hPa.

22 Determining this maximum altimeter setting variance represents a significant milestone in the development of the UK TA project. It provides a pragmatic solution to the challenge of managing aircraft altimeter settings in complex airspace whilst, subject to satisfactory

[19] The method of operations proposed is that ATCOs operating within terminal and en-route CAS will instruct the pilot to set the ASR QNH on initial contact.
[20] The application of a 4 hPa altimeter setting variance between an aircraft formation and another flight would result in a vertical separation of 791 ft before the effects of TVE are taken into account – (4 x 27.3 ft) + 100 ft = 209.2 ft reduction.
[21] Subject to concept development and provision of a safety argument by the MOD, and agreement between the MAA and CAA on the potential implications for compliance with SERA, there may be scope to explore the application of a QNH tolerance against a military aircraft formation that has agreed to operate with all elements at the same level and contained within one mile laterally and longitudinally.

implementation, fulfilling the FAS objective of maintaining current levels of safety whilst delivering benefits in other areas.

FURTHER APPLICATIONS OF NOMINAL VSM CONCEPT

23 **Altimeter Setting Changes.** Updates to the ASR QNH will typically be delivered on a ½-hourly basis through the ASR Bulletin[22]. However, it has been identified that an updated ASR QNH could pose a challenge to ATCOs in managing the altimeter settings of coordinated flight, where two aircraft operating within an ASR are vertically separated by an absolute 1 000 ft following coordination but need to be transitioned to an updated ASR pressure. Using today's method of operations, the ATCO would be required to either:

a. re-coordinate the flights in order to avoid a loss of separation, thereby increasing their workload; or,

b. delay the altimeter setting change until the coordination agreement was no longer required, thereby introducing a risk that the ATCO would forget to issue the change.

24 The TA Project proposed a concept[23] which utilised nominal VSM principles and would permit ATCOs to alter an aircraft's altimeter setting, up to a specified maximum value of change, without further coordination being required, thus avoiding the related additional workload or a loss of separation. Originally this proposal was considered wholly for use within CAS; however, the TA Safety Committee (TASC) considered that it would be both credible and pragmatic for the concept's utilisation to be extended throughout UK airspace and not solely conducted between NERL and MOD. Consequently, it was agreed that this concept should be included within the MATS Part 1 in order to permit its delivery across the UK, without being subject to local interpretation.

25 Whilst more detailed hazard analysis work and the accompanying MATS Part 1 text is still to be developed, based upon MetO data and other planned uses of a variance in aircraft altimeter settings, the following principles have been proposed by the UK TA Project Team (TAPT) and agreed in principle by the CAA TA Working Group (TAWG):

a. The aircraft subject to the coordination agreement must be vertically separated by an absolute 1 000 ft prior to any change in aircraft altimeter setting being instructed.

b. The aircraft subject to the coordination agreement must be operating on the same altimeter setting datum and remain so during the period of validity of the coordination agreement.

c. Provided that the change in ASR QNH is no greater than 2 hPa, controllers may instruct aircraft in receipt of a service to change to that new QNH without further coordination taking place. Stipulating a value of 2 hPa ensures that:

(i) there would be no adverse effects on ACAS;

(ii) it is likely to encompass a significant majority of ASR Bulletin pressure events; and complements the proposed delivery mechanism of QNH Tolerance - ± 2 hPa.

d. The use of an altimeter setting variance associated with the publication of an ASR bulletin must be contained within the maximum altimeter setting variance which should not exceed 4 hPa and shall not exceed 5 hPa.

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[22] An interim ASR Bulletin concept is currently being researched and developed which would see an updated Bulletin issued where the ASR QNH is observed to change by 2 hPa or more.
[23] 20140701-TA_ARU_ROD_CONOP

26 **Airspace Containment.** Airspace containment is affected by atmospheric pressure variance in 3 significant ways, all of which are issues which exist, in some way, within the current UK ATM system:

a. Where the Base of CAS (BoCAS) is defined as an altitude, the maintenance of an absolute 500 ft above the BoCAS becomes unachievable due to the inevitable delay between the promulgated update of a change in the published pressure datum for the BoCAS and adjustment in the aircraft's altimeter setting.

b. For some flights within the London TMA (and likely other CTA/TMA structures), the minimum level in CAS allocated by ATC is based upon the aerodrome QNH, whilst the BoCAS is defined by the London QNH. Therefore, when the aerodrome's QNH varies from the London QNH, the aircraft may have less than 500ft vertical separation above the base of CAS.

c. The vertical profile of a SID based on the QNH of aerodrome A, may terminate 500 ft above the BoCAS of a CTA with a datum based on the QNH of aerodrome B. This situation could result in less than 500 ft of air between the aircraft and the BoCAS, as illustrated in Figure 1.

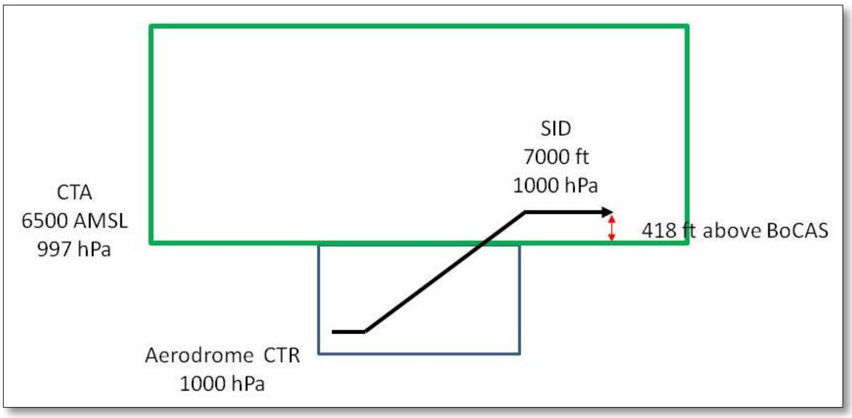


Figure 1: Nominal SID Containment

27 CAA policy on airspace containment states that the vertical profile of a flight must remain at least 500 ft above the base of CAS[24]. This is complemented by MATS Part 1[25] which states that '…controllers should not normally allocate a level to an aircraft which provides less than 500 ft vertical separation above the base of a control area or airway'. On the face of it, this text refers to an absolute[26] 500 ft; however, this is not the operational reality practised within complex airspace today, either through procedure design or through tactical vectoring by ATCOs.

28 Turning first to the delay between the publication of the ASR Bulletin and the provision of the updated altimeter setting to the aircraft, the UK TAPT agreed that that there was a requirement to determine a means for ATCOs to avoid what would, in effect, be a 'technical' loss of airspace containment. The CAA TAWG considered that a similar concept to that proposed for the pressure management of coordinated flights could be used, as detailed at paragraph 25.

29 Regarding the assignment of levels through either procedure design or ATCO vectoring, the provision of an absolute 500 ft of containment within CAS where altitudes currently apply,

24 Derived from ICAODoc 8168 PANS Ops Volume II Part II Section 3 Chapter 1 requirement for half-MOC, 492 ft.
25 MATS Part 1 Section 1 Chapter 7 Paragraph 9.1
26 Absolute means that the vertical position of both objects is being measured from the same atmospheric pressure datum. An Absolute VSM is where 2 aircraft are separated by 1 000 ft with both aircraft being operated on the same altimeter subscale setting, or, the separation of 2 aircraft by 1 000 ft, correcting for a variance in altimeter subscale settings using the operational assumption of 1 hPa equating to 30 ft.

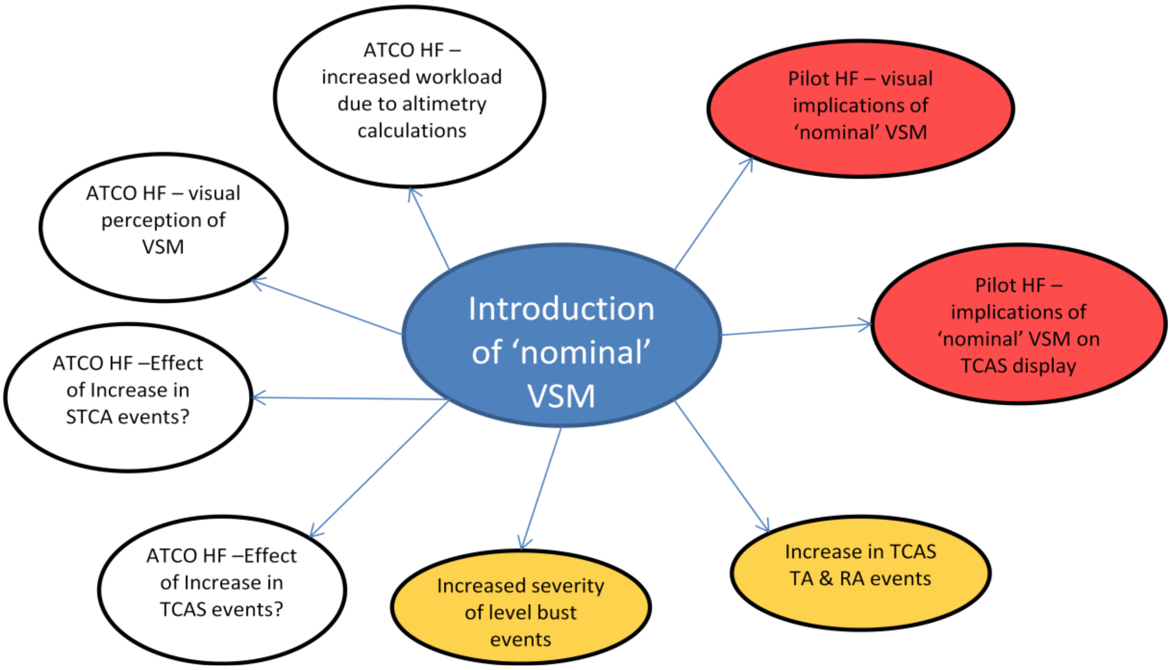
poses a significant financial threat through the cost of procedure re-design and through the loss of airspace capacity required in order to mitigate the effects of atmospheric pressure variance. The CAA have recognised that there may be a need to factor the provision of an absolute 500 ft vertical containment into future instrument procedure design, based on an established and agreed percentile of pressure variance. However, it acknowledged that, in principle, the current method of operation within CAS would need to continue to be enabled after the implementation of a raised TA. On that basis, whilst acknowledging that further work is required to develop the concept and that this would need to address both the terminal and en-route environments, the TAWG proposed that a CAA Policy could be developed to permit operations at a nominal 500 ft above the BoCAS, with an altimeter setting that was up to a specified variation greater than the pressure datum which defined the BoCAS. The meteorological information detailed in Annex G indicates that this is a feasible option. Moreover, it was also recognised that the use of an altimeter setting variance associated with the provision of nominal airspace containment must be contained within the maximum altimeter setting variance which should not exceed 4 hPa and shall not exceed 5 hPa. Finally it was also recognised that ANSP would, as part of TA implementation activity, need to assess any change in legacy nominal airspace containment potentially generated by the new use of an ASR QNH, and/or from the BoCAS being defined as an altitude instead of a flight level.

30 Given that the provision of nominal airspace containment would not obviate the requirement upon ATCOs to provide clearances that are terrain safe and ensure safe aircraft interactions, it is reasonable to argue that the risk associated with nominal airspace containment is that of airborne conflict with aircraft operating outside CAS. However, whilst more detailed hazard analysis work is yet to be completed, it is worthy of note that existing mitigations including the carriage of ACAS and electronic conspicuity will remain extant, irrespective of any amendment to or clarification of airspace containment policy. Given the TCAS II alarm thresholds of 850 ft (TA) and 600 ft (RA), it is possible to see that the existing airspace containment policy does not aim to reduce the incidence of ACAS events for flights operating inside CAS; it merely seeks to limit the interaction between flights inside and outside CAS and prevent MAC. Moreover, evidence from a recent Class G airspace user workshop indicated a belief from attendees that where the BoCAS would be defined on the ASR QNH, their task in avoiding infringement had been simplified. This task will be supported by material that is planned to be incorporated into the UK AIP describing the effects of atmospheric pressure variance on an aircraft's position relative to the BoCAS and highlighting the need to select an appropriate cruising level and, where possible, obtain an up to date ASR QNH. Consequently, it is reasonable to argue that the introduction of a nominal 500 ft of airspace containment that was limited to no greater than 2 hPa would not affect the incidence of ACAS events.

Annex A

Hazard Analysis – Impact Upon ATM System Of Adopting Nominal VSM

In assessing the impact of the introduction of 'nominal' VSM, the following issues were considered for further investigation:



a. **Pilot HF – Visual Implications of 'nominal' VSM.** Will the pilot be able to detect when 'nominal' VSM are utilised due to the reduced vertical separation between aircraft? If so, what are the implications?

b. **Pilot HF – Implications of 'nominal' VSM on ACAS Display.** What are the implications of the pilot being aware, via the ACAS situational display, that 'nominal' VSM are being utilised?

c. **Increase in ACAS TA and RA Events.** The impact of the use of 'nominal' VSM on ACAS would require to be assessed.

d. **Increased Severity of Level Busts.** The impact of the use of 'nominal' VSM on the level of vertical collision risk would require to be assessed.

e. **ATCO HF – Effect of Increase in ACAS Events.** Whilst outwith the State's responsibility to assess, ANSPs utilising a QNH Tolerance concept will be required to assess and mitigate the potential impact upon their personnel of any identified/potential increase in ACAS RA events.

f. **ATCO HF - Effect of Increase in STCA Events.** Whilst outwith the State's responsibility to assess, ANSPs utilising a QNH Tolerance concept will be required to assess and mitigate the impact of any identified/potential increase in STCA events that is attributable to the use of QNH Tolerance.

g. **ATCO HF – Visual Perception of VSM.** The utilisation of a QNH Tolerance concept will have an impact upon the altitude of the aircraft and thus the SSR Mode C/Mode S Altitude information presented to the ATCO; ANSPs will be required to assess and mitigate the impact of this upon their personnel.

h. **ATCO HF – Increased Workload Due to Altimetry Calculations.** Whilst outwith the State’s responsibility to assess, ANSPs utilising a QNH Tolerance concept will be required to assess and mitigate the impact upon their personnel of the increased workload associated with altimetry calculation.

Annex B

Derivation of 1 000 ft VSM and its Associated Regulatory Context

1 The advent in the early 1950s of commercial turbo jet aircraft operating at high levels necessitated a re-evaluation of the vertical separation minimum and thus, in June 1954, ICAO established the Vertical Separation Minima panel. Based on the work of the panel, the use of 1 000 ft vertical separation minima between IFR traffic below 29 000 ft was agreed by ICAO at the 1958 RAC/SAR Divisional Meeting. ICAO Doc 4444 Chapter 5 Para 5.3.2[27] states that the "vertical separation minimum shall be a nominal 300 m (1 000 ft) below Flight Level 290". Appendix 3 to Annex 2 of the Convention on International Civil Aviation provides tables of IFR cruising levels outside RVSM airspace and highlights the nominal equivalence of 300 meters to 1 000 ft. Although ICAO does not define nominal, it is reasonable to argue that it refers to the fact that 300 meters is equal to 984.3 ft, whilst 1000ft is equal to 304.8m. Critically however, the tables highlight that, in states where the primary unit of measurement for altitude is meters, cruising levels are separated by 300 m. Thus, by implication, ICAO endorse the separation of aircraft by less than 1 000 ft of air. Moreover, ICAO do not explicitly state that aircraft subject to vertical separation minima should have the same QNH value set on the altimeter subscale, nor do they explicitly endorse any deemed variation. Furthermore, the vertical distance between aircraft being measured from their static pressure ports, not the centre of mass, thus effecting the magnitude of separation achieved when you consider the 'height' of aircraft; for example, an Airbus A380 is 89.8 ft tall. Finally, at risk of stating the obvious, it is also worth highlighting that it is likely that one aspect of the selection of 1 000 ft as the vertical separation minima, was due to the benefits that it afforded in reducing controller workload by being a simple number to manipulate in mental calculation.

2 Of further note is that on 24 July 14, the UK adopted Commission Implementing Regulation (EU) No. 923/2012 – Standardised European Rules of the Air (SERA) which transposed ICAO Annex 2 and elements of ICAO Annex 11 into directly binding EU Law. Of specific interest in this context is ICAO Annex 2 3.1.8 (SERA.3135), which states that within controlled airspace, all aircraft within a formation shall be flown at 'a distance not exceeding… 30 m (100 ft) vertically from the flight leader'. Consequently, ICAO and SERA permit operations of ± 100ft[28] from the formation's datum altitude, in addition to the effects of ASE and the AAD on the formation leader. Thus, between 2 formations operating within CAS, the column of air between the aircraft could be reduced to 800 ft, which, in terms of its effect, equates to the application of an altimeter setting variance of 7.33 hPa[29]. That said, as the formation elements would not be transponding, the reduced column of air would not have a subsequent impact upon ACAS. It is reasonable to argue therefore that the latitude extended by ICAO and SERA through Annex 2 3.1.8/SERA.3135, could be pragmatically expanded to apply to the use of nominal VSM, as long as it could be demonstrated that the aircraft's Mode S Altitude was contained within SSR level occupancy criteria and that there was no increase in ACAS events attributable to the use of nominal VSM.

[28] 100 ft divided by an assumed value of 27.3 ft per hPa = 3.6630hPa.

[29] In those countries where m are used as the unit of measurement, the provision of 300 m of vertical separation between 2 formations operating within CAS potentially reduces the column of air between the aircraft to 240 m or 787.4 ft and, in terms of its effect, equates to the application of an altimeter setting variance of 7.79 hPa.

Annex C

ATM System Vertical Error

1 **Aircraft TVE.** The TVE of an aircraft is the vertical geometric difference between the actual pressure altitude flown by an aircraft and its assigned pressure altitude[30] and is the result of the "statistically independent and additive contributions of" Altimetry System Error (ASE) and Assigned Altitude Deviation (AAD) of the aircraft. Figure B1 represents this diagrammatically.

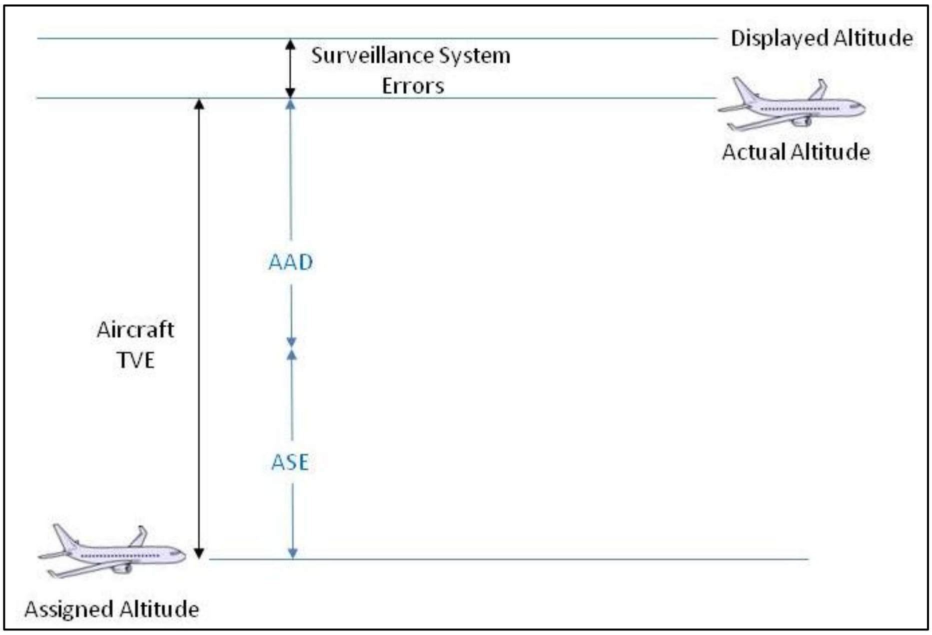


Figure B1 – Relationship between Assigned and Actual Aircraft Altitude[31].

a. **ASE.** ICAO[32] defines ASE as 'the difference between the altitude indicated by the altimeter display, assuming a correct altimeter barometric setting, and the pressure altitude corresponding to the undisturbed ambient pressure[33]. ASE varies dependent upon aircraft type, the 'age' of the aircraft's altimetry system and, specifically, the condition of the aircraft's static pressure source; more detailed information on system specification is provided at Appendix 1 to Annex C. The issue that this poses to the present study is that no single figure exists for ASE, on which to assess the implications of the addition of an altimeter setting variance. Moreover, at present, 'real-time' ASE data is not collected below 18 000 ft; the only data available was sourced from the UK HMU at STRUMBLE and thus pertains only to aircraft operating within RVSM airspace[34]. Whilst it is accepted that ASE reduces as air density increases (albeit that it has not been possible to determine how to apply this correction to the data obtained) and thus HMU data is not representative of ASE values experienced beneath 18 000 ft, this data showed that, although the mean ASE within the sample (see Appendices 2 and 3 of Annex C) was 76.5ft and 11.3 ft respectively, there was significant deviation from these values. It is this variance and inability to accurately quantify ASE in the UK airspace user community that is problematic. Options to mitigate this could be to limit the use of the concept by airspace classification and introduce specific airborne equipage requirements; however, it is likely that there would

[30] ICAO doc 9574
[31] Surveillance system error includes Correspondence Error of airborne transponder equipment.
[32] ICAO doc 9574
[33] ASE includes errors in the altimeter's pressure sensing capability and the pressure altitude conversion process through use of the ICAO standard atmosphere.
[34] Research was undertaken with NATS to determine whether the UK HMU at STRUMBLE could collect ASE data on aircraft operating beneath FL180; however, this turned out to not be possible.

be an associated requirement to implement height monitoring beneath 18 000 ft in order to monitor ASE in the user community; this is not considered to be a realistic aspiration.

b. **AAD.** ICAO defines AAD as 'the difference between the transponder Mode C altitude and the assigned altitude/flight level'. AAD includes errors introduced through the pilot's accuracy in aircraft handling, accuracy of the aircraft autopilot systems, aircraft reaction to turbulence etc.

(i) Whilst ICAO Doc 9426 cites a maximum value, based on a 95 per cent probability and on a manually flown aircraft, of 200 ft for AAD, it goes on to state that a number of factors contributing to this value have been improved since it was recorded in 1966.

(ii) Appendix 7 to EU No 1178/2011 states that the altitude keeping requirement for the award of an Instrument Rating is +/- 100 ft, corrected to make allowance for turbulent conditions and the handling qualities and performance of the aircraft used; albeit that it does not provide guidance on the scale of these allowances.

(iii) The Air Navigation (General) Regulations 2006 Part 6 Paragraph 16 requires that 'in respect of aircraft registered in a Contracting State on or after 1st January 1997 altitude can be automatically controlled within a tolerance band of + / - 65 feet; and in respect of aircraft first registered in a Contracting State before 1st January 1997 altitude can be automatically controlled within a tolerance band of + / - 130 feet'.

2 **Surveillance Systems Vertical Error.** Although they do not affect the actual column of air that exists between 2 aircraft, the air and ground based elements of a surveillance system introduce additional errors relating to the transmission and display of an aircraft's pressure altitude. In turn, these errors can affect the controller's and pilot's perception of the vertical separation that exists between the 2 aircraft.

a. **Airborne Systems.** As with ASE, the Correspondence Error introduced by airborne surveillance related equipment varies dependent upon the 'age' and type of the transponder and associated equipment; more detailed information on these is provided at Appendix 1 to Annex C. Of greatest relevance to this paper is the greater functionality provided by Mode S transponders. Subject to the capability of the pressure source that is utilised in conjunction with the transponder, Mode S Elementary Surveillance (ELS) can provide altitude reporting in 25 ft increments, whereas Mode C provides 100 ft increments. From the perspective of the creation of a safety argument, the concern is that the altitude transponded by an aircraft is reliant upon the accuracy of the altimetry system; in effect, the data coming out, is only as good as the data going in. Consequently, ASE is not apparent on a controller's surveillance display and is thus transparent to the controller and would 'breach' the ATS related mitigation – the SSR level occupancy criteria. Of greater concern is that ACAS utilises transponded altitude data on which to base its assessment of conflict. Consequently, ASE would not be apparent on ACAS displays and could then affect the timeliness of ACAS derived warnings. However, it is important to stress that the risk associated with this exists in today's operation and is thus considered Tolerable and ALARP by international regulatory bodies and operators alike. The addition of a QNH tolerance would not cause MAC in and of itself but would affect the severity of level bust incidents and the magnitude of separation loss.

b. **Ground Based Systems.** A number of aspects of RDPS reduce the clarity of the aircraft's exact vertical position in the air, through processing and the limitations of the surveillance display itself. Many modern RDPS display predicted aircraft altitudes, based on previously received data, to 'smooth' the presentation to the controller.

Moreover, the data displayed to the controller is rounded, with the lowest multiple unit of measurement being 100 ft.

3 Taking a worked example[35] of the combination of SSR Mode S and RDPS level 'rounding', where an aircraft is assigned a level of 5 000 ft based upon a QNH of 1010 hPa and the RDPS datum is 1008 hPa; i.e. a QNH tolerance value of 2 hPa has been applied.

a. The aircraft's altimetry system measures the pressure altitude based upon 1013.2 hPa and, in displaying the aircraft' altitude to the pilot applies the correction based upon the altimeter sub-scale setting.

b. Using the standard atmosphere, the aircraft's altitude is equivalent to:

5000 + ((1013.2 – 1010)*27.3) = 5087.4 ft

c. Rounded by SSR Mode S to nearest 25 ft = 5075 ft and then transponded.

d. 5075 ft is corrected by the RDPS as follows:

5075 - ((1013.2 – 1008)*27.3) = 4933.4 ft

e. Rounded by RDPS to nearest 100 ft and displayed to controller as 4900 ft.

4 By extending the example above to include increasing degrees of QNH tolerance, it is possible to determine that one aircraft could be exposed to up to 6 hPa of QNH tolerance and remain within the level occupancy criteria; albeit resulting in a variance of 200ft between the level displayed to the ATCO and that of the pilot.

QNH tolerance applied	**Pressure setting**	**Altitude (Ft)**	**Displayed Level**
± 2 hPa	1010	4 933	049
	1006	4 878	049
± 3 hPa	1011	5 015	050
	1005	4 851	049
± 4 hPa	1012	5 042	050
	1004	4 824	048
± 5 hPa	1013	5 070	051
	1003	4 797	048
± 6 hPa	1014	5 097	051
	1002	4 769	048
± 7 hPa	1015	5 124	051
	1001	4 742	047

[35] NATS Analysis of Deviations from Flight Levels in Current Operations, 16 July 2014.

Appendix 1 to Annex C

The Accumulation of Altimetry Errors.

Item #	Contributor	Reference Standards	Notes	Basic Requirement	Effect at 10,000ft	Effect at 18,000ft
1	**Altimeter Accuracy**	SAE AS392C (ETSO-C10b)	Old, but current, standard for altimeters. Typical on older/simpler GA aircraft.	Scaled to altitude (allowable error increases with altitude)	+/- 80ft	+/- 120ft
2	**Air Data Computer (Minimum Operational Performance Standard)**	SAE AS8002 (ETSO-C106)	Fairly old, but current minimum performance standard for ADC output used to display altitude.	Scaled to altitude (allowable error increases with altitude)	+/- 30ft (TBC)	+/- 50 ft (TBC)
3	**Air Data Computer Typical**	ARINC 706 Subsonic Air Data System.	Industry standard for last generation ADCs – output used to display altitude. Typical of Boeing 757/767 type architecture.	Scaled to altitude (allowable error increases with altitude)	+/- 20ft	+/- 30ft
4	**Air Data Module Accuracy MOPS**	ED-140	New minimum performance standard. Not yet adopted, but typical in modern transport aircraft (e.g. A320).	+/- 0.25hPa	+/- 9ft	+/- 11ft
5	**Position Error (Static Source)**	CS 2x.1525	Static system performance from aircraft certification specifications. Excludes instrument calibration error. Similar for all aircraft types.	+/- 30ft at Sea Level per 100knots		
6	**Altitude Encoder**	SAE AS8003 (ETSO-C88a)	Encoded data output (to transponder). MOPS for stand-alone encoder.	• Correspondence +/- 125 ft max • At transition point +/- 75ft	Same	Same
7	**Transponder Altitude Data Correspondence**	ED-26	Similar to above, but cited as transponder system performance in TGL13, AMC 20-13 etc.	• Correspondence +/- 125 ft max • At transition point +/- 75ft		
8	**Latency**	Not explicitly stated.	Error due to processing time between pressure sensing and altitude display.	Not specified	Minimal	Minimal

9	**Data Resolution**	ED-73C (ETSO-C112c) Transponder MOPS	This is the resolution of the data as transmitted by the transponder. If the altitude data source to the transponder is Gillham coded, as on older/simpler aircraft, then irrespective of resolution of the transponder output, the source is only 100ft.	Transponder output: • 100ft (Gilham Code) • 25ft other	Up to 51 ft (for Gillham) Up to 13ft for other	Up to 51 ft (for Gillham) Up to 13ft for other
10	**Temperature (correction)**			4% for every 10degC		

Notes

- Items 1 through 5 (and 8 and 10) contribute to the accuracy of the altitude displayed in the cockpit.
- Aircraft systems would not be subject to all items 1 through 4. Dependent upon aircraft altimeter system design, just one of these values would be used.
- Items 8 and 10 included for fuller picture of considerations but not taken into account separately in further notes below.
- Items 6, 7 and 9 are added to the aircraft displayed value and represents transponder Mode C output.
- Aircraft system would not be subject to both items 6 and 7 – they are essentially equivalents and represent the same issue.

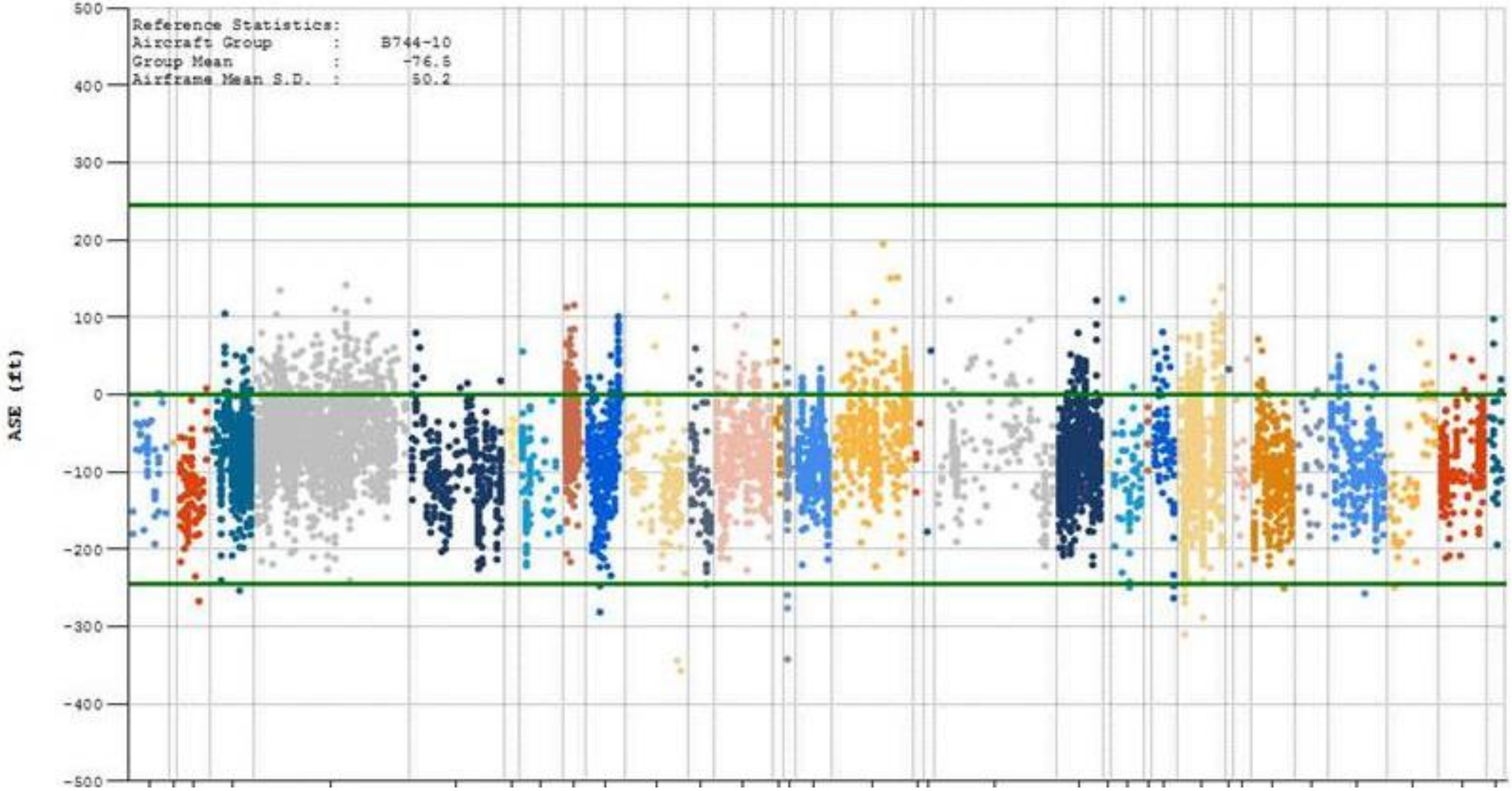
Typical (example) <u>maximum</u> error accumulation for a simple GA aircraft:
The total display tolerance would be the <u>sum</u> of items 1 and 5. For the Mode C output then <u>add</u> possible sum of errors from items 6 and 9 (chance that this is Gillham coded).

Typical (example) <u>maximum</u> error accumulation for a Boeing 757 generation Transport aircraft:
The total display tolerance would be the <u>sum</u> of items 3 and 5. For the Mode C output then <u>add</u> possible sum of errors from items 6 and 9 (likely to be 25ft resolution).

Typical (example) <u>maximum</u> error accumulation for a later Transport aircraft:
The total display tolerance would be the <u>sum</u> of items 4 and 5. For the Mode C output then <u>add</u> possible sum of errors from items 6 and 9 (likely to be 25ft resolution).

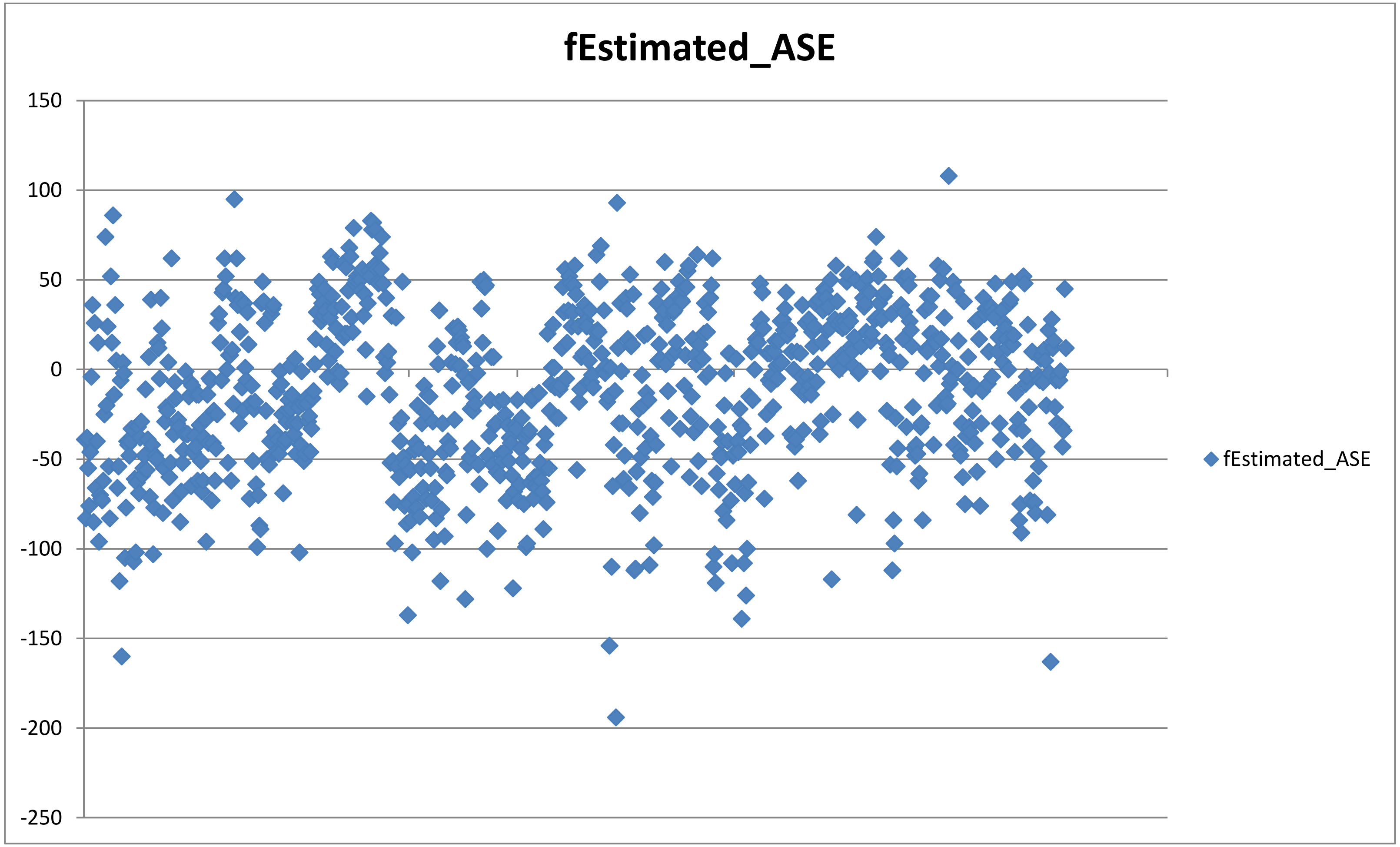
Appendix 2 to Annex C

ASE for Boeing 747-400 Operators passing STRUMBLE



Appendix 3 to Annex C

ASE Data for Aircraft of Commercial Operator Passing STRUMBLE in February 2013



The Fleet mean ASE for this commercial operator in February 2013 was -11.5ft, based on 906 flights of 106 airframes (flights not equally distributed between airframes) between FL290 and FL410 (flights not equally distributed between FLs).

Annex D

Effect of an Altimeter Sub-Scale Setting Change on Automated Aircraft

1 **Airbus.** When the aircraft is in level flight beneath the final, programmed, cruise level ("ALT" (altitude hold) mode), Airbus aircraft will not react to an altimeter sub-scale setting change that is initiated after altitude capture ("ALT* (altitude capture) mode). Altering the altitude to react to such a change would require the flight crew to interact with the Flight Control Unit (FCU) – Boeing refer to this as the Mode Control Panel (MCP) – in order to re-capture the cleared level.

2 **Boeing.** There are 2 automatic modes of operating the height keeping of an aircraft; each provides a unique reaction to a change in the altimeter sub-scale setting and are determined, to an extent, by the age of the airframe:

a. **Vertical profile determined by output from the "static source" via the Air Data Computer (ADC).** A change to the altimeter subscale setting will change the indicated altitude on the altimeter but the aircraft will remain at the previously captured pressure level and will not change level. In this mode, re-capturing the cleared level would necessitate the engagement of a vertical mode (vertical speed) to re-capture the cleared level.

b. **Vertical profile determined by output from the Flight Management Computer (FMC).** The alt/FL indicated on the active line on the "Legs" page of the FMC will be followed by the autopilot so that the indicated altitude on the altimeter will be recaptured to that programmed on the FMC.

3 **Other.** It is considered likely that other airframe manufacturers will have similar system design logic to that utilised by Boeing or Airbus. For instance, Gulfstream have confirmed that on their 'PlaneView' equipped aircraft, when the Automatic Flight Control System (AFCS) is in ALT Hold mode and the aircraft's altimeter setting is changed, the aircraft will manoeuvre to maintain the cleared level.

Annex E

Summary of Eurocontrol ACAS Analysis

1 **Level Flight ACAS Interactions.**

a. No ACAS RA event was recorded in level flight nominal VSM interactions, in all altitude bands, utilising a 6 hPa tolerance.

b. Due to the vertical threshold activation minima, all nominal VSM interactions within the lateral threshold criteria, that utilised a 6 hPa tolerance, resulted in a ACAS TA event. For comparison purposes, absolute VSM interactions that take place within the lateral threshold criteria do not result in a ACAS TA; thus the use of a 6hPa tolerance generates an adverse safety effect which would require further analysis to assess its tolerability.

c. Nominal VSM interactions within the lateral threshold criteria that utilise a 5 hPa tolerance will be less likely to result in a ACAS TA event. Those using a 4 hPa tolerance will be much less likely to result in a ACAS TA event; however, it is not possible to quantify this probability. Nevertheless, the use of a 4 hPa variance would significantly ease the creation of a supporting safety argument and would also provide a buffer from the most critical effects in order to cater for unintended cumulative error.

2 **Climb/Descent ACAS Interaction.** Interactions assessed by Eurocontrol were as follows:

a. Aircraft climbing to an altitude a nominal 1 000 ft below an aircraft in level flight.

b. Aircraft descending to an altitude a nominal 1 000 ft above an aircraft in level flight.

Note 1. In terms of ACAS II logic, there is no difference between any of these scenarios.

Note 2. Except where specified, Eurocontrol utilised the stipulated maximum Rate of Climb/Rate of Descent (RoC/RoD) of 1 500 feet per minute (FPM) in the final ‘1 500 ft to go to a cleared level’.

3 The analysis determined that:

a. No ACAS RA events were recorded in scenarios 2a and 2b, in all altitude bands, utilising a 6 hPa Tolerance.

b. Due to TCAS II vertical threshold activation minima, all VSM interactions, either nominal or absolute, that occurred within the lateral threshold criteria, resulted in a ACAS TA. That said, the analysis determined that a ACAS TA event may occur approximately 7-secs ‘earlier’ in a nominal VSM environment, using a 6 hPa tolerance, than in an absolute VSM environment.

4 Eurocontrol were also requested to determine a minimum RoC/RoD that would activate a ACAS RA in all relevant altitude bands; the following tables provide this information.

a. The two tables indicate the different points at which a ACAS RA would be generated in the respective aircraft; A in level flight and B descending towards a datum altitude above A.

b. The simulation was run with both nominal (using a 6 hPa tolerance) and absolute VSM; the number in brackets in column 2 relates to the RoC/RoD required to generate a ACAS RA in aircraft separated by absolute VSM.

Aircraft A (level)	Vertical rate of B at first RA *
1000ft – 2350ft	3025ft/min (3400)
2350ft – 5000ft	2650ft/min (2925)
5000ft – 10000ft	2400ft/min (2825)
10000ft – 20000ft	2175ft/min (2600)

Aircraft B (descending)	Vertical rate of B at first RA *
1000ft – 2350ft	3225ft/min (3250)
2350ft – 5000ft	2425ft/min (2800)
5000ft – 10000ft	1850ft/min (2325)
10000ft – 20000ft	1550ft/min (1850)

Eurocontrol ACAS Analysis – Embedded Document

Please see following pages for the contents of this document.

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EUROCONTROL

TCAS analysis for UK CAA

Input for HETA safety studies: final results

27 May 2014

Stan Drozdowski & Ben Bakker
EUROCONTROL

Tools and methodology

- Tools:
  - Encounter generator(make_enc_7.5): Microsoft Excel-based tool that allows definition of a single encounter or series of encounters that are variations on a theme
  - Interactive Collision Avoidance Simulator (InCAS 3.0 Pro): PC-based TCAS logic simulator that can simulate a single encounter (interactively) or series of encounters (batch processing)

- Methodology for each scenario:
  - Initial investigation using single encounters to identify meaningful variations on the theme
  - If meaningful, generation and simulation of the resulting series of encounters and analysis of the resulting InCAS statistics using Microsoft Excel

Notes

- Encounters are mathematically constructed and output by make_enc as radar data with 4s update rate in .eu1 format
- InCAS reads the radar data and constructs an interpolated trajectory with 1s update rate that emulates the output of the TCAS surveillance function, taking into account intruder transponder version (25ft or 100ft increment altitude reporting)
- Consequently, theoretical and actual HMD and VMD are not always identical in particular in case of manoeuvring aircraft
- Results presented hereafter are representative for real-world situations, in the understanding that real-world surveillance variability may lead to somewhat different results on a case-by-case basis
    - InCAS performs simulations using the certified TCAS II collision avoidance logic

Notes (cont.)

- Real-world surveillance variability (in particular variability resulting from 25ft or 100ft increment altitude reporting) also interacts with altimeter variability
- The table to the right shows the actual separation dependent on variance of altimeter sub-scale settings
- ZTHR is a relevant TCAS altitude threshold; the value for TA is 850ft; consequently (if other conditions are met as well) a 5hPa difference is likely to cause a TA and a 6hPa difference is very likely to cause a TA whilst smaller differences are unlikely to cause a TA

hPa	30ft	27.3ft
1	970	972.7
2	940	945.4
3	910	918.1
4	880	890.8
5	850	863.5
6	820	836.2

Notes (cont.)

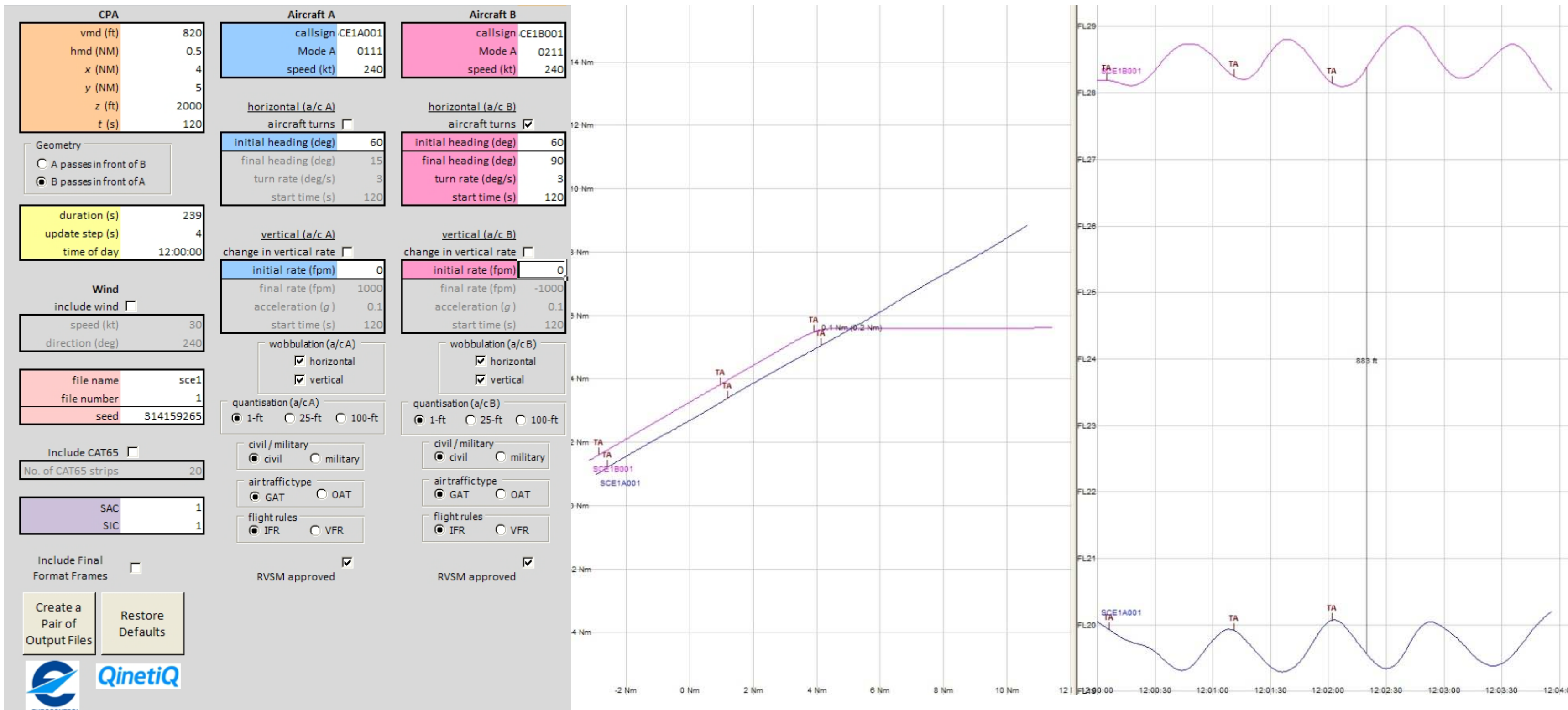
- All InCAS simulations are performed using barometric altitude, i.e. 0ft is at Mean Sea Level (in real-world situations the lower altitude layers are influenced by the use of radar altitude in TCAS)
- InCAS simulations involving RAs assume standard pilot responses to these RAs (in real-world situations the actual pilot response may provide different RA sequences and timings)

Scenario 1

- **Two aircraft in level flight, within 1nm laterally and separated vertically by 820ft**

- Initial investigation
  - Sce11: A and B initially at 0.5nm laterally with identical speed and heading. After 120 sec B turns and crosses A.
  - Sce12 and Sce13: A and B at 0.5nm with identical headings. A overtakes B.
  - Sce14: A and B at 0.1nm with identical headings. A overtakes B.
  - Horizontal wobbulation (a combination of wobble and modulation, typical for aircraft motions) is on in Sce11, Sce12, Sce13 and Sce14. Vertical wobbulation is on in Sce11 and Sce12.

Sce11



Analysis: TA conditions are met in principle from the beginning until the aircraft are diverging. Vertical wobbulation causes interruptions (when relative altitude exceeds 850 ft or relative altitude rate is less then -1 ft/min). TAs last 19 sec, 7 sec and 13 sec.

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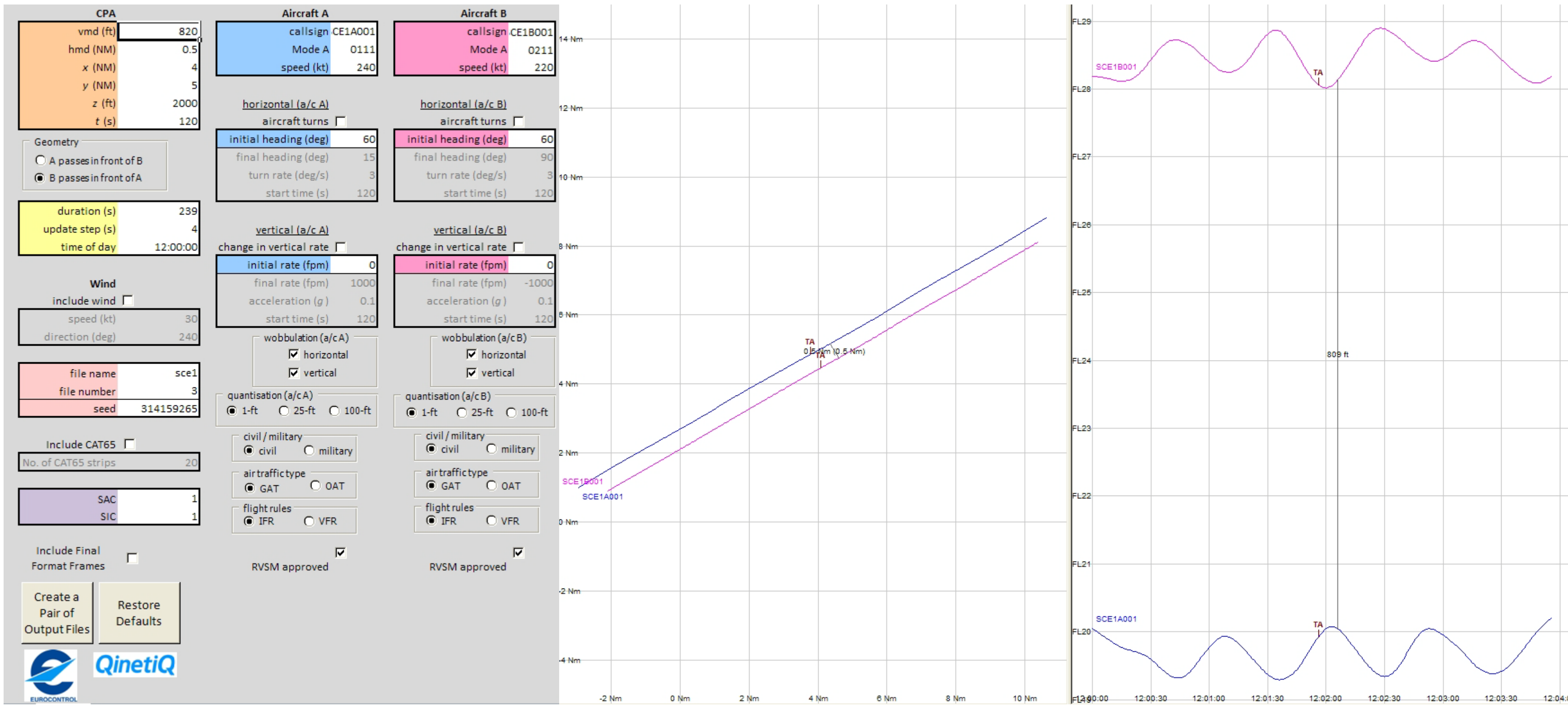
Sce12



Analysis: TA conditions are met in principle around the time that A passes B. Vertical wobbulation causes early termination of the TA (when relative altitude exceeds 850 ft or relative altitude rate is less then -1 ft/min). TA lasts 16 sec.

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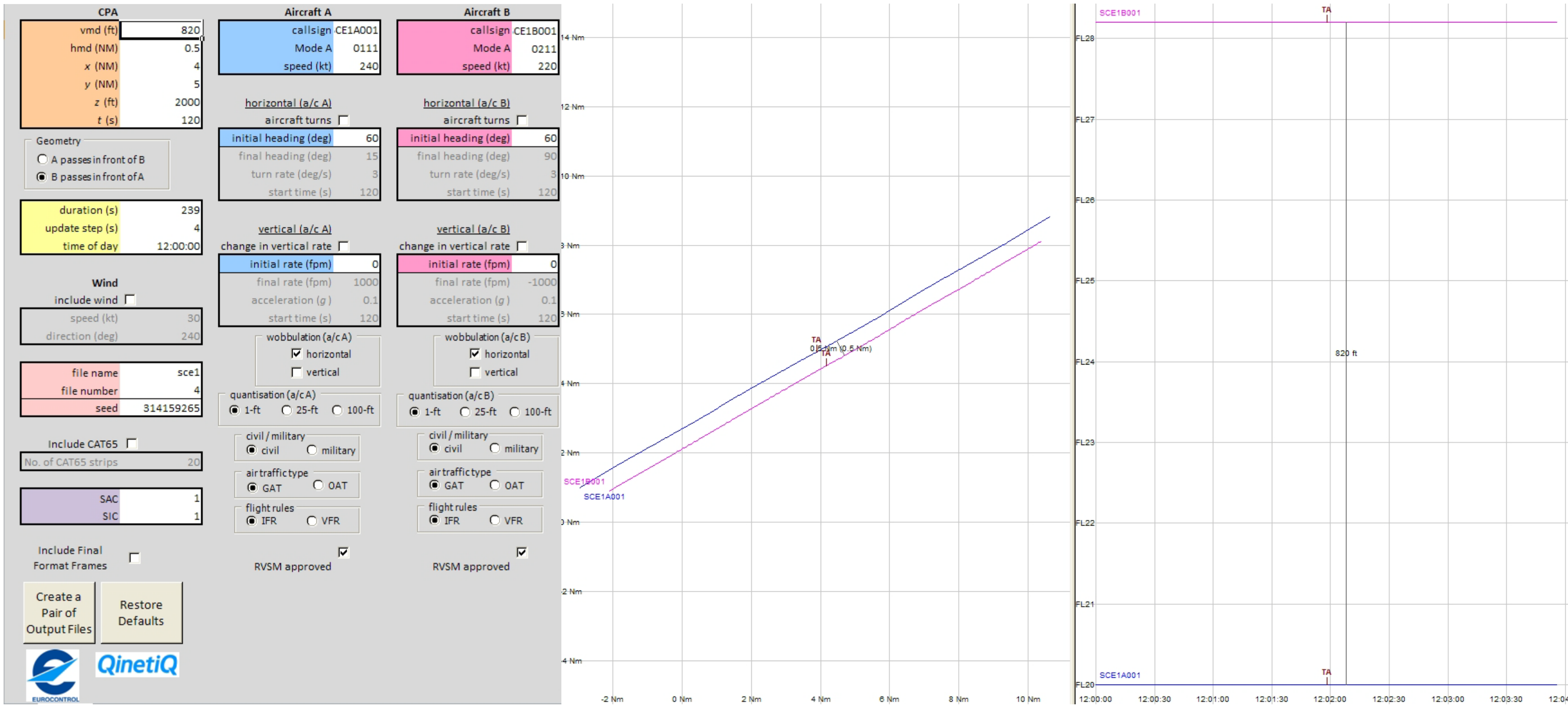
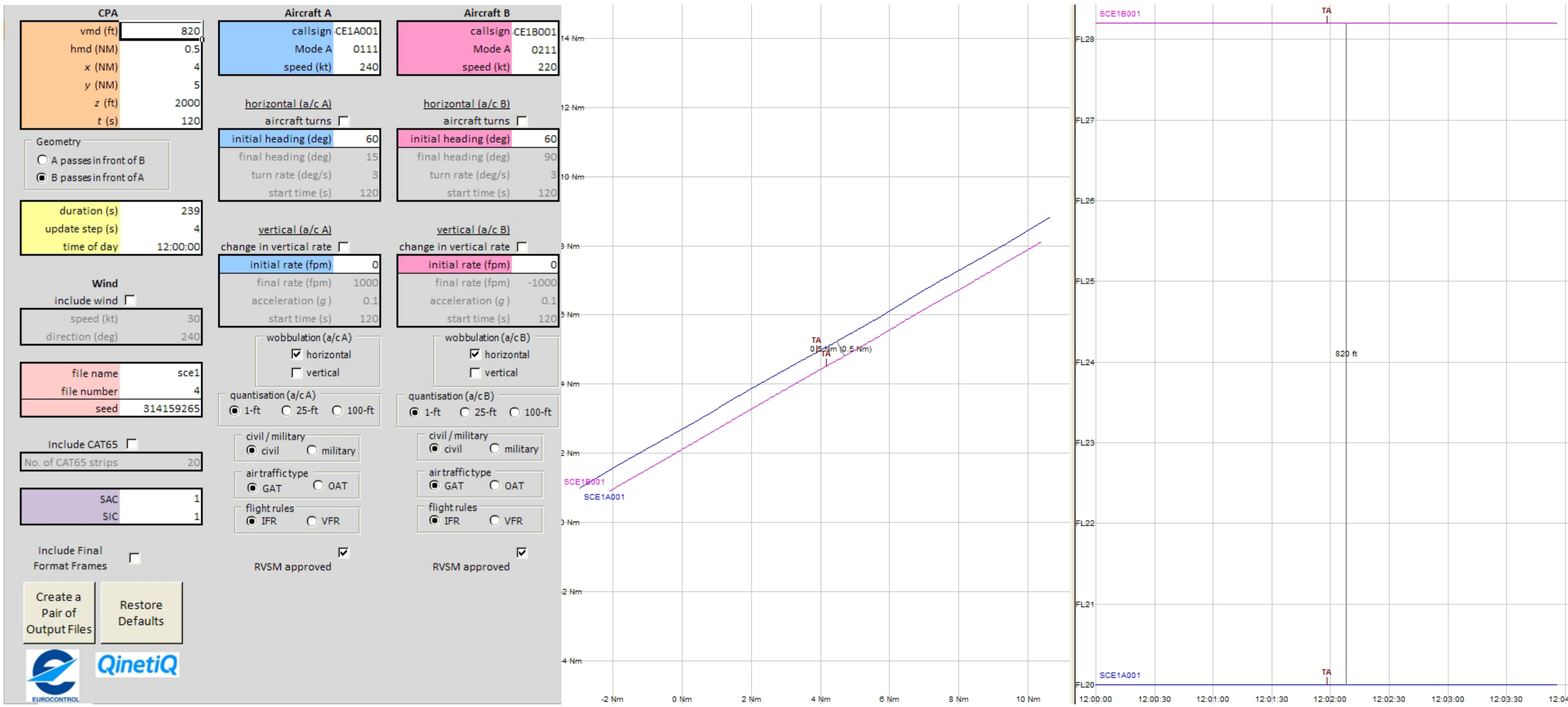
Sce13



Analysis: TA conditions are met around the time that A passes B. TA lasts 90 sec.

Sce14



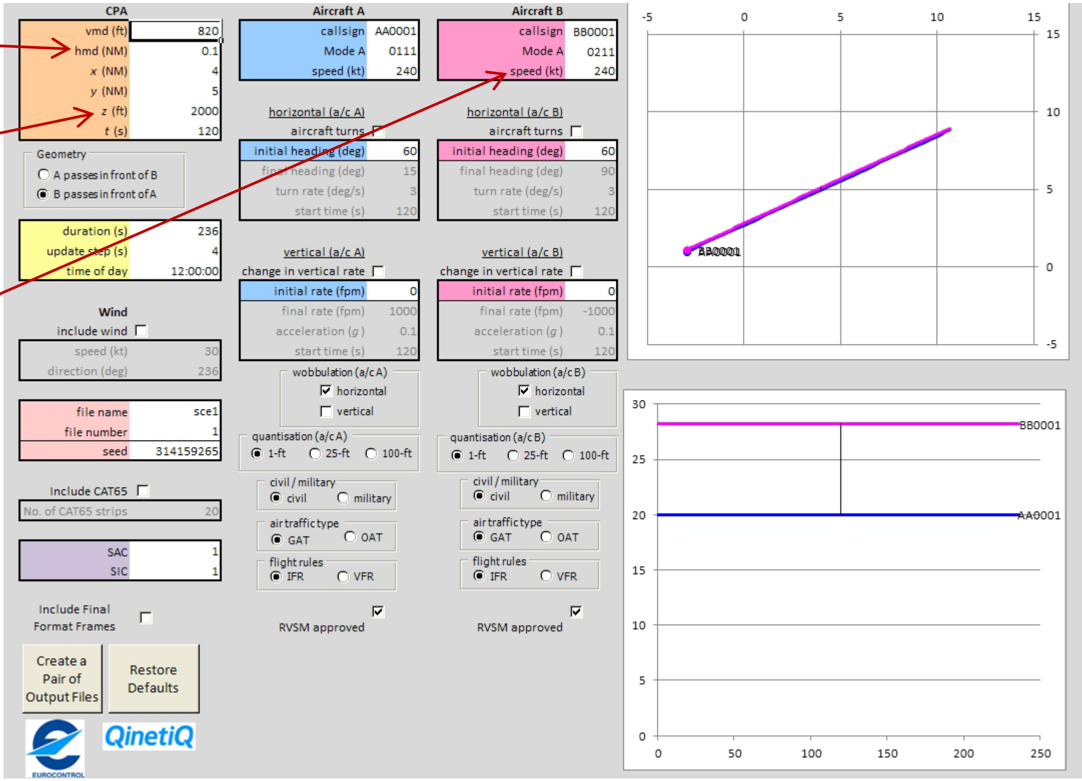
Analysis: TA conditions are met around the time that A passes B. TA lasts 204 sec.

Intermediate conclusions

- Wobbulation
  - The effects are random and can cause split TAs or change the duration of a TA
  - More appropriate in large-scale simulations
  - Not further used in this study
- Heading change, speed/HMD difference
  - No added value in heading change, added value in speed/HMD difference
- Variables for Scenario 1
  - HMD: 0.1nm, 0.2nm, …, 0.7nm, 0.8nm
  - altitude: A at 2000ft, 4000ft, …, 14000ft, 16000ft
  - speed: A at 240kt, B at 240kt, 235kt, …, 210kt, 205kt

Scenario 1 - first encounter

inner loop	middle loop	outer loop
0.1	2000	240
0.2	4000	235
0.3	6000	230
0.4	8000	225
0.5	10000	220
0.6	12000	215
0.7	14000	210
0.8	16000	205

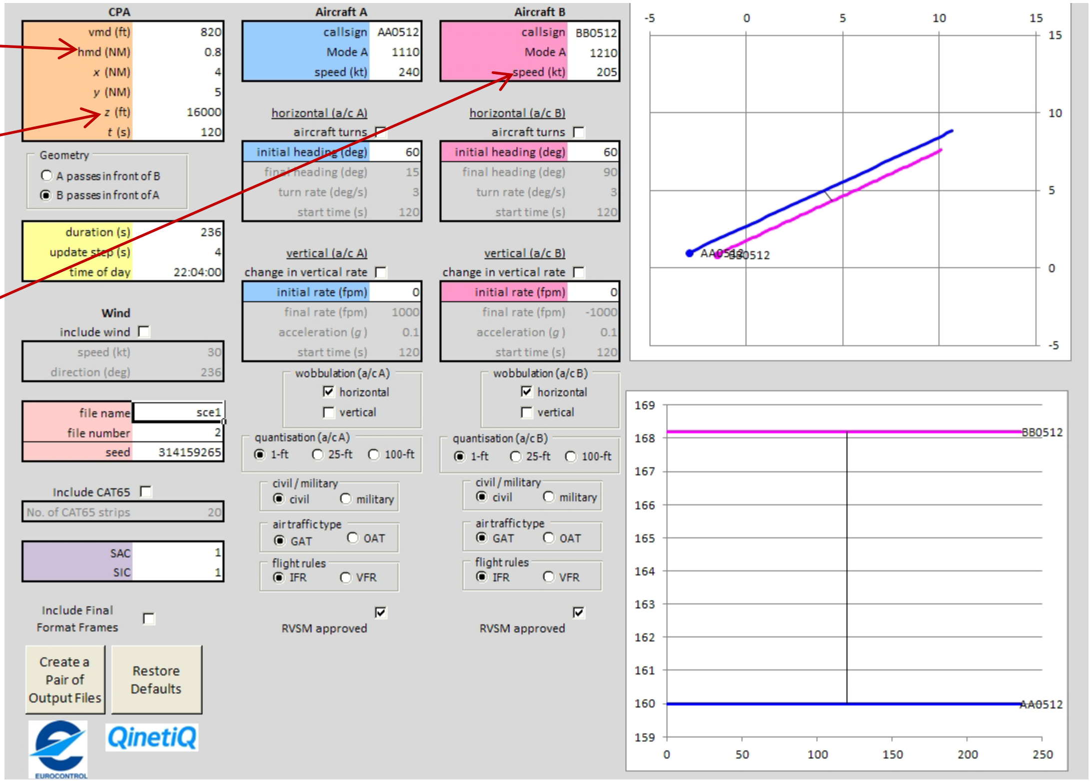


nested loops

Scenario 1 - last encounter

inner loop	middle loop	outer loop
0.1		
0.2		
0.3		
0.4		
0.5	2000	
0.6	4000	
0.7	6000	
0.8	8000	
	10000	240
	12000	235
	14000	230
	16000	225
		220
		215
		210
		205

nested loops



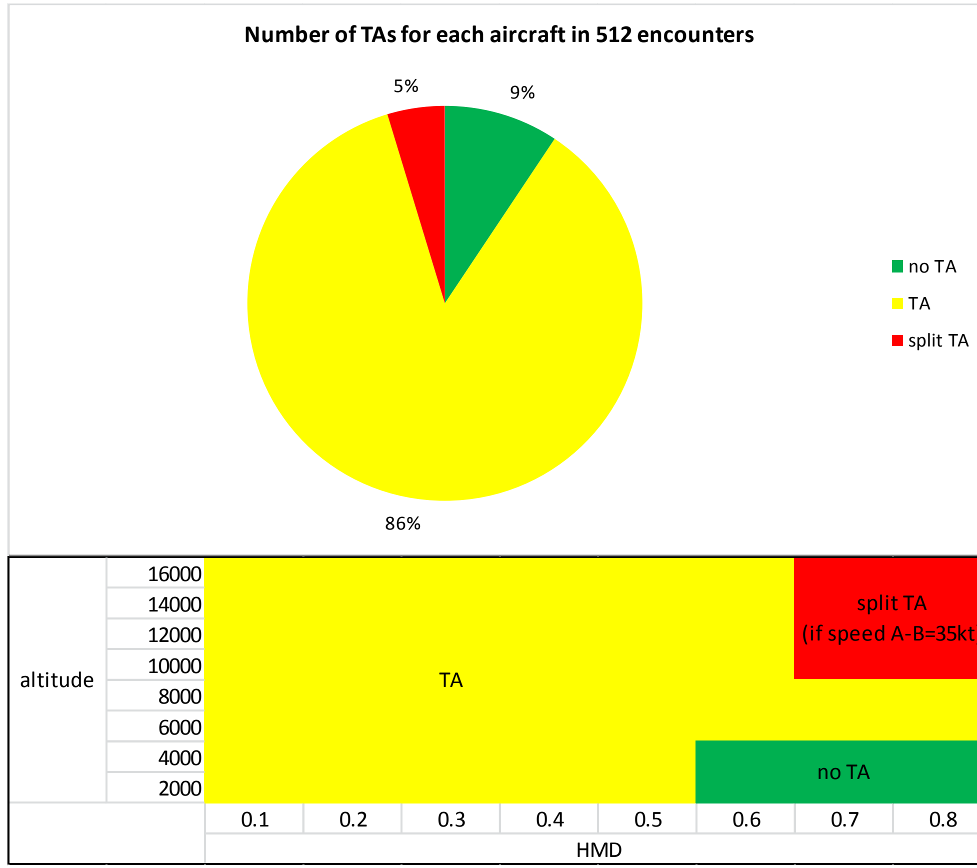
Scenario 1 – study results

No TA when HMD equals 0.6nm, 0.7nm or 0.8nm and altitude equals 2000ft or 4000ft.

Split TA when speed difference equals 35kt and altitude equals 10000ft or more, except when HMD equals 0.7nm or 0.8nm.

TA in all remaining cases.

TA on average starts 102 sec before CPA, second (split) TA starts on average 70 seconds after CPA.

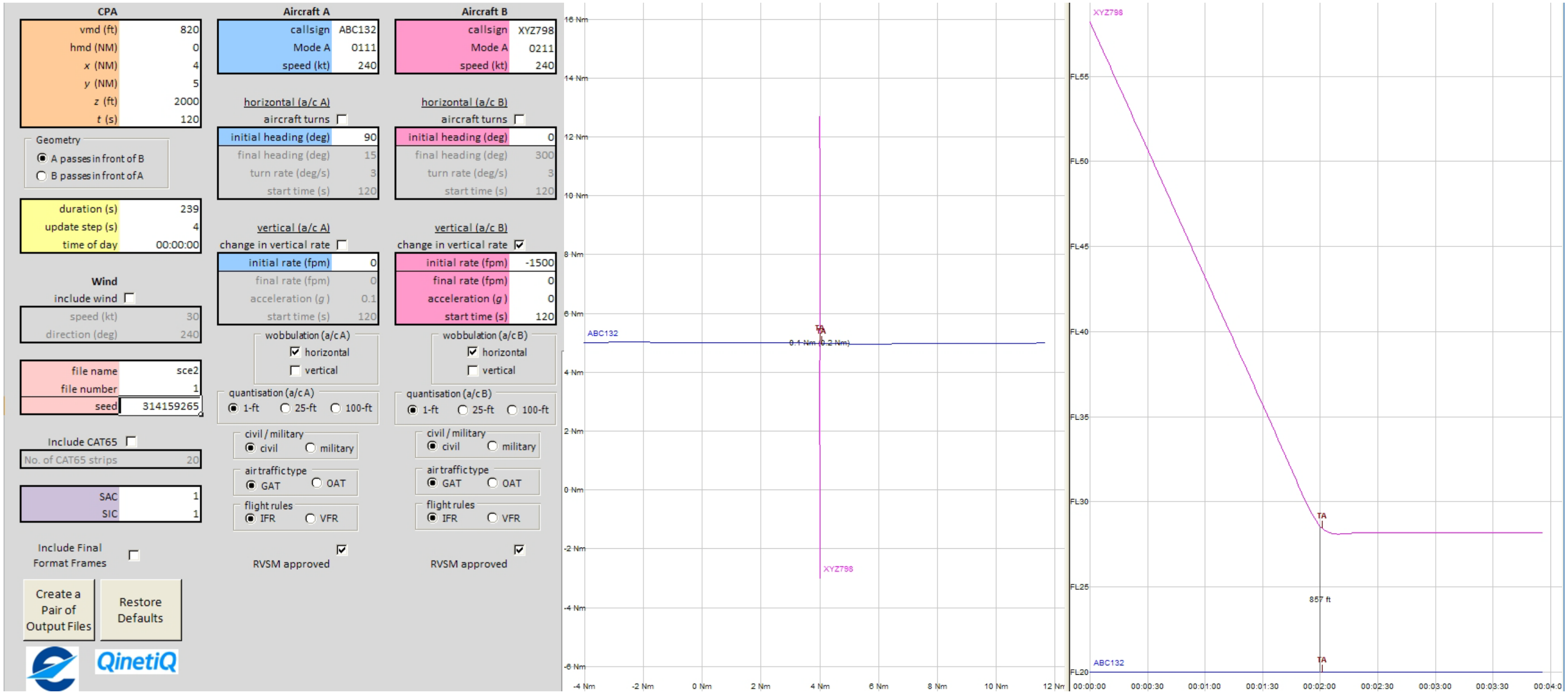


Scenario 2

- **One aircraft in level flight, one aircraft descending to an altitude 820ft above, within 1nm laterally**

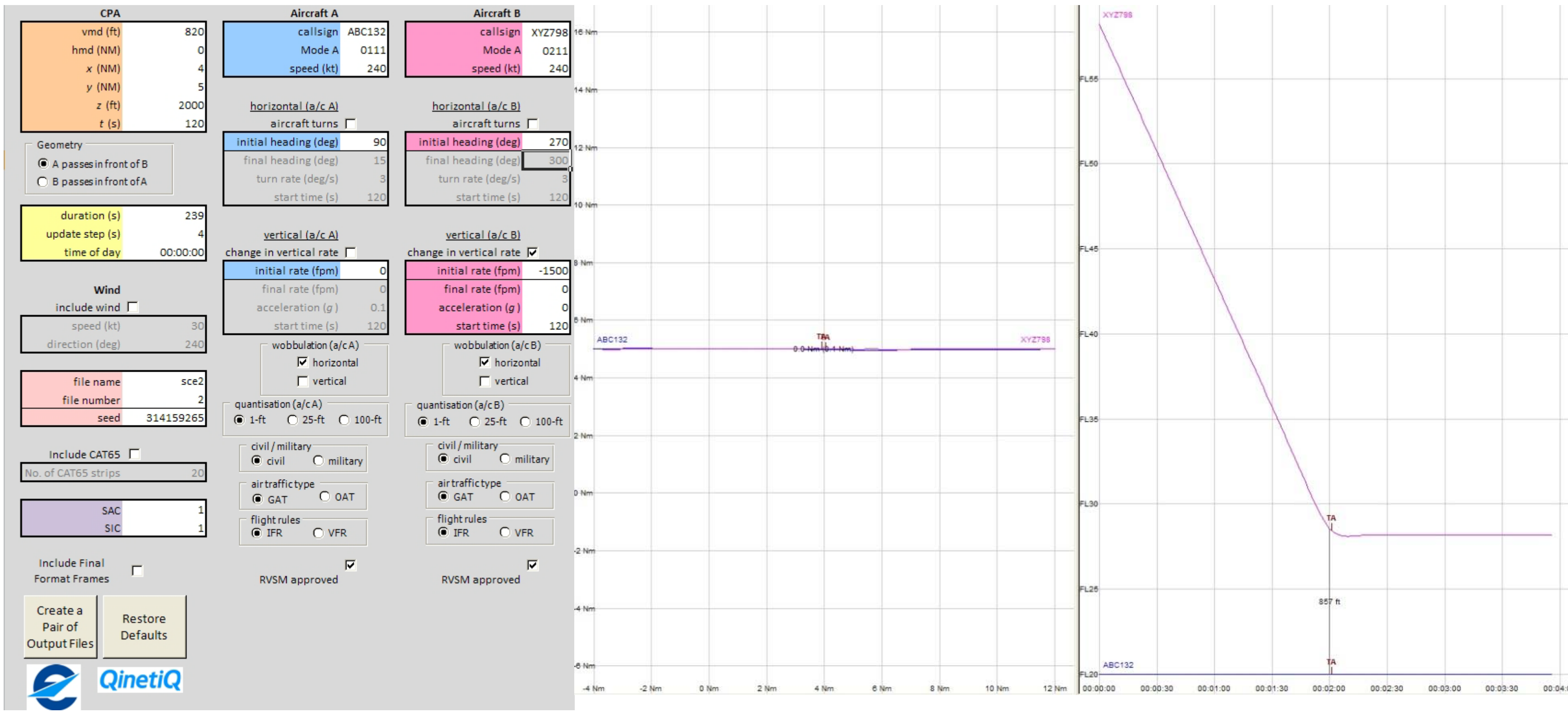
- Initial investigation
  - Sce21: CPA at 0nm and 820ft. Crossing tracks, vertical rate before level off 1500ft/min.
  - Sce22: As Sce21 but head-on tracks.

SCE21



Analysis: TA conditions are met when relative altitude drops below 850 ft. TA lasts 3 sec.

SCE22



Analysis: TA conditions are met when relative altitude drops below 850 ft. TA lasts 3 sec.

Intermediate conclusions

- Relative heading has little or no effect, except for small values (refer to scenario 1)
  - Note that the 850ft threshold is valid below FL420 and therefore Sce21 and Sce22 are valid for all altitudes of interest
  - Note that the observations are valid for all vertical rates up to 1500ft/min (the maximum rate vertical rate recommended by ICAO during the last 1000ft before levelling off when the adjacent level is occupied)

- Variables for Scenario 2:
  - None

Scenario 2 – study results

TA in all cases.

TA starts just before levelling off (but only when the aircraft are sufficiently close and converging) and ends when the aircraft are diverging.

No RA in all cases.

Note: Results are valid for all altitude layers up to 18000ft, provided that the vertical rate does not exceed 1500ft/min.

Scenario 3

- **One aircraft in level flight, one aircraft climbing to an altitude 820ft below, within 1nm laterally**

- Initial investigation
  - From a TCAS perspective this geometry is identical to the geometry in Scenario 2

Scenario 4

- **Two aircraft in level flight, within 1nm laterally and separated vertically by 850ft (based on a 5hPa variance between the two aircraft altimeter sub-scale settings), where one aircraft is instructed to change their altimeter sub-scale setting by 1hPa, leading to the aircraft adjusting it's altitude and reducing vertical separation to 820ft**

- Initial investigation
  - Not performed and no longer required

Scenario 5 – follow-up question

- **What is the minimum vertical rate required to generate a TCAS RA in all altitude bands up to 18000ft?**

- Scenario 5
  - A and B are on the same heading with the same ground speed flying on top of each other
  - B descends and levels off 820ft above aircraft A

- Variables for Scenario 5
  - altitude: A at 1000ft, 3000ft, …, 9000ft, 11000ft
  - Vertical rate: B at 1525ft/min, B at 1550ft/min, …, 3975ft/min, 4000ft/min

- Baseline scenario
  - As above but B descends and levels off 1000ft above aircraft A

Scenario 5 - first encounter

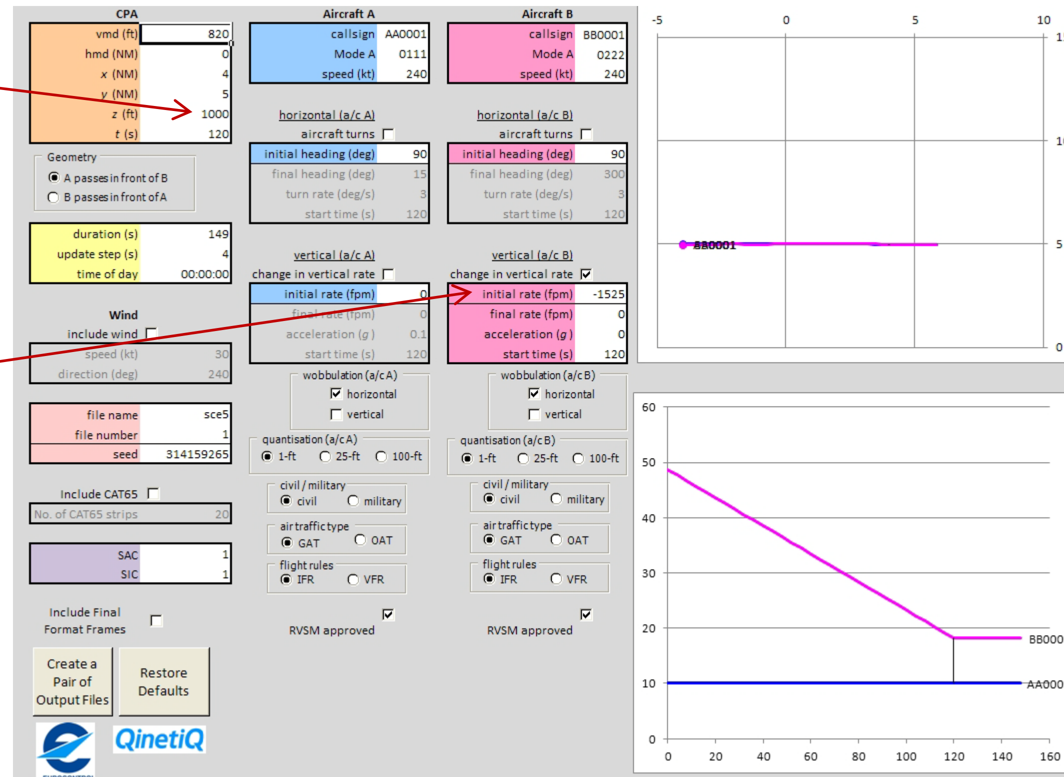
1000
3000
5000
7000
9000
11000

inner loop

1525
1550
1575
…
3950
3975
4000

outer loop

nested loops



Scenario 5 – last encounter

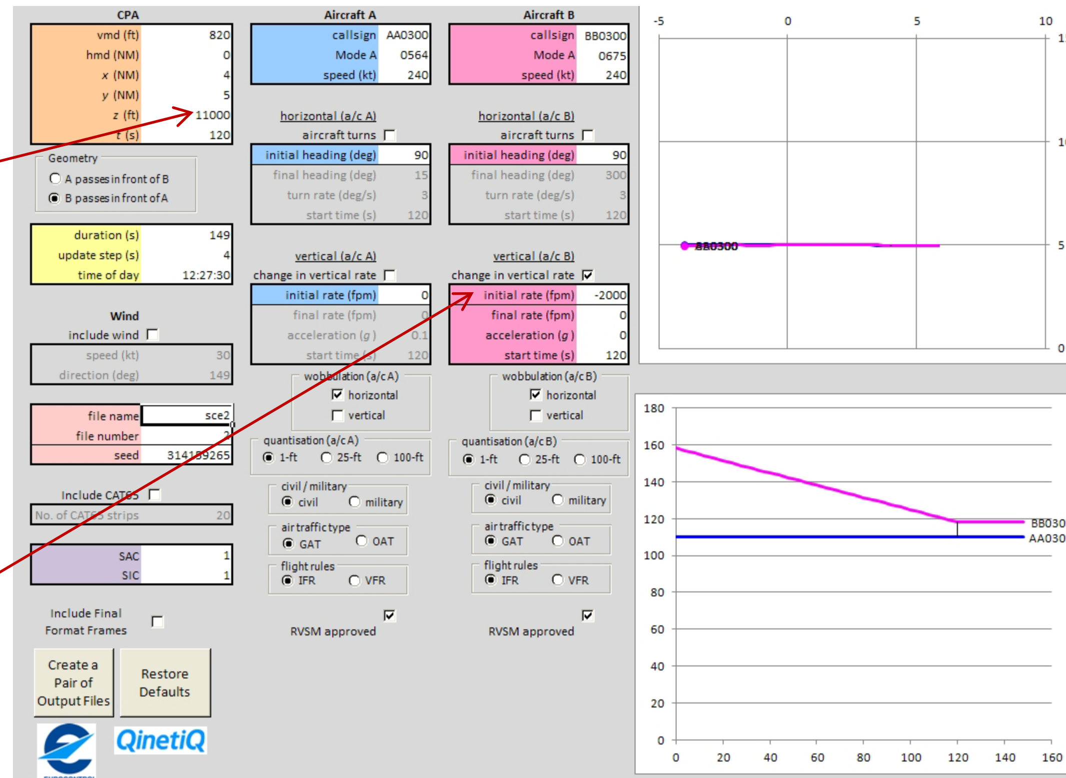
1000
3000
5000
7000
9000
11000

inner loop

1525
1550
1575
...
3950
3975
4000

outer loop

nested loops



Scenario 5 – study results

Aircraft A (level)	SL	Vertical rate of B at first RA *	Total number of RAs **
1000ft – 2350ft	3	3025ft/min (3400)	38 (23)
2350ft – 5000ft	4	2650ft/min (2925)	36 (23)
5000ft – 10000ft	5	2400ft/min (2825)	46 (43)
10000ft – 20000ft	6	2175ft/min (2600)	6 (8)
Aircraft B (descending)	**SL**	**Vertical rate of B at first RA ***	**Total number of RAs ****
1000ft – 2350ft	3	3225ft/min (3250)	32 (29)
2350ft – 5000ft	4	2425ft/min (2800)	64 (49)
5000ft – 10000ft	5	1850ft/min (2325)	87 (68)
10000ft – 20000ft	6	1550ft/min (1850)	99 (87)

(number) is value for baseline scenario

* No RAs generated below the rate indicated
** In 100 encounters per layer

Annex F

TCAS II SENSITIVITY LEVEL DEFINITION AND ALARM THRESHOLDS[36]

Aircraft Altitude	**Tau (Seconds to CPA)**	**Vertical Bubble (ft) Assumes RoC/RoD 1500 fpm**	**Tau (Seconds to CPA)**	**Vertical Bubble (ft) Assumes RoC/RoD 1500 fpm**	**Projected Lateral minima at which ACAS will annunciate (nms)**		**Projected Vertical minima at which ACAS will annunciate (ft)**	
	TA		**RA**		**TA**	**RA**	**TA**	**RA**
1 000-2 350 (AGL)	25	625	15	375	0.33	0.20	850	600
2 350-5 000	30	750	20	500	0.48	0.35	850	600
5 000-10 000	40	1000	25	625	0.75	0.55	850	600
10 000-20 000	45	1125	30	750	1.00	0.80	850	600

Tau – How far ahead the aircraft 'looks' in time, differentiated by altitude band.

Vertical Bubble (ft) – How far ahead the aircraft 'looks in space', based upon a maximum RoC/RoD of 1500ft per minute.

Projected Lateral minima at which ACAS will annunciate (nms) – The actual distance between aircraft at which time a ACAS alert will be annunciated.

Projected Vertical minima at which ACAS will annunciate (ft) - The actual vertical distance between aircraft, at which time a ACAS alert will be annunciated.

[36] Introduction to TCAS II Version 7.1 dated 28 February 2011, US Department of Transportation, Federal Aviation Administration.

Annex G

MET OFFICE DATA

Airfield	ASR	Max diff (hPa)	Mean diff (hPa)	Std dev (hPa)	2 x Std dev (hPa)	Diff ≤1hPa (%)	Diff >1hPa (%)	Diff ≤2hPa (%)	Diff >2hPa (%)	Diff ≤3hPa (%)	Diff >3hPa (%)	Diff >4hPa (%)	Diff >5hPa (%)	Diff ≤6hPa (%)	Diff >6hPa (%)
Gatwick	London	2.22	0.46	0.35	0.7	91.98	8.02	99.96	0.04	100	0	0	0	100	0
London City	London	2.22	0.31	0.25	0.5	98.44	1.56	99.99	0.01	100	0	0	0	100	0
Northolt	London	0.69	0.14	0.10	0.21	100	0	100	0	100	0	0	0	100	0
Farnborough	London	1.79	0.28	0.22	0.44	99.12	0.88	100	0	100	0	0	0	100	0
Blackbushe	London	2.13	0.29	0.24	0.48	98.53	1.47	99.97	0.03	100	0	0	0	100	0
Fairoaks	London	1.0	0.14	0.11	0.22	100	0	100	0	100	0	0	0	100	0
Biggin Hill	London	1.55	0.26	0.21	0.41	99.43	0.57	100	0	100	0	0	0	100	0
Luton	London	2.82	0.56	0.42	0.85	85.73	14.27	99.3	0.7	100	0	0	0	100	0
Stansted	London	3.16	0.56	0.43	0.86	85.76	14.24	99.22	0.78	99.99	0.01	0	0	100	0
Birmingham	London	8.06	1.54	1.24	2.48	41.54	58.46	70.62	29.38	87.39	12.61	4.86	1.56	99.4	0.6
East Midlands	Potter	9.91	1.92	1.48	2.95	32.73	67.27	60.15	39.85	78.95	21.05	9.64	4.06	97.9	2.1
Southampton	London	4.26	0.71	0.56	1.12	75.47	24.53	96.65	3.35	99.75	0.25	0.01	0	100	0
Liverpool	Potter	2.19	0.34	0.29	0.58	96.58	3.42	99.99	0.01	100	0	0	0	100	0
Leeds	Potter	6.1	1.04	0.81	1.62	56.73	43.27	87.9	12.1	97.27	2.73	0.56	0.06	99.99	0.01
Warton	Potter	3.87	0.61	0.52	1.05	80.24	19.76	96.84	2.16	99.92	0.08	0	0	100	0
Blackpool	Potter	4.2	0.71	0.61	1.21	74.93	25.07	95.73	4.27	99.57	0.43	0.03	0	100	0
Birmingham	Potter	6.48	1.03	0.85	1.69	57.59	42.41	86.84	13.16	96.96	3.04	0.5	0.08	99.99	0.01
East Midlands	Potter	4.8	0.79	0.67	1.33	69.63	30.37	94.21	5.79	99.02	0.98	0.11	0	100	0
Prestwick	Kelvin	3.91	0.58	0.46	0.92	83.66	16.34	97.96	1.04	99.94	0.06	0	0	100	0
Edinburgh	Kelvin	3.89	0.71	0.57	1.13	74.49	25.51	97.04	2.96	99.72	0.28	0	0	100	0
Belfast	Kelvin	12.28	1.75	1.41	2.82	37.07	62.93	64.89	35.11	82.83	17.17	6.98	2.97	98.05	1.95
Aldergrove	Kelvin	12.09	1.77	1.4	2.81	36.23	63.77	64.32	35.68	82.85	17.15	6.95	2.97	98.13	1.87
Bristol	Avon	2.70	0.38	0.32	0.65	95.28	4.72	99.79	0.21	100	0	0	0	100	0
Exeter	Avon	3.68	0.78	0.6	1.19	70.26	29.74	95.7	4.3	99.68	0.32	0	0	100	0
St. Athan	Avon	0.83	0.12	0.1	0.19	100	0	100	0	100	0	0	0	100	0
Swansea	Avon	2.85	0.45	0.41	0.81	90.26	9.74	99.2	0.8	100	0	0	0	100	0

Notes.

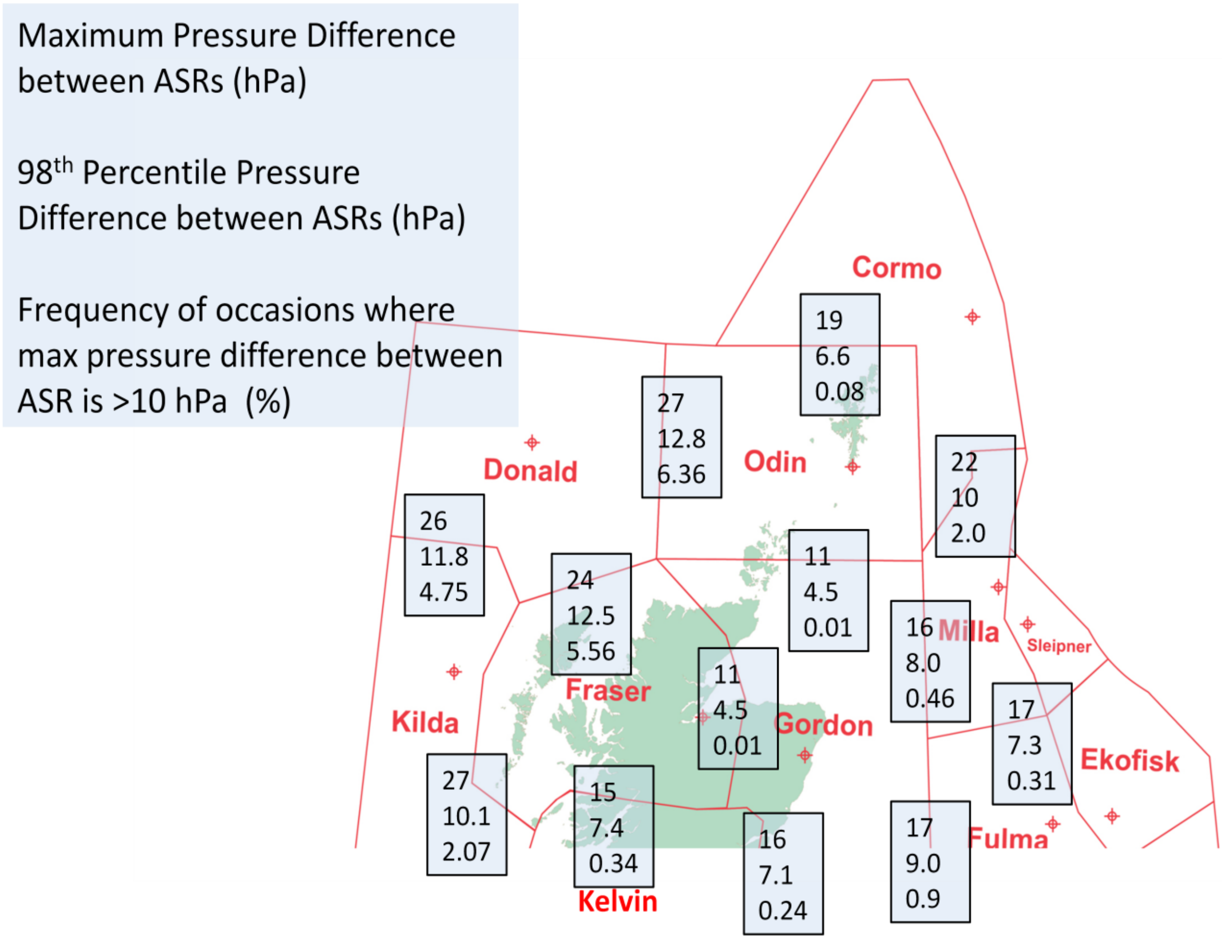
1 Data from the Met Office's North Atlantic & Europe (NAE) limited area forecast model were extracted from the archive for the 5-year study period from October 2006 to September 2011 inclusive. Occasional archive storage failures have resulted in isolated instances of missing model data including 1-15 October 2006 and 1-12 December 2006. In total, 169 model analysis data files were missing during the 5-year study period, out of a total theoretical availability of 7304, giving a data availability of 97.7%.

2 The data herein represent model mean sea level pressure at analysis time for all four runs of the model per day (00, 06, 12 & 18Z). The data are not based on METAR from the NASAS.

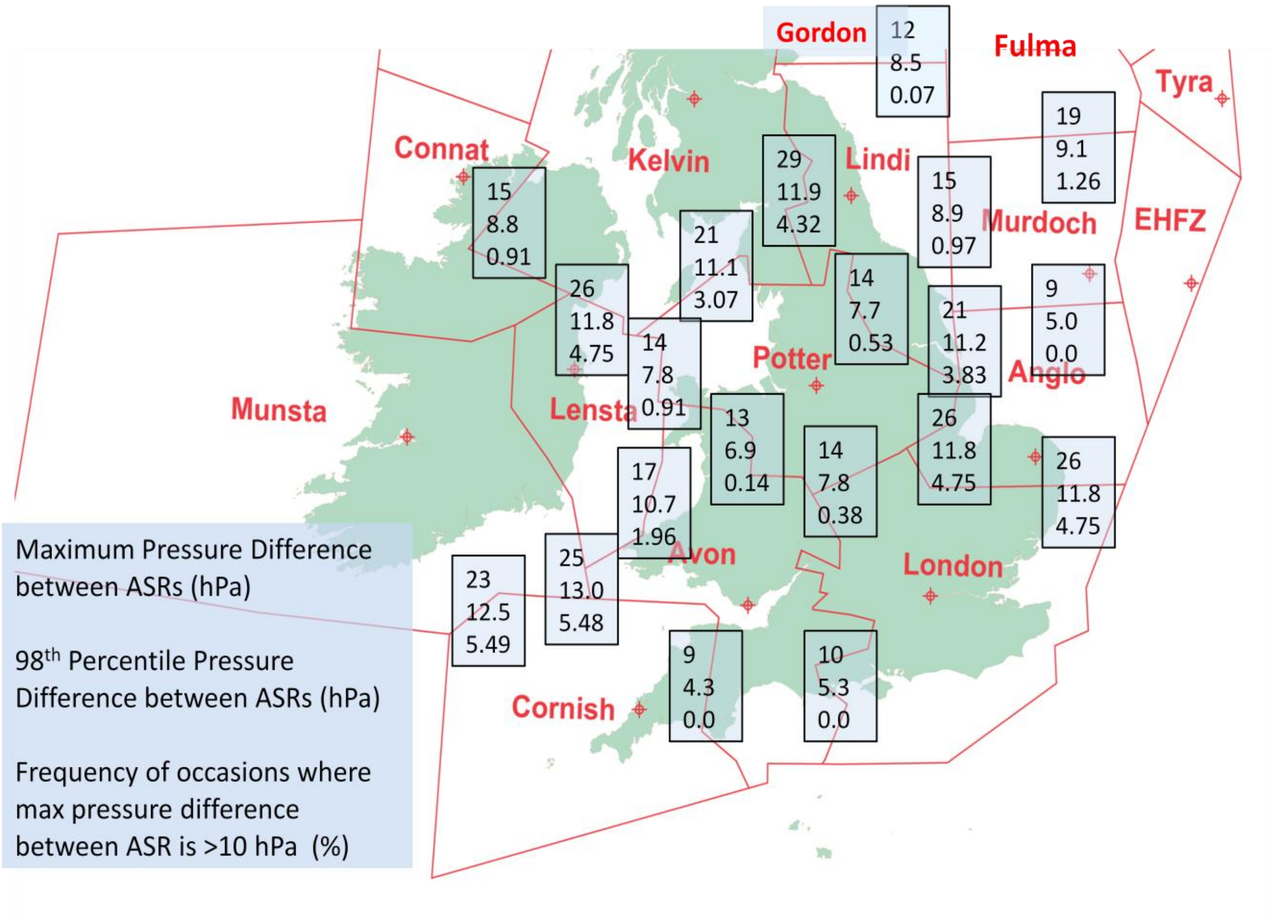
3 The columns highlighted in blue were calculated by the author, based upon the Met Office data, and represent the percentage of occasions within the data set where the aerodrome QNH was less than or equal to 1 hPa, 2 hPa and 3 hPa of the NASAS QNH.

Annex H

VARIANCE OF PRESSURE BETWEEN NASAS



Northern UK



Southern UK

Data from the Met Office's North Atlantic & Europe limited area forecast model were extracted from the archive for the 5-year study period from October 2006 to September 2011 inclusive.
Met office reference document: 'Variation of pressure between neighbouring ASRs' dated 28th January 2014.