AAIB Bulletin No: 6/2001 **Ref: EW/C2000/10/2** **Category: 1.1**

INCIDENT

Aircraft Type and Registration:	i)	Airbus A330 C-GGWD	
	ii)	Airbus A340 TC-JDN	
No & Type of Engines:	i)	2 GE CF6-80-E-1 turbofan engines	
	ii)	4 CFM56-5C4 turbofan engines	
Year of Manufacture:	i)	1999	
	ii)	1997	
Date & Time (UTC):	1422 hrs on 2 October 2000		
Location:	North Atlantic Track E at position 58° 28.4'North 016° 46.1'West		
Type of Flight:	i)	Scheduled Public Transport	
	ii)	Scheduled Public Transport	
Persons on Board:	i)	Crew - 12	Passengers - 320
	ii)	Crew - 14	Passengers - 228
Injuries:	i)	Crew - None	Passengers - None
	ii)	Crew - None	Passengers - None
Nature of Damage:	i)	None	
	ii)	None	
Commander's Licence:	i)	Airline Transport Pilot's Licence	
	ii)	Airline Transport Pilot's Licence	
Commander's Age:	i)	46 years	
	ii)	60 years	
Commander's Flying Experience:	i)	13,806 hours (of which 1,205 were on Type) Last 90 days - 205 hours Last 28 days - 56 hours	
	ii)	15,131 hours (of which 5,175 were on Type) Last 90 days - 264 hours Last 28 days - 70 hours	
Information Source:	AAIB Field Investigation		

Background

The A340 was en-route from Istanbul to New York and the A330 was en-route from London to Ottawa. Both aircraft were assigned to North Atlantic (NAT) Track E with an entry point into Oceanic Airspace of 58°North 10°West and a next reporting point of 59°N 20°W. Both aircraft were cleared by the

Scottish Oceanic Area Control Centre to cruise at Mach 0.82 with the A340 at Flight Level (FL) 360 and the A330 1,000 feet above at FL 370. The vertical separation distance of 1000 feet was in accordance with RVSM (Reduced Vertical Separation Minima) used by approved aircraft within NAT MNPS (Minimum Navigation Performance Specification) Airspace. The objective of RVSM is to reduce the vertical separation of aircraft flying between FL 290 and FL 410, inclusive, from the previous 2,000 feet to 1,000 feet, in order to improve fuel efficiency and increase traffic capacity. At the time of the incident each aircraft was using SELCAL (Selective Calling) but on different HF radio frequencies. They were beyond radar coverage but both crews were monitoring the common VHF radio frequency used for air to air messages. Both aircraft had a limiting speed at their respective flight levels of 0.86 Mach.

Meteorological situation

A meteorological aftercast described the synoptic situation at 1400 hrs UTC as a low pressure area centred to the west and south west of Iceland with an occluding front lying through 60° North and 16° West. Visible spectrum satellite pictures taken at 1400 hrs clearly showed the position of the front. A change in the height of the tropopause was very likely at or near the incident position with an associated change in air temperature across the frontal boundary. Moreover, NAT Track E lay some 150 nm to the north of the core of a westerly Jetstream with a speed of 170 kt at FL 310. The 1200 hrs NAT Significant Weather Chart showed the position of the Jetstream and the occluded front. At the incident location, NAT track E lay within the boundary of an area marked as likely to contain clear air turbulence between FL 200 and FL 400. This area was associated with the westerly flow of the Jetstream.

TCAS

The acronym TCAS is an abbreviation of Traffic alert and Collision Avoidance System. All aircraft operating within MNPS airspace must have Airborne Collision-Avoidance System (ACAS) equipment installed and TCAS is a proprietary version of this system. It detects the presence of other aircraft equipped with a functional transponder which are within the vicinity of the host aircraft and indicates their relative positions with white diamond shaped symbols on a navigation display or vertical speed indicator. When the predicted flightpath of an 'intruder' aircraft will bring it into close proximity to the host aircraft, but not necessarily on a collision course, TCAS may issue a verbal and pictorial traffic alert (known as a TA). The crew of the host aircraft hear a synthetic voice message of "TRAFFIC TRAFFIC" and the 'intruder' aircraft symbol changes to an amber coloured circle.

TAs are intended to promote increased awareness and vigilance from the pilots but they do not require a change of flight path. Should the predicted distance between two aircraft become unsafe, the TCAS equipment issues a Resolution Advisory (RA) which requires one or both aircraft to alter their flight

path to restore safe separation. If both aircraft have TCAS, the verbal and pictorial warnings are co–ordinated so that the action required in one aircraft either augments or does not counteract the action required in the other. TCAS does not issue instructions to alter heading. Instead, TCAS RAs require the flight crew either to maintain or adjust their vertical speed. There are a variety of aural warnings most of which include either the word "CLIMB" or the word "DESCEND" ; the exact wording depends on the circumstances which create a confliction.

For a descend warning, the word "DESCEND" is issued three times by a synthetic voice broadcast from the flight deck loudspeakers. At the same time, in the Airbus fly-by-wire aircraft types, the intruder aircraft is indicated by a red square symbol on the pilots' navigation displays and the required rate of descent is indicated by a green colour-coded band within the vertical speed scale of the pilots' Primary Flight Displays (PFDs).

Both aircraft were equipped with TCAS software version 6.04 which was not optimised for RVSM and this software can produce nuisance warnings. Software version 7.0, which is compatible with RVSM operations, has been developed and is being deployed.

The A330 commander's report

Both aircraft were in clear air as the A330 was slowly overtaking the A340 below it. The A330 commander stated that his aircraft was slightly to the right of the A340 and almost abeam it when he saw the A340's wings start to flex. At about that time he felt a bump, which he described as similar to entering a mountain wave. Five to ten seconds later there was another bump during which the A330's altimeter reading decreased by 200 feet. Immediately thereafter, the A330 commander heard a TCAS "climb climb" warning and he noted that the A340 TCAS symbol had changed colour to red on his navigation display. He looked out and down at the A340 which was some 200 to 300 feet to his left in a nose-up attitude and climbing steeply. The A340 passed through the A330's level before the commander had time to react to the TCAS warning and the TCAS was still issuing a "climb" instruction for a short while after the A340 had climbed above the A330. The commander continued to monitor the A340 visually and on TCAS. It appeared to reach an apogee above FL 380 although by this time it had fallen behind the A330. Nevertheless, it was still laterally quite close to the A330's track so the commander altered course to the right to make space for the A340 to descend back to FL 360. After a short discussion with the A340 crew on VHF radio, the A330 commander broadcast a warning of severe turbulence on the common VHF frequency and then reported both the turbulence and the aircraft proximity (AIRPROX) occurrence to Shanwick on HF Radio. There were no injuries on board the A330 although there were spillages in the cabin.

The A340 commander's report

At FL 360 the A340 was 1000 feet below the maximum cruising level displayed on the Flight Management and Guidance System (FMGS). The commander was expecting a turbulence encounter around 59°N 20°W and when the aircraft first entered light turbulence he made a cabin announcement and switched on the seat belt signs. Shortly before the AIRPROX event he experienced moderate turbulence and noticed outside air temperature changes. Suddenly the aircraft began to climb, the Master Warning sounded and the autopilot self-disengaged as the aircraft exceeded the speed limit of 0.86 Mach. The indicated airspeed dropped below V_{LS} (the lowest selectable) as the aircraft climbed and the commander took manual control of the aircraft because neither autopilot would engage. The crew subsequently reported the incident to Shanwick on HF radio and using their TCAS, they descended back to FL 360 in a safe area. At the time of the AIRPROX the commander estimated the aircraft were one mile apart laterally. After landing at New York the commander had the aircraft inspected by technical staff but no defects were found. There were no injuries on board the aircraft.

The commander could not remember the sequence of warnings but he did recall being unable to re-engage either autopilot which prompted him to make manual control inputs. He also remembered seeing an 'Alpha Lock' warning displayed on his Primary Flying Display.

Flight Data Recordings

The Cockpit Voice Recordings in both aircraft had over-run the event before they landed but digital flight data readouts were obtained from the aircraft by the airlines involved. Both sets of data were made available to the AAIB and subsequently to Airbus Industrie. However, since the aircraft clocks were not synchronised, there was no accurate method of determining a coherent sequence of events for both aircraft on one timescale. Therefore, a brief description of the salient data for each aircraft follows.

A330 Data

Analysis by the AAIB showed that the aircraft first received a TCAS TA (Traffic Advisory) at 14:10:08 hrs (A330 clock time) which remained active for 12 minutes until the TCAS issued an RA (Resolution Advisory) at 14:22:07 hrs. The RA persisted for about 19 seconds and the issue of a verbal "CLIMB CLIMB" command was recorded. The aircraft remained under autopilot control and within 150 feet pressure altitude of FL 370 throughout the event. Its Mach number stayed below 0.86 except for a momentary excursion to 0.87 which did not trigger an autopilot disconnect. The angle of attack was generally about 2.5° and the highest recorded value in turbulence was 3.2°. The derived wind direction remained within 10° of 240° but the wind speed varied between 68 kt and 98 kt in turbulence. In the same period the static air temperature fluctuated between –44°C and –50°C. The first fluctuation was the

most severe and there were five more cycles of decreasing severity. The overall temperature change during the turbulence encounter was a 3°C increase at FL 370. An excerpt from the A330 Data is shown at Appendix A to this report.

A340 Data

The A340 crew received a TCAS TA at 14:09 hrs (A340 clock time) alerting them to the proximity of the A330. At 14:20:40 hrs the aircraft entered a region of successive and increasing variations in wind and air temperature, which in turn caused fluctuations in pitch angle, normal g, altitude, calibrated airspeed, engine N1% and Mach number. One minute later in a particularly vigorous fluctuation, the aircraft's Mach number briefly increased to 0.87. This speed excursion above the Mach 0.86 limit triggered a Master Warning at 14:21:40 and automatically disengaged the autopilot. One second later the TCAS issued an RA with a "DESCEND, DESCEND, DESCEND"audio warning. In the two second period after the initial speed excursion above Mach 0.86 the Mach number decayed to 0.855 and then increased again to 0.882. It remained above 0.86 for two seconds before decreasing and remaining below 0.86 for the remainder of the turbulence encounter.

Five seconds after the autopilot disengaged, the thrust levers were closed and then the autothrust was disconnected, probably by the handling pilot in an effort to prevent another overspeed condition. Ten seconds after the autopilot disengaged, the corrected or phase-advanced angle of attack (a computed parameter which is not recorded but can be calculated by Airbus Industrie from the DFDR data) reached the *'alpha prot'* value. This angle of attack excursion beyond *alpha prot* caused a change in the pitch flight control law from normal law (N_Z law) to angle of attack protection law (AoA law). If both sidesticks are at neutral, the AoA protection law seeks to hold the angle of attack constant at *alpha prot* until a sidestick pitch command is made. If the stick is pulled fully aft then the angle of attack increases to *alpha max*. If the sidestick is not moved aft, AoA protection law remains active until a nose-down command greater than half forward travel is made or until a nose down sidestick input has been applied for more than one second. The first recorded sidestick input was made at 14:22:08 which was some 28 seconds after the commencement of the Master Warning.

For 18 seconds after the autopilot disengaged the aircraft remained within 200 feet altitude of FL 360 but once AoA law was invoked at 14:21:50 hrs, the aircraft's attitude began to pitch nose-up. The pitch-up trend continued for 17 seconds reaching a peak of 15° nose-up shortly before the first nose-down sidestick command was applied. Throughout this phase the aircraft climbed rapidly (reaching a peak rate of about 6,000 ft/min) due to the increase in lift created by the flight control system's capture of *alpha prot.* The aircraft reached its apogee at FL 384 at 14:22:28 hrs where the airspeed had decayed to 205 KIAS and 0.67 Mach even though full thrust had been applied. Throughout the turbulence

encounter, the normal g fluctuations were between 0.5g and 1.5g. The recorded wind direction remained within 20° of the mean of 240° but the wind speed varied between 67 kt and 108 kt and the static air temperature fluctuated between –42° C and –52°C. There were 7 cycles of temperature change, the second cycle being the most severe. The mean air temperature before the AIRPROX event was –46.5° C and afterwards it was –44.5°C. The crew subsequently descended back to FL 360 and successfully re-engaged the autopilot and autothrust systems.

The DFDR recorded a change from TCAS TA to RA at 14:21:41which was about one second after the Master Warning started. The RA persisted in the aircraft logic for 27 seconds by which time the aircraft was climbing rapidly through FL 372. The alert then changed to a TA which persisted for 8 seconds, ceasing as the aircraft climbed through FL 378. An excerpt from the A340 Data is shown at Appendix B to this report.

Analysis

General

Before the incident, both flight deck crews would have been aware of the presence of the other aircraft because both had received at least one 'traffic traffic' synthetic voice message and they would have seen the intruder aircraft symbol on their navigation displays about 10 minutes before the turbulence encounter.

The incident began when both aircraft deviated from their assigned flight levels whilst the lateral separation between them was less than nautical two miles triggering TCAS RA warnings in both aircraft. Initially the risk was minimal because when TCAS RAs were issued, the aircraft were about 800 feet vertically separated with transient variations in vertical speed due to the turbulence; at that stage the A340 had not begun its 'zoom climb'. The incident became serious about 10 seconds later when the A340's flight control system captured alpha prot and commenced a vigorous climb which resulted in the A340 climbing through the A330's assigned flight level whilst both aircraft were laterally separated by a few hundred feet.

A340 crew awareness

The TCAS voice message "DESCEND DESCEND DESCEND" may not have been noticed by the A340 crew because of other concurrent warnings. The logic of the A340 Fault Warning Computer (FWC) prioritises warnings and requires a period of one second between successive warnings. The sequence of aural warnings commenced with a CRC (a Continuous Repetitive Chime that also illuminated the

MASTER WARNING light) which was active for two seconds, then deactivated for one second, and then active for a further two seconds. The TCAS RA aural warning should have started at about the same time as the CRC and have been active during the five second period of near continuous repetitive chime but it probably ceased before the chime stopped. Both warnings are generated through the cockpit loudspeakers and although the respective systems can generate only one aural warning and one synthetic voice message at any moment, the loudspeakers can generate simultaneously one synthetic voice and one aural tone warning. Consequently, the crew should have heard both warnings but they may not have assimilated both. Moreover, another warning, th*e 'Cavalry Charge'* alert for autopilot disconnect, was suppressed for approximately six seconds by the FWC logic and this warning would have followed the CRC and remained active until it was cancelled by one of the pilots after a further five seconds. Therefore, the succession of aural warnings could have affected the crew's ability to assimilate a concurrent synthetic voice warning.

Even though the A340 crew may not have registered the TCAS synthetic voice message, they would have had visual indications of the TCAS generated instruction not to climb. However, they were experiencing what they described as severe turbulence, which may have made reading the displays very difficult. Also, it would have been natural for their attention to have been captured by the Master Warning triggered by the overspeed condition which took priority over the autopilot disconnect warning. That they reacted to the overspeed warning is indicated by closure of the thrust levers five seconds after the onset of the continuous repetitive chime.

Angle of Attack protection law

Once AoA law is active, rearward movement of the sidestick controls angle of attack between *alpha prot* (neutral sidestick) and *alpha max* (full aft sidestick). Forward movement of the sidestick disengages AoA protection law and the system reverts to normal pitch law. However, there is no aural or text message which informs a crew that AoA protection law has been invoked. If the sidestick is not moved from its neutral position, the pitch flight control system is programmed to capture *alpha prot* and not the airspeed that corresponds to *alpha prot* in 1g flight. Consequently, in turbulence the speed scale will probably be oscillating, the aircraft pitch angle could also be oscillating, and the change from normal pitch law to AoA protection law could be difficult to detect.

The commander's reported sighting of an 'Alpha Lock' message was probably an *alpha floor* warning on the flight mode annunciator portion of the PFDs. Alpha floor is an autothrottle function which applies full thrust, irrespective of the position of the thrust levers, if the airspeed is likely to reduce to a value approaching *alpha max.* In this incident, the A340's calibrated airspeed decreased from around 270 kt before the turbulence encounter to 205 kt at the apogee of the climb.

Aircraft response to turbulence

Changes to the A340's flightpath caused by the aircraft's flight control system response to the overspeed warning and autopilot disconnect were negligible until AoA law was triggered. The fact that this law was not triggered until 10 seconds after the autopilot disconnected was a random event driven by the severity of the turbulence. Had the turbulence been more severe at the first encounter and coincident with the overspeed warning, reversion to AoA law could have been triggered as soon as the overspeed condition disconnected the autopilot. Nevertheless, it should be noted that had the autopilot remained engaged, the AoA law would not have been invoked because it is inactive except in manual control.

Such was the vigour of the A340's climb in AoA law, the aircraft could well have climbed through FL 363 (thus provoking a TCAS RA with revised software version 7.0) in a very short time, even if the crew had applied nose-down sidestick as soon as they heard the (delayed) autopilot disconnect warning. The climb to FL 363 would have been sufficient to generate a TCAS RA in any adjacent aircraft at FL 370 but, if the intruder aircraft continues its climb, there can be no guarantee that an aircraft directly above it could respond in sufficient time to avoid a collision. Therefore, the RVSM safety case should not be driven by any assumption that a different crew might have contained the situation by making an earlier nose-down sidestick command than the A340 crew involved in this incident.

Navigation Accuracy

The safety case for RVSM is partially dependent on accurate plan position navigation. The accuracy of modern navigation systems is such that contemporary aircraft types assigned to the same airway or NAT Track will tend to be very close to each other laterally. Moreover, as aircraft navigation systems increasingly use GPS (Global Positioning System) for long-term accuracy, the tendency for aircraft to fly precisely along the same track will probably increase. Therefore, although aircraft on adjacent NAT tracks will be 60 miles apart, aircraft on the same NAT track may be vertically aligned and 1,000 feet apart. Consequently, improvements in navigation technology have reduced, and continue to reduce, any random lateral scatter between aircraft on the same track or airway. This reduction in natural scatter increases the hazard when aircraft adopt unexpected or uncommanded pitch manoeuvres.

NAT track tactical separation procedures

The need for tactical procedures to increase lateral separation between aircraft at different flight levels on the same NAT track is recognised in Edition 8 of the Operations Manual for flights within the North Atlantic Minimum Navigation Performance Specification Airspace. Special Procedures in Chapter 12 take account of the possibility of wake turbulence which is most likely to be encountered by aircraft in trail. The most probable situation is where the leading aircraft is 1,000 feet above the trailing aircraft and there is no strong crosswind component. If wake turbulence is experienced, commanders are permitted to offset their track by not more than 2 nm upwind of the designated track. However, there is no mention in the Special Procedures section of contingency measures which might augment safe separation when one aircraft overtakes another on the same track when their vertical separation is 1,000 feet.

Overtaking procedures

This incident arose (and was reported) because one aircraft was overtaking another whilst they were following the same track and vertically separated by 1,000 feet. There was no risk of a wake turbulence encounter because the leading aircraft was below the overtaking aircraft. However, there was a serious loss of separation when both aircraft entered clear air turbulence which caused the A330 to experience height perturbations and brought about a significant undemanded pitch-up manoeuvre in the A340. Moreover, although the TCAS systems in both aircraft detected the loss of separation and immediately issued appropriate warnings to the two crews, the A340 crew may not have heard the warning and the A330 crew did not have the time or aircraft performance reasonably required to take successful avoiding action. In essence, although the TCAS computers issued appropriate instructions in both aircraft, the combination of TCAS equipment, crew reactions time and aircraft performance was not capable of resolving and preventing a serious collision hazard provoked by clear air turbulence.

Risk reduction measures

This collision risk could have been reduced if the commander of the overtaking aircraft had been permitted (and expected) to temporarily increase the lateral separation between the two aircraft before they reached the line abreast position. A simulation conducted at the request of Airbus Industrie indicated that for one aircraft slowly overtaking another at high altitude, a lateral separation of 1.5 nm would be sufficient to preclude a TCAS RA if the vertical separation of two aircraft on parallel tracks was compromised. The ability to offset by up to 2 nm for wake turbulence reasons is already an approved contingency procedure and there would appear to be a safety case for extending this contingency procedure to overtaking, particularly in regions where turbulence of any kind is evident or forecast. Therefore, it was recommended on 29 November 2000 that the CAA take forward a

recommendation to the appropriate international bodies to review overtaking procedures in RVSM airspace.

ATC reporting

Whether or not aircraft are within land-based radar coverage, Oceanic ATC will not issue a clearance for a contingency lateral offset manoeuvre. However, commanders are still required to inform ATC if they take such action. Without radar coverage and with the in-built time delay through messages being received by HF radio in one place and relayed to controllers in another place, it is difficult to see what practical use ATC can make of such messages.[1] Certainly pilots are not usually able to assimilate the information because they will be maintaining an HF radio SELCAL watch. Moreover, the requirement to inform ATC may inhibit pilots from taking timely action to offset from a preceding aircraft's track. Consequently, since all aircraft in Oceanic RVSM airspace must have TCAS equipment, any safety benefit acquired through notifying ATC would appear to be of inferior use to TCAS derived information.

Because the presence of any aircraft which is a proximity threat to another aircraft will already be known to both crews via their TCAS equipment, the need to inform ATC of a lateral offset of not more than 2 nm seems superfluous when adjacent tracks are 60 nm apart. Therefore, it was recommended on 29 November 2000 that the CAA should take forward a recommendation to the appropriate international bodies that they reconsider the need for commanders to inform ATC of all lateral offset manoeuvres of less than 2 nm in Oceanic airspace, irrespective of the reason for the manoeuvre.

European RVSM airspace

RVSM procedures are due to be implemented in European airspace in January 2002 between FLs 290 and 410 inclusive. To meet this target date aircraft require full technical approval by 31 March 2001. The target level of safety (TLS) is expressed as 2.5×10^{-9} fatal accidents per aircraft flight hour '*as a consequence of technical (altimetry) errors'* for the implementation of RVSM. Modelling of this risk has been based on a modified version of the Reich Collision Risk Model which has three key parameters: the height keeping accuracy of the aircraft population; the aircraft passing frequency; and the lateral track keeping accuracy of the aircraft population.

It is not clear whether the European (or Oceanic) safety case studies and models have taken account of the risks of clear air turbulence coupled to the response of sophisticated flight control systems such as

[1] Shanwick Control's radio operators are at Ballygireen in Eire whilst the controllers are at Prestwick in Scotland.

those fitted to the Airbus fly-by-wire aircraft series. Moreover, the European RVSM safety case will be different to the NAT safety case because there is far more traffic flying opposing tracks or crossing the tracks of other aircraft. Consequently, it was recommended on 29 November 2000 that the CAA should bring this incident to the attention of the Eurocontrol RVSM Safety Assurance Section as soon as practicable so that its impact on the safety case may be properly considered.

Offset direction

The approved contingency measure to alleviate wake turbulence on NAT Tracks is to offset by up to 2 nm upwind of the aircraft ahead. The logic behind this instruction is sound for aircraft flying predominantly in the same direction but will be less sound for aircraft flying on opposing tracks in European RVSM airspace. In this region, aircraft offsetting upwind by 2 nm from the aircraft ahead will tend to place themselves in a head-on position relative to another aircraft performing a similar manoeuvre but flying in the opposite direction. Whilst the European area procedures will be different because of the extensive radar control, and clearance from ATC will be required to offset track, there may be a safety benefit in adopting a standard procedure for offsetting to the right. Such a procedure would be in accordance the Rules of the Air for overtaking aircraft and if action is taken early, wake turbulence could be avoided irrespective of the wind direction. In this way aircraft adopting a lateral offset to overtake or for wake turbulence would be well separated from all traffic travelling in the opposite direction on the same datum track or airway. Therefore, it was recommended on 29 November 2000 that the CAA take forward a recommendation to the appropriate international bodies to consider standardising lateral track offset procedures which are independent of wind direction.

Summary of Safety Recommendations

The following safety recommendations were made on 29 November 2000:

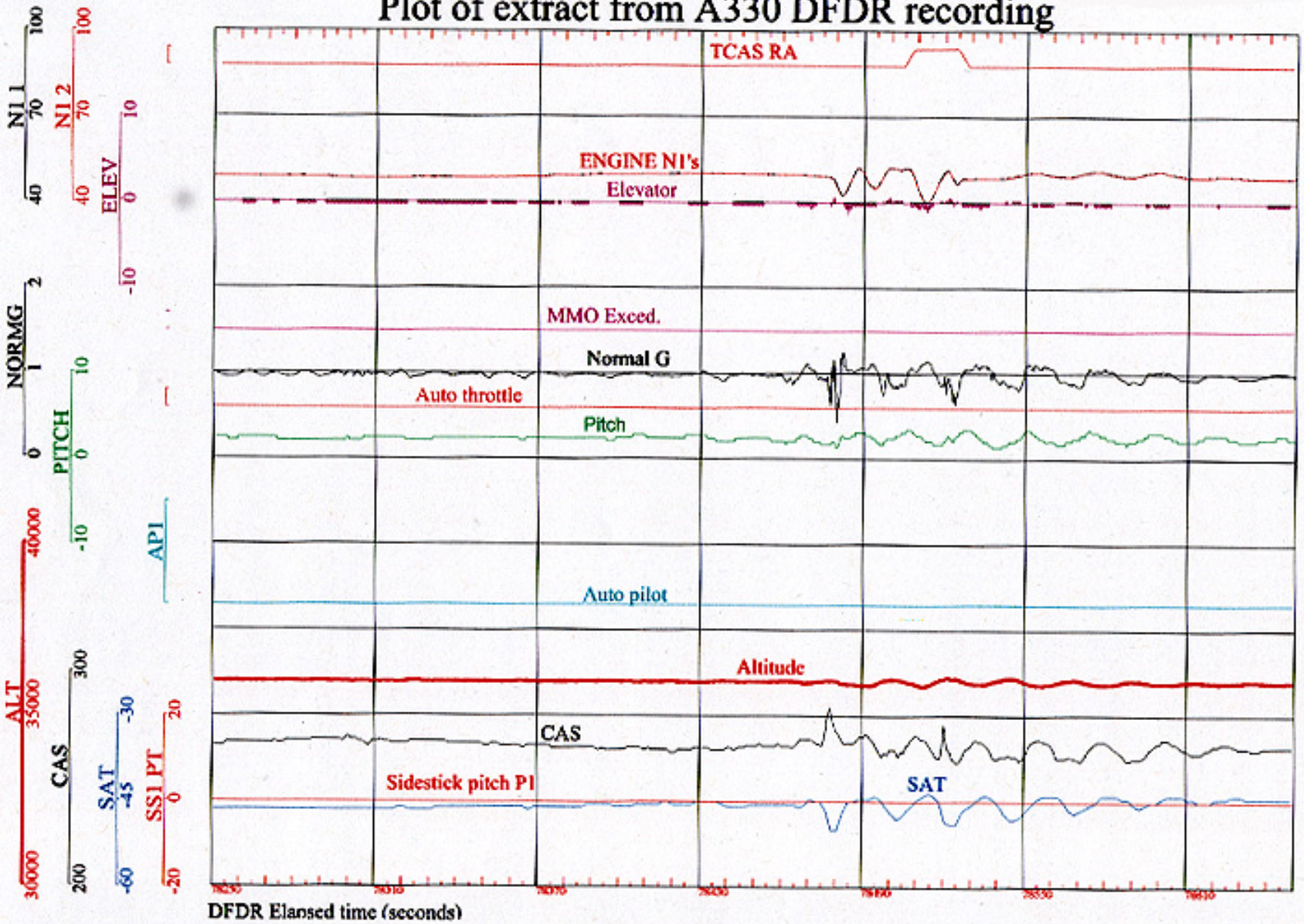
a) It was recommended that the CAA take forward a recommendation to the appropriate International bodies to review overtaking procedures in RVSM airspace.

2000-68 It was recommended that the CAA take forward a recommendation to the appropriate international bodies that they reconsider the need for commanders to inform ATC of all lateral offset manoeuvres of less than 2 nm in Oceanic airspace, irrespective of the reason for the manoeuvre

b) It was recommended that the CAA bring this incident to the attention of the Eurocontrol RVSM Safety Assurance Section as soon as practicable so that its impact on the safety case may be properly considered.

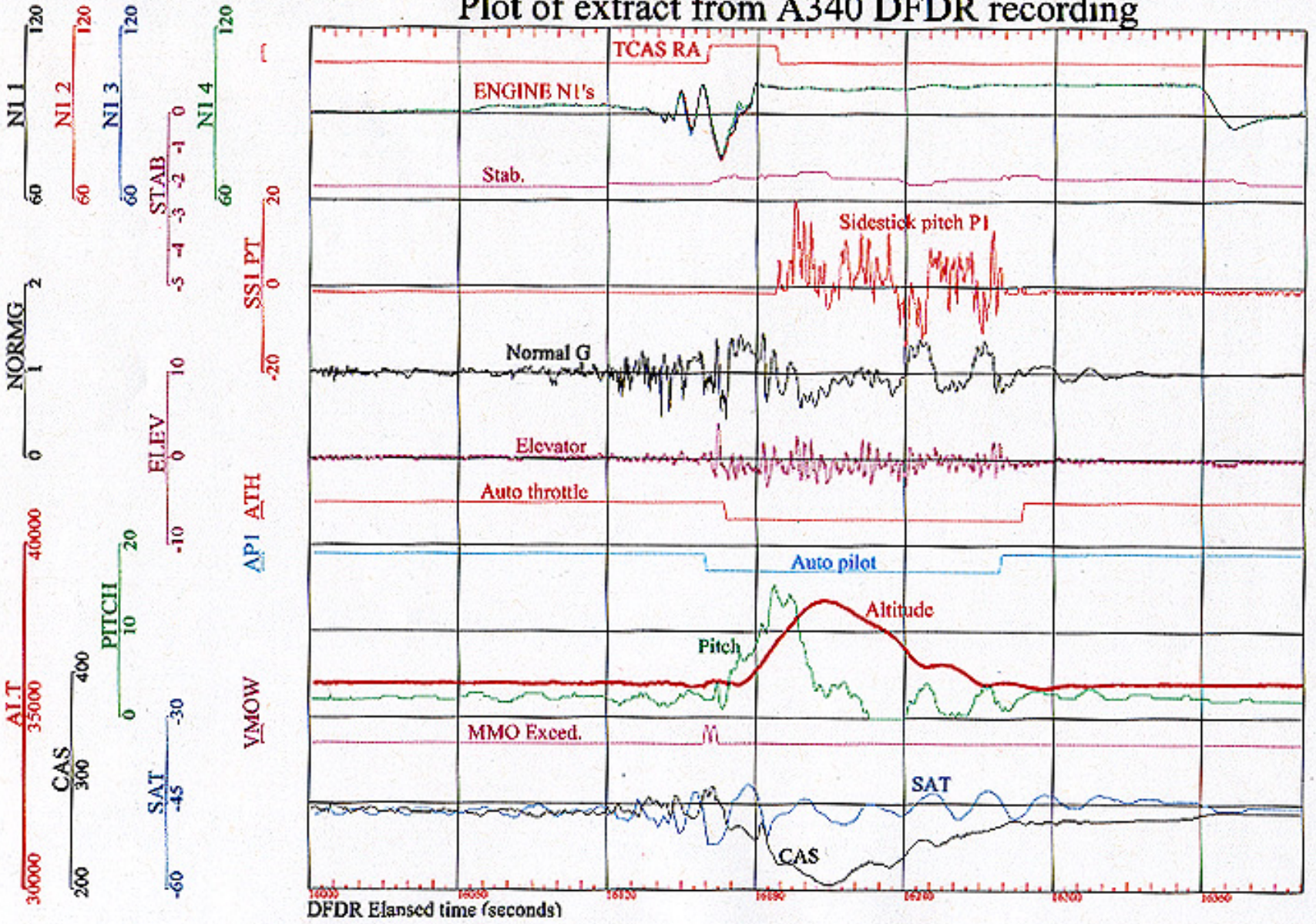
2000-70 It was recommended that the CAA take forward a recommendation to the appropriate International bodies to consider standardising lateral track offset procedures which are independent of wind direction.

Plot of extract from A330 DFDR recording



Appendix A

Plot of extract from A340 DFDR recording



Appendix B