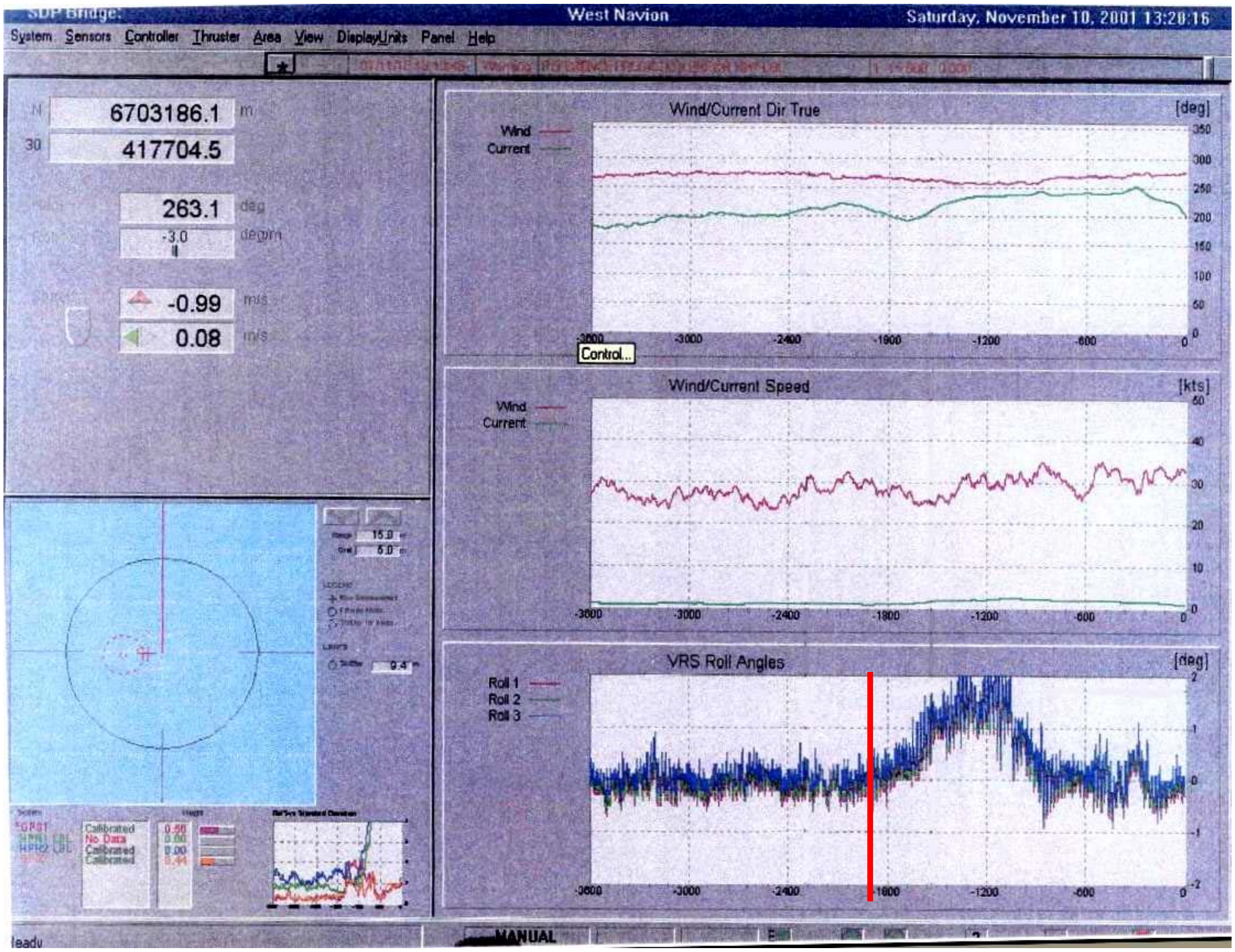
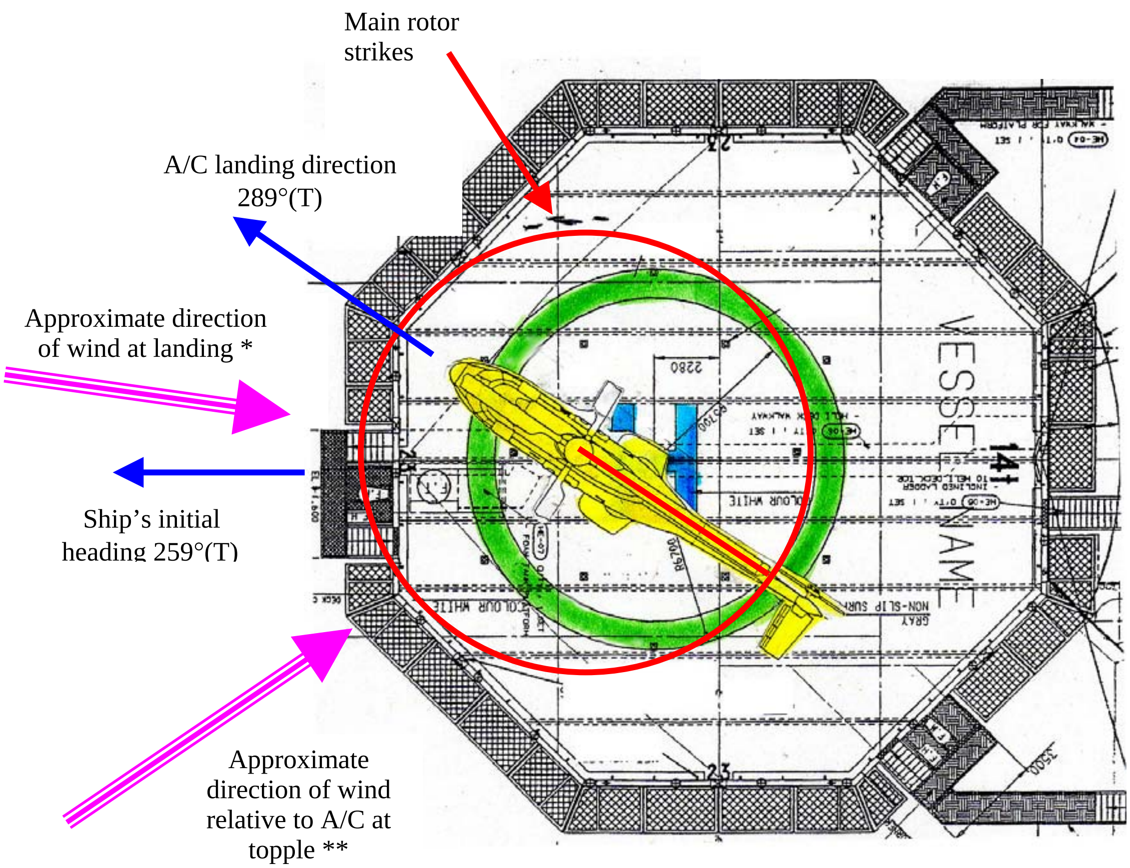
Appendix A



= Point at which G-BKZE toppled over

Figure 1. Dynamic Positioning System 'Screen Shot' covering the period of the accident



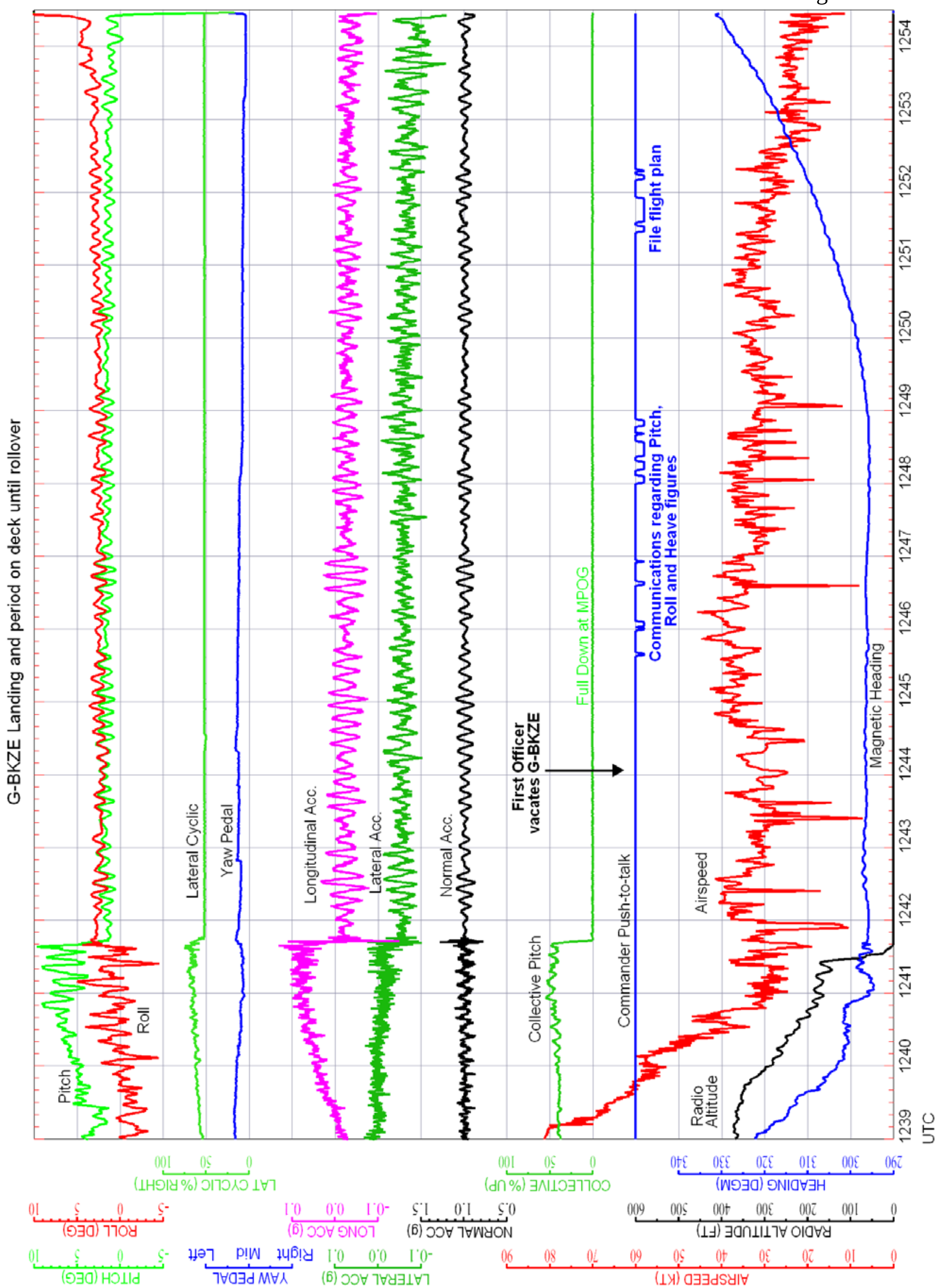
***** Landing wind direction: 285° (Schiehallion); 270° (Met aftercast); 270° (West Navion DP console); 250° (Faroe Connector).

****** Relative wind immediately prior to A/C toppling given by wind direction of 260° and ship yawing 35° to the right.

Note: all bearings are True

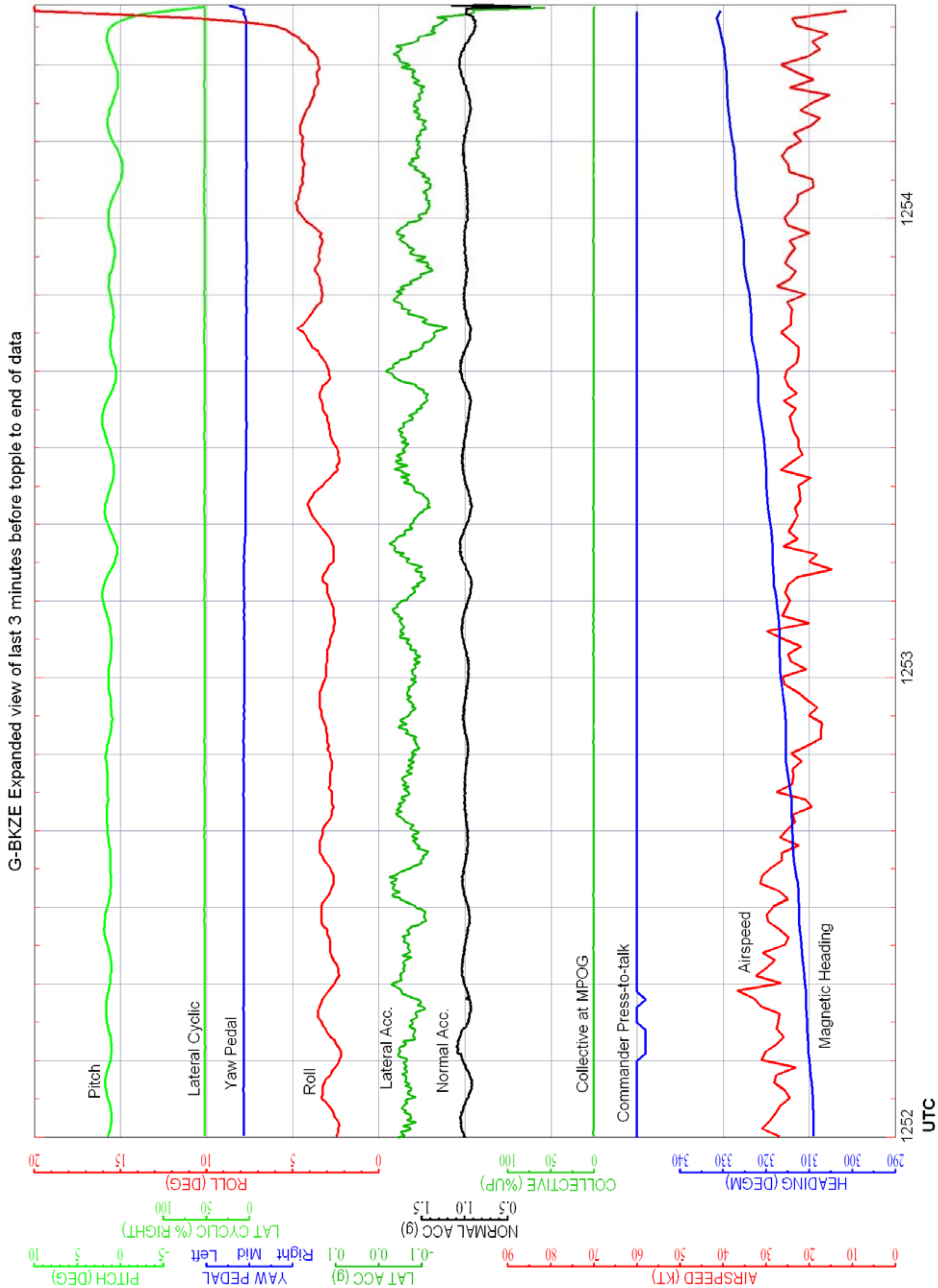
Figure 2. Illustration of aircraft position on helideck after landing, showing variation of wind vector between landing and toppling

Appendix B
Figure 1a



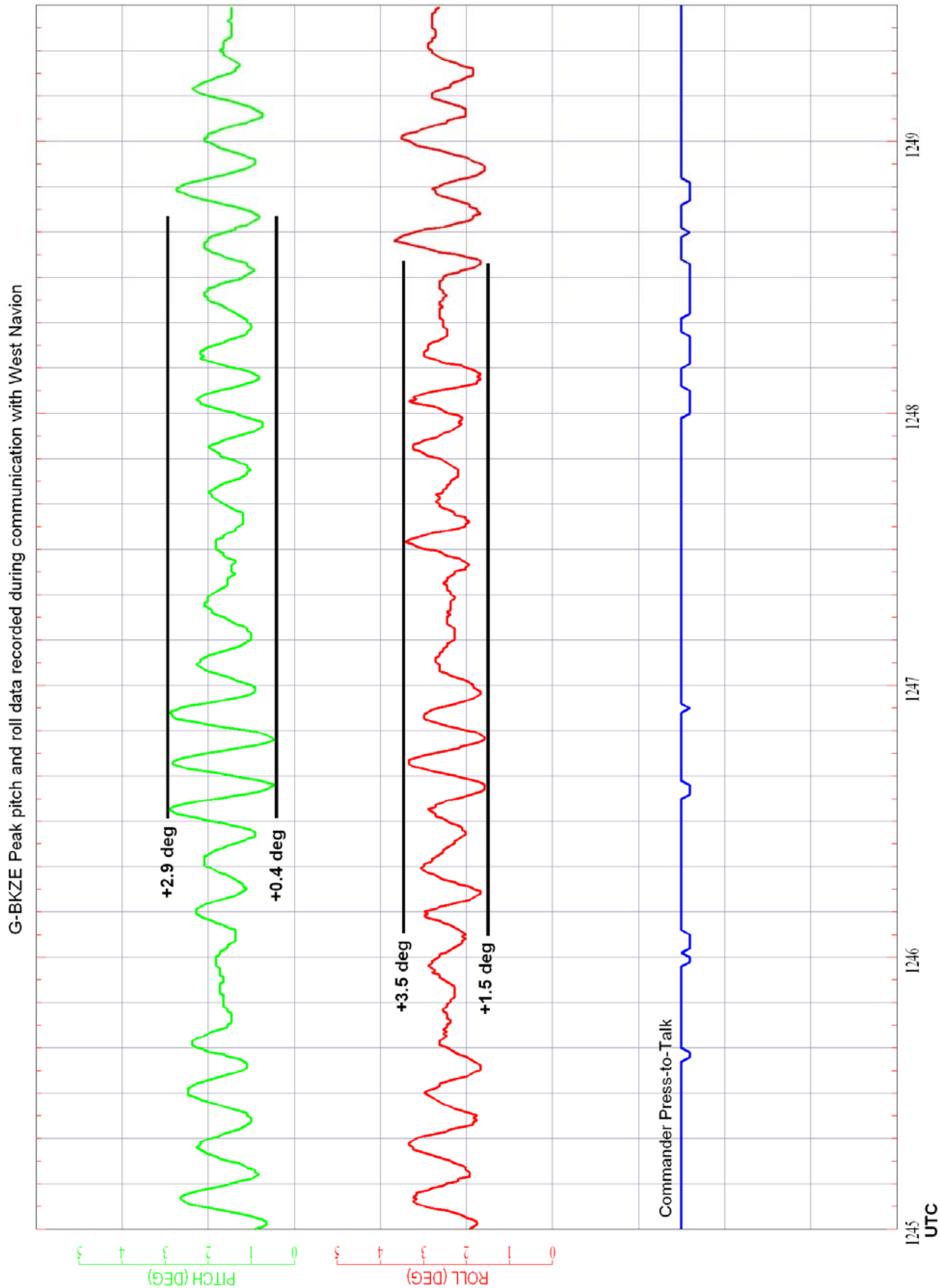
Appendix B

Figure 1b



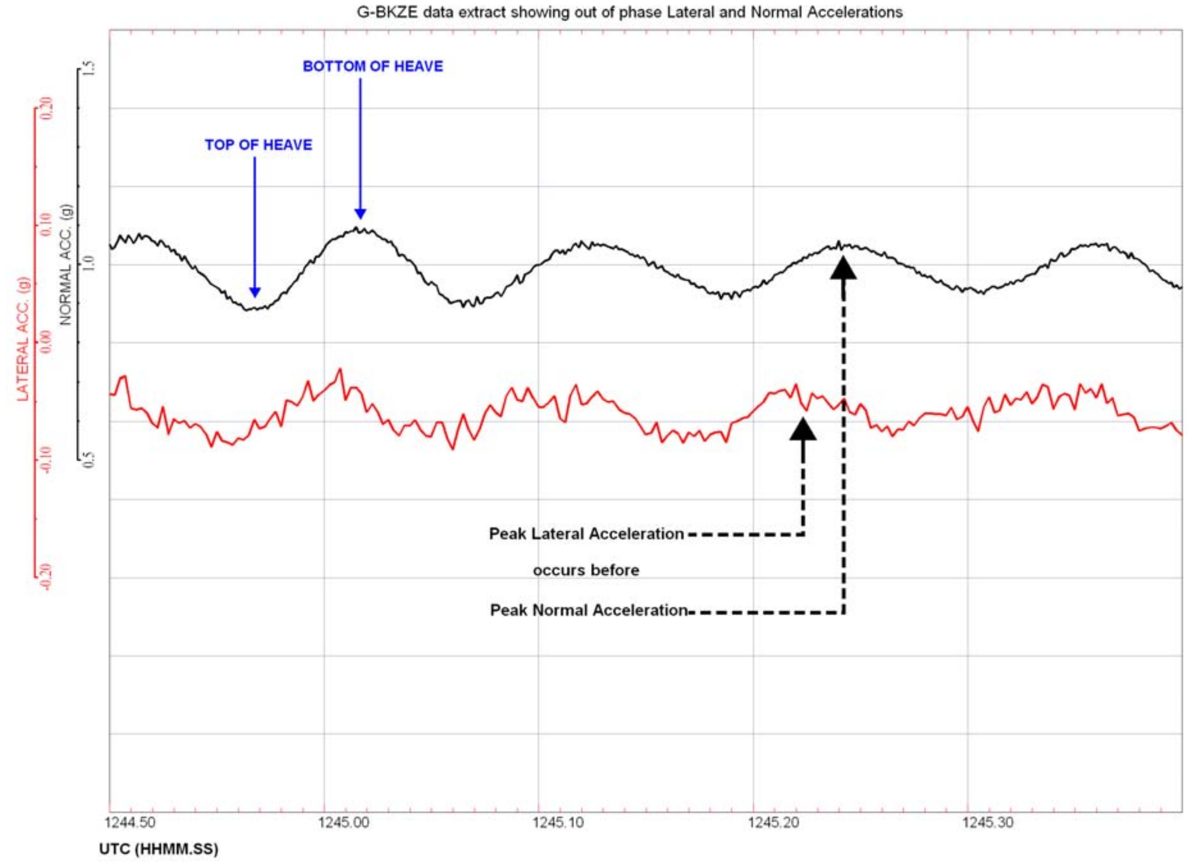
Appendix B

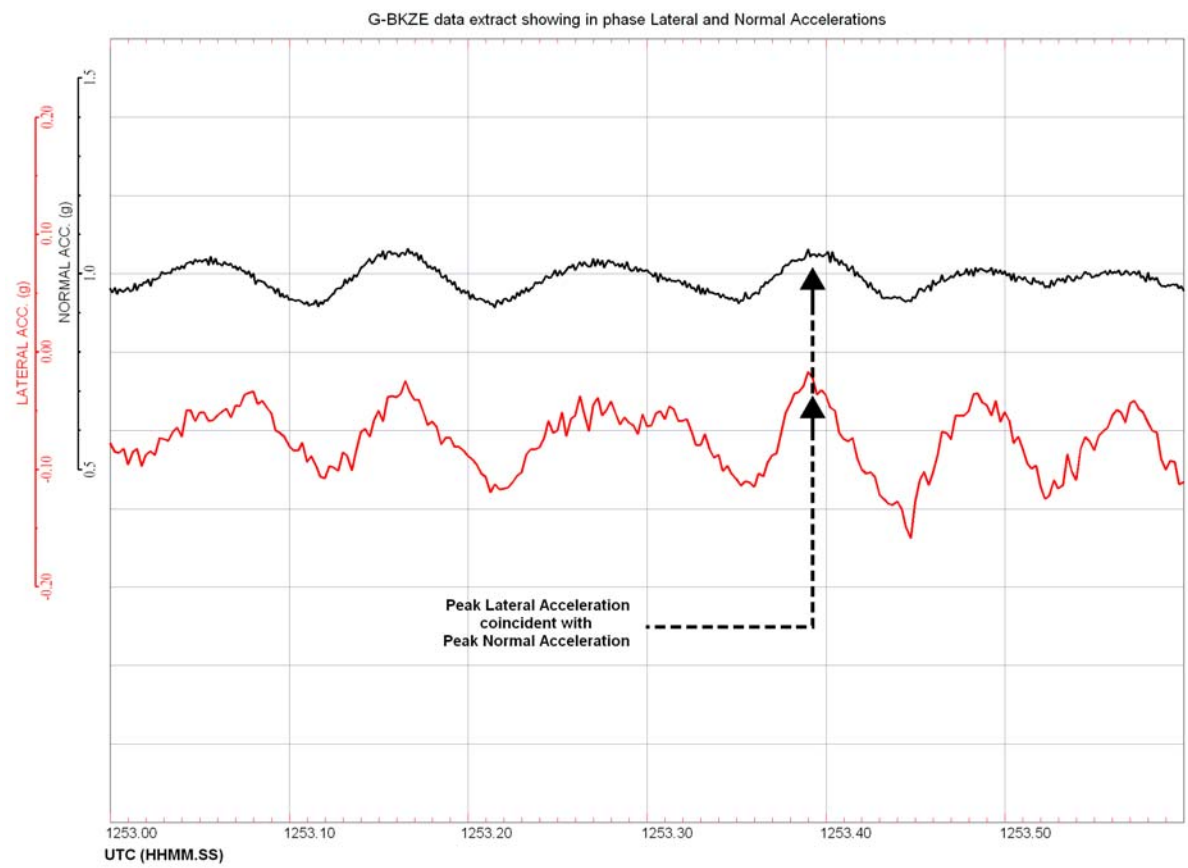
Figure 2



Appendix B

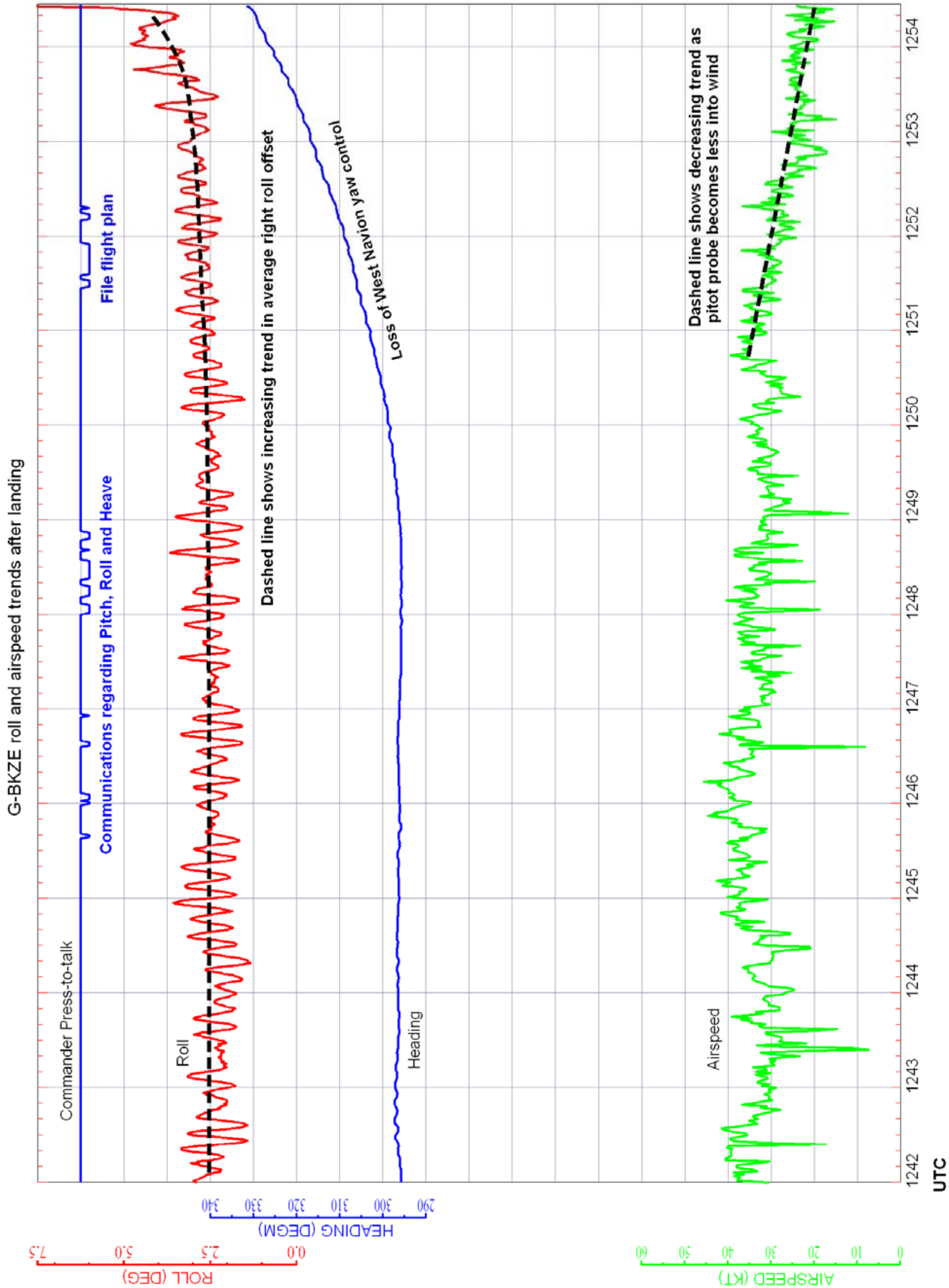
Figures 3a and 3b





Appendix B

Figure 4



Synopsis of the analyses conducted by QinetiQ and W S Atkins

QinetiQ Analysis

The work was conducted in two stages: the first was a reconstruction of the ship motion from the CVFDR data, with the second being a modelling of helicopter aerodynamic components. The latter consisted of applying industry standard equations to calculate forces and moments from the main and tail rotors, combined with aerodynamic data from Eurocopter to represent the contributions from the fuselage and fin. The effects of the horizontal stabiliser were assumed to be negligible. Calculations were made of the inertial effects of the aircraft mass on the overall moments acting on the aircraft, using acceleration values from the CVFDR data. A positive moment was defined as one that caused the aircraft to rotate to the right about the toppling axis, which was assumed to be a line joining the nose wheel and the right main landing gear wheel.

In some respects, the analysis was simplified by the fact that the flying control positions did not change significantly during the time the aircraft was on the helideck. The yaw pedal position drifted from slight left pedal applied towards approximately neutral during the period. Right pedal application has the effect of increasing tail rotor thrust to the left (producing an anti-toppling moment) and generating a yawing moment to the right.

The collective pitch remained on its minimum setting throughout, thus, thrust only needed to be calculated for this Minimum Pitch On Ground (MPOG) setting. However, the potential problems of relying on numerical methods were immediately apparent on comparison of the results of the Eurocopter and QinetiQ main rotor thrust models, as seen in Appendix C, Figure 1a. This shows an increasingly negative thrust (ie downforce) with increasing horizontal wind speed for the QinetiQ predictions, with a near constant, although still negative, value for the Eurocopter model. However, the Eurocopter calculations include the weight of the Main Rotor in the overall lift values, meaning that they predict a small positive lift value. Although the reasons for this were not clear, QinetiQ indicated that it might be due to effects not included in their model, most likely connected with an assumed ground effect. For hovering flight in zero wind over open terrain, the ground effect can increase the rotor thrust by up to 25-30%, a factor that will rapidly decrease for winds of up to around 10 kt and thereafter be minimal. The increasing value of negative thrust with wind speed was due to translational lift effects as the rotor became more efficient.

The twist on the main rotor blades results in a negative incidence at the tip such that the tip incidence is approximately 9° less than at the "virtual root" at the rotor mast. Thus, in theory, at MPOG the relatively high speed of the airflow over the outboard, negative incidence region of the blades results in a net downforce. A small increase in collective pitch from the MPOG setting would produce a net upwards force, with an upward vertical velocity component of the wind having the same effect. The QinetiQ and Eurocopter models were in reasonably close agreement with regard to the sensitivity of rotor thrust with vertical wind speed, as shown in Appendix C, Figure 1b.

The input data included the mean wind value of 285°T/34 kt, together with the accelerations as recorded by the CVFDR. The ship's motion could be calculated where necessary by assuming they were the same as for the aircraft, but allowing for the fact that the aircraft longitudinal axis was offset by 30° from that of the ship. Following a review of the available wind data, an additional calculation was performed with a wind of 276°T/34 kt.

The CVFDR data was used to generate a 'height rate', or heave velocity, by integrating the aircraft vertical accelerations. As transducer bias may caused errors in this process, the results were checked by transforming the aircraft pitch and roll attitudes into ship axes and then differentiating the ship pitch attitude to obtain a pitch rate. This was converted to a helideck heave rate by multiplying by the moment arm of 96 m, the distance between the ship pitch axis (assumed to be at the centre of gravity location amidships) and the helideck. Reasonable correlation was achieved, leading to an estimate for the maximum heave rate of ± 2 m/s.

The heave rate was considered important because of the vertical component of airflow that would be induced through the main rotor, and the consequential effect on rotor thrust. For similar reasons, the airwake effects from the ship's hull and superstructure were also considered. Whilst there was no accurate method of assessing these for the West Navion, QinetiQ referred to some earlier research, conducted for the CAA, which measured vertical wind velocity by means of an anemometer positioned at the edge of the helideck of a similar vessel. This showed that for a horizontal wind of 12 m/s (23 kt), there was a mean upward component of 5 m/s (9.7 kt), peaking at 9 m/s (17.5 kt). If these are scaled up for a horizontal wind of 17.5 m/s (34 kt), then the upwash mean and peak values become 7 m/s (13.6 kt) and 12.7 m/s (25 kt) respectively. If the same upwash were present at the edge of the West Navion helideck, then the value experienced at the main rotor would be some fraction of this, since the deck was solid, as opposed to mesh construction on the ship where the measurements were taken. However, it was not clear what fraction would be appropriate in this case.

Calculations were performed for a range of upwash values and the results compared. In the absence of airwake effects, the worst case for aircraft toppling would be a downward heave velocity of 2 m/s, producing an effective upwash and increased main rotor thrust, combined with a lateral acceleration to the left and downward vertical acceleration (ie, reduced g).

QinetiQ Results

For the aircraft to topple over, a net positive moment is required, ie, the sum of the individual contributions must be greater than zero. The predominant stabilising contribution comes from the aircraft mass acting downwards within the footprint of the landing gear, as can be seen (inertial line) in Appendix C, Figure 2. This plot shows the results for the wind case of 276°/34 kt, but with no heave rate or airwake-induced upwash. It can be seen that the total moment remains negative by more than 20,000 Nm. Perhaps surprisingly, it can be seen that the tail rotor contributes a positive moment, ie a force to the right, which is the opposite direction necessary to counteract the main rotor torque. The main reason for this is that the lateral wind component has the same effect on the tail rotor as upwash on the main rotor, ie increased thrust. Some confidence in this result was provided by the fact that Eurocopter predicted a similar value for tail rotor thrust, also to the right. The thrust would be comparatively small with the aircraft facing into wind. It should also be noted that a linkage between the collective lever and the tail rotor pitch change mechanism ensures that, for a given yaw pedal position, tail rotor thrust is considerably increased at high collective pitch settings.

As noted earlier, a slight change in pedal position, in a yaw right direction, during the time the aircraft was on the deck, results in the toppling moment remaining approximately the same despite an increase in the lateral wind component.

The only other positive moment contributions were from the fuselage drag and main rotor. Thus, it was clear that a significant increase in positive moment was required to topple the aircraft. Realistically this could only be supplied by the main rotor, and the thrust corresponding to a moment of sufficient magnitude was assessed as being around 3,850 kg, or around 55% of the aircraft weight. In order for this amount of thrust to be generated, the upwash would have been of the order of 10 m/s (19.4 kt). A revised plot of the moments reflecting the increased upwash is shown at Appendix C, Figure 3.

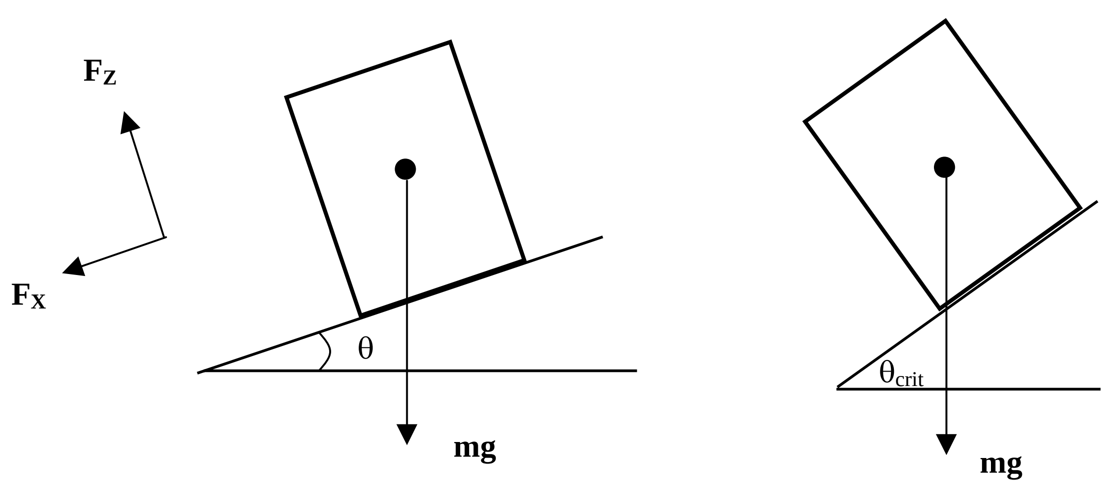
Following consideration of these results, and comparing them with those from W S Atkins (see the next section), it was felt that the rotor thrust was unrealistically high. Furthermore, by the time the W S Atkins research was conducted, the wind conditions had been reassessed, to the extent that they were more severe. Accordingly, part of the QinetiQ modelling was repeated with an input wind of 42 kt (21.6 m/s), from a direction of 280° at landing, backing to 260° immediately prior to the accident, with a linear variation between the two. This resulted in a derived rotor thrust of 2,227 kg being required for toppling, with the upwash necessary to produce this reducing to 4.5 m/s (8.7 kt). Appendix C, Figure 4, shows the moment plot for the revised wind conditions, and the increased contribution from the increased wind drag on the fuselage can clearly be seen.

W S Atkins Analysis

The Motion Severity Index (MSI) will essentially consist of a single number indicator of deck motion severity and accompanying limits of operability for helicopters. The limit of operability is dependent on aircraft type and is also a function of wind speed and direction. Development of the system has assumed that, in typical commercial operations, the aircraft is not tied down and that the rotors remain turning. The purpose of the MSI is to provide the crew of a helicopter with an indication of the likelihood of the aircraft tipping, sliding or otherwise losing stability whilst on deck, due to inertial loads arising from deck motions and aerodynamic forces due to wind, eg wind drag and enhanced lift from the rotors.

The MSI is defined as the predicted most likely maximum of the Measure of Motion Severity (MMS), over a set period of, say, ten minutes. This will be based on real time measurements of deck motion over a similar time period prior to landing. Helideck motion is to be monitored by sensors, which will measure the pitch and roll angles, together with the accelerations in the deck's x, y and z axes, these being respectively the longitudinal, lateral and vertical axes. W S Atkins have chosen to define the MMS as the ratio of the components parallel and perpendicular to the deck of the total gravitational and inertial forces acting on the aircraft, as a result of deck inclination and accelerations.

To illustrate the physical meaning of MMS, consider the case of a rectangular block of mass *m* resting on a plane inclined at an angle θ to the horizontal; see the diagram below. So long as the plane is not being accelerated, the only force acting on the block is gravity (ignoring frictional forces, which do not contribute to tipping). This force, F, is acting vertically downwards, ie F = *mg*.



Assuming the block tips before it slides, the value of the angle θ at which it tips will depend on whether it is resting on its "long" or "short" side, since this determines the position of the centre of gravity. Clearly, the tipping angle will be lower for when the block is on its short side, when the centre of gravity is at its highest, and nearest to the tipping axis at the edge of the block.

The gravitational force can be resolved into the horizontal and vertical components acting on the block, viz:

Force acting parallel to inclined plane, $Fx = mg.\sin\theta$

Force acting normal to inclined plane, $Fz = mg.\cos\theta$

The ratio of horizontal to vertical forces is thus:

$$\frac{Fx}{Fz} = \frac{mg.\sin\theta}{mg.\cos\theta} = \tan\theta \quad = \text{MMS}$$

Or: $\theta = \tan^{-1}(\text{MMS})$

The critical angle at which the block tips over, θ_{crit}, will depend on the dimensions, or the geometry, of the block. At this angle, the centre of gravity of the block will be directly above the lower edge, about which the tipping action occurs, as shown in the right hand diagram.

If the block is replaced by a helicopter, in this case G-BKZE, the geometry is clearly more complex, and the axis about which it will tip is a line drawn between the nose wheel and a main wheel. Calculations show that the static roll-over angle (ie θ_{crit}) is 23.3° for the same weight and centre of gravity position that applied to G-BKZE, although this reduces to a theoretical minimum of about 18.4° for the most adverse loading condition. By way of comparison, the equivalent figures for a Sikorsky S76 aircraft are 27.5° for a typical operational loading, with a 'worst case' value of 23.5°.

Next, consider the same block resting on a horizontal plane, which is being laterally accelerated at *a* metres/second^2. At some limiting value of *a*, the block will start to tip about one edge. Up to this point, the stabilising moment, provided by the mass acting downwards, is greater than the destabilising moment, which results from the horizontal force arising from the lateral acceleration. At the limiting value of *a*, the resultant force vector, applied at the edge about which tipping occurs, will pass through the centre of gravity of the block. This is similar to the arrangement of forces for the case of the inclined plane.

Since Force = Mass x Acceleration, horizontal force, $Fx = ma$, and the vertical force, $F_z = mg$

Thus, the ratio of Horizontal Force to Vertical Force = MMS = $\frac{a}{g}$

Note that if the plane is also being accelerated upwards or downwards, in the manner of a heaving deck, then the denominator in the above equation would be some value other than 1 g, thus changing the MMS.

As the blocks are the same, the critical MMS value will also be the same. Whilst in the case of the inclined plane, it represented the tangent of the angle of inclination, in the second case, it represented the tangent of an 'equivalent roll angle'. In considering the case of a helicopter on a deck, components of pitch motion could also help destabilise the helicopter relative to its lateral axis, thus the MMS is more properly described as the dynamic deck angle. Thus, if θ_{crit} is 23.3° for the case of an AS332L helicopter (in roll) on an inclined plane, then for a laterally accelerated horizontal plane, the critical MMS would be tan (23.3°), or 0.43. In other words, the value of *a* at which the aircraft might be expected to tip is *g* x 0.43, or approximately 4.2 metres/second^2. This of course assumes no aerodynamic loads and does not allow for the effects of a compliant landing gear.

Finally, in considering the case where sliding occurs before tipping, the force parallel to the inclined plane, Fx, is opposed by the frictional force, F_{fric}. The latter is simply the force normal to the plane multiplied by the coefficient of friction, μ, and sliding will occur when $Fx \geq F_{fric}$.

For a block on an inclined plane, this can be expressed simply as : $\frac{Fx}{Fz} = \tan\theta \geq \mu$

Thus the onset of sliding also correlates with the ratio of horizontal to vertical forces. For a block, the critical value of the ratio is equal to the coefficient of friction μ. Deriving the critical value for a helicopter is more complex, since the latter has three points of contact with the deck. The vertical reactions, which determine the maximum frictional force that can be resisted at each wheel, are unequally distributed between the three wheels, as a function of their distance from the centre of gravity. Also, it is possible for the helicopter to slide in rotation, about any of the three wheels, as well as in pure translation. As a result, it is not possible to derive a simple expression to relate the onset of slide directly to the ratio of forces, though the overall tendency to slide will depend on this ratio and can be calculated.

Calculation of the MMS takes into account all the gravitational and inertial forces acting parallel to and normal to the deck, as a result of deck motion. The greater the deck accelerations, and in consequence the MMS (or the dynamic deck angle $\theta = \tan^{-1}$ (MMS)), the closer the aircraft comes to tipping over. In the case of G-BKZE, the CVFDR recorded the attitude and accelerations in the aircraft's x, y and z axes, which arose as a result of the deck's six degrees of freedom, ie pitch, roll, yaw, heave, surge and sway. It was thus possible to calculate the MMS (referenced to the aircraft vertical axis, rather than the deck) for the time the aircraft was on the deck, up to the point at which tipping occurred. Since this was mostly well below the critical value, it reasonably can be assumed that the remainder of the forces required to make the aircraft tip or slide were the result of rotor thrust and aerodynamic drag acting on the fuselage. Note that the MMS relative to the deck could also be inferred from the CVFDR data, based on estimates of the roll offsets due to the uneven aircraft oleo deflection.

Input data

The ship's motion was reconstructed from the CVFDR data in the same manner as for QinetiQ's analysis.

As well as the aircraft weight, centre of gravity position, the input parameters included the following:

- Wind: the direction was taken as 280°T at the time of landing backing to 260°T at the time of the accident, with a linear variation between the two. W S Atkins conducted their analysis after QinetiQ, and it was considered more appropriate to use a gust speed, as opposed to a mean value. This resulted in a value of 22.7 m/s being used, which corresponded to the likely maximum gust of 42 kt. As there was no way of knowing the timing of the gusts, this was applied to the model as a constant value.

- The deck coefficient of friction, μ: two values, 0.65 and 0.60 were used, based on data supplied by the ship operator. These were used to examine the possibility of sliding having occurred prior to tipping.

- Main rotor torque: On the AS332L, the main rotor rotates in a clockwise direction when viewed from above, creating an anticlockwise reaction on the fuselage. This in turn results in a tendency for the main wheels to slide to the right. In addition there is a 5°forward tilt of the main rotor mast, which results in a component of the main rotor torque acting along the longitudinal axis of the aircraft. This is in a clockwise direction when viewed from the rear, and thus contributes a destabilising moment about the aircraft's tipping axis. A simple mathematical model was used to obtain an estimate of 12,700 Nm for the rotor torque during the time the aircraft was on the helideck. Other estimates based on actual measurements made during trials on an aircraft, together with values supplied by Eurocopter, fell 20% either side of this figure.

- Main rotor lift: As noted earlier, QinetiQ and Eurocopter used their own mathematical models to predict rotor forces, with both giving negative lift values at minimum collective pitch in ground effect. W S Atkins' own AS332L model, together with that of a Sikorsky S76, also produced negative lift values. However, field trials conducted with S76 and Super Puma aircraft in support of the MSI research project indicated that significant positive (upward) lift occurred under these conditions, and which increased with wind speed. The first AS332L trial was carried out in zero wind conditions, the method of force measurement being by means of load cells placed under the wheels. This showed that the lift force at 100% N_r and at MPOG was around 400 daN (decaNewtons), or just over 400 kg force. The second trial was conducted in winds of 10 m/s, or approximately 20 kt, allowing the reactions at the wheels to be measured with the aircraft parked at various orientations to the wind direction. This showed that the rotor lift varied with the relative wind direction, this being attributed to the variation in the effective updraught through the rotor disc as a result of the 5° forward tilt of the mast. The results of these trials are shown in Appendix C, Figure 5, and it can be seen that a linear extrapolation to a wind speed of 22.7 m/s gives lift values of between 1,300 daN (-45° orientation to the wind) and 2,000 daN (maximum lift case, 180°, or tail to the wind). A significant amount of vertical wind component is expected to have been present over the helideck, due to the wind being deflected by the vessel's superstructure. The magnitude of this at the main rotor would be of the order of 0.9 m/s, or 1.75 kt, for a 25 m/s wind, according to the guidance in Section 3.3.6 of CAP 437, which approximates to a 2° upward tilt of the wind vector. This was used to justify a lift value at the high end of the extrapolated range, ie, 2000 daN, for inclusion in the analytical model at the time tipping occurred.

Finally, there was uncertainty associated with assigning values to the following factors, but were assumed to be small and were set to zero:

- Rotor forces parallel to tip path plane
- Lateral tilt of the tip path plane
- Tail rotor force
- Main rotor flapping moment

Of these, perhaps the tail rotor force was potentially the most significant: QinetiQ and Eurocopter independently calculated the value to be 1,500 and 1,250 N respectively to the right, at a relative wind of 45° from the left at 34 kts. The force increased slightly with the wind angle despite the blocking effect of the pylon due, it was argued, to the change in the airflow through the tail rotor disc, in much the same way as the main rotor thrust changed depending on whether the aircraft was facing into or away from, the wind. Whilst this seemed plausible, W S Atkins stated that the results of the trials were not sufficiently detailed to allow an accurate determination of the magnitude of the tail rotor force, or the change with wind angle. Given this uncertainty, they opted not to include any force due to the tail rotor, with the justification that including it would further destabilise the aircraft and that neglecting it merely increases the main rotor lift required for toppling or sliding. It can be seen for example, that if the tail rotor force is assumed to be 1,500 N, acting at a distance of 9.42 metres from the main rotor axis (essentially the longitudinal CG position), then it exerts over 14,000 Nm about the rotor axis, which is significant in comparison to the assumed 12,700 Nm (albeit a pure moment) supplied by the engines.

Atkins Results

The point at which the aircraft tipped could be defined in two different ways:

The calculated vertical reaction at any wheel (with the left main wheel being critical in this case) became equal to zero.

The sum of the moments acting about the tipping axis, arising from all the forces acting on the aircraft, is equal to or greater than zero. (Moments are assumed positive to the right, ie in the direction that the aircraft actually tipped.)

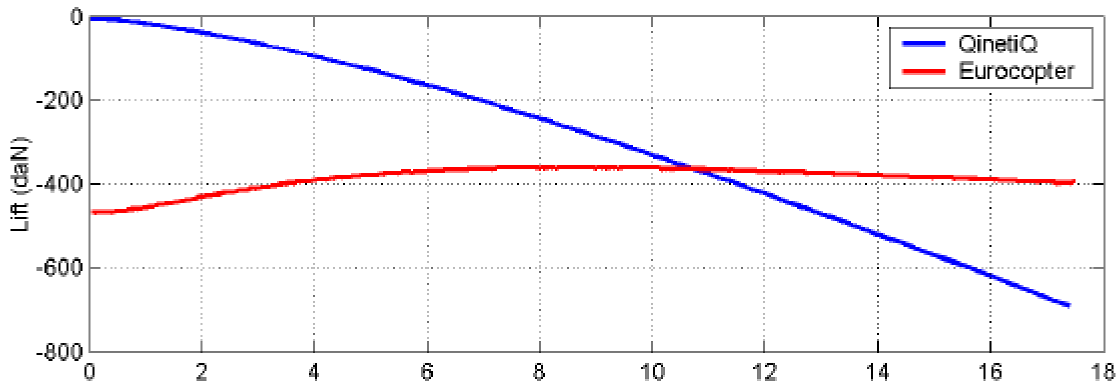
The ratio of horizontal to vertical components of the total forces can also be used as a tipping failure criterion, ie when its value reaches tan 23.3°. Note that the ratio = MMS in the special case when the aerodynamic forces are zero. Although this provides a useful illustration of the relative contribution of the aerodynamic forces and those due to deck motion in destabilising the helicopter, mathematically, the criterion is only approximately correct. Gravitational and inertial forces act at the centre of gravity; however, wind drag and rotor forces do not necessarily act at the centre of gravity, and pure moments, such as main rotor torque, contribute to a net moment acting on the aircraft. Such additional moments do not form part of the horizontal to vertical force ratio, although they can serve to stabilise or destabilise the aircraft, depending on the direction in which they act.

Appendix C, Figure 6, shows the variation of the total and individual moment contributions for the time the aircraft landed to the time the accident occurred. It can be seen that tipping occurs when the 'total moments' line crosses the 'zero moment' line. The wind drag force increases considerably during the period, and the contribution from the gravitational and inertial forces shows an increase towards the end, particularly in some of the peak values. Note, however, that the contribution from the rotor is shown as a constant line. This is due to the wind input to the model being a constant 42 kt, as described earlier, and because the lift has been assumed to be a constant 2,000 daN. In reality, the lift would have been lower than this value earlier in the time line, due to the effect of the forward tilt of the main rotor mast. There is consequently an effect on the "total" moment line, which would also have increased from a lower initial value.

Appendix C, Figure 7, shows the results of the simulation presented as a function of the various ratios of the horizontal to vertical force components. DECK MMS is the ratio of the gravitational and inertial forces of the deck. CVFDR MMS is the ratio of gravitational and inertial forces recorded by the CVFDR and thus represents the effective MMS experienced by the aircraft, including the oleo deflection. The CVFDR MMS essentially follows a parallel path to the deck MMS, but displaced an additional 2.5° or so to the right. In fact the displacement is not a constant 2.5°, as variations about this value occur due to the aircraft rocking back and forth about this mean value. An expanded and consequently less cluttered representation is shown in Appendix C, Figure 8. The point at which sliding occurs is also shown in this Figure.

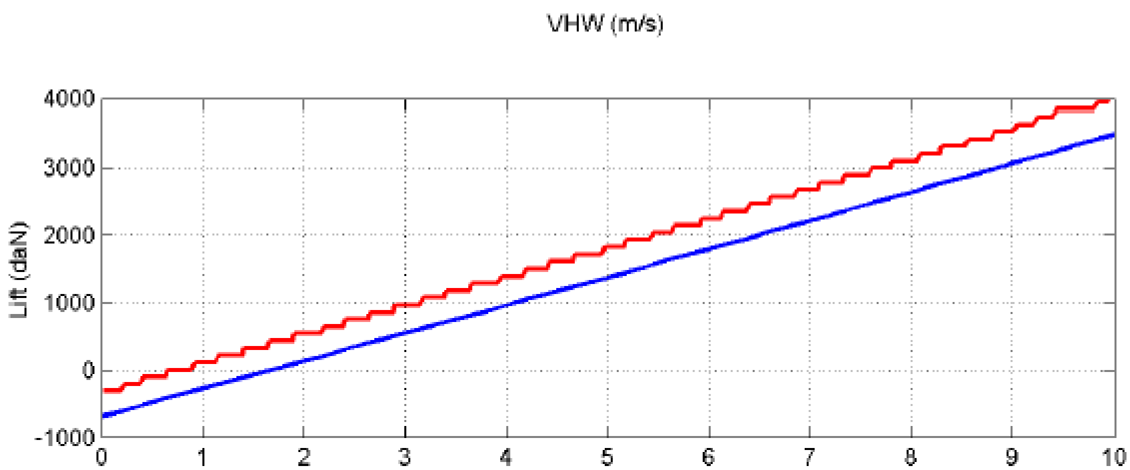
Sliding failure

The model predicted that sliding could occur, in an anticlockwise direction about the nose wheel, but only when the coefficient of friction, μ, was set to 0.60, at which value it was almost concurrent with the tipping failure. If μ was increased to 0.65, then sliding did not occur. This demonstrated the sensitivity of μ on the predicted outcome, and was consistent, up to a point, with the evidence of the short skid-mark on the helideck, which suggested that sliding might have occurred prior to tipping. The 10% variation in μ that determined whether or not sliding occurred is a small margin and could of course be a result of other input uncertainties, such as not including the effect of lateral main or tail rotor forces. If these were to be included, then sliding would be predicted for values of μ in excess of 0.60.



Horizontal wind component (m/s)

Figure 1a



Vertical wind component (m/s)

Figure 1b

Mathematical Models: Comparison of QinetiQ and Eurocopter results

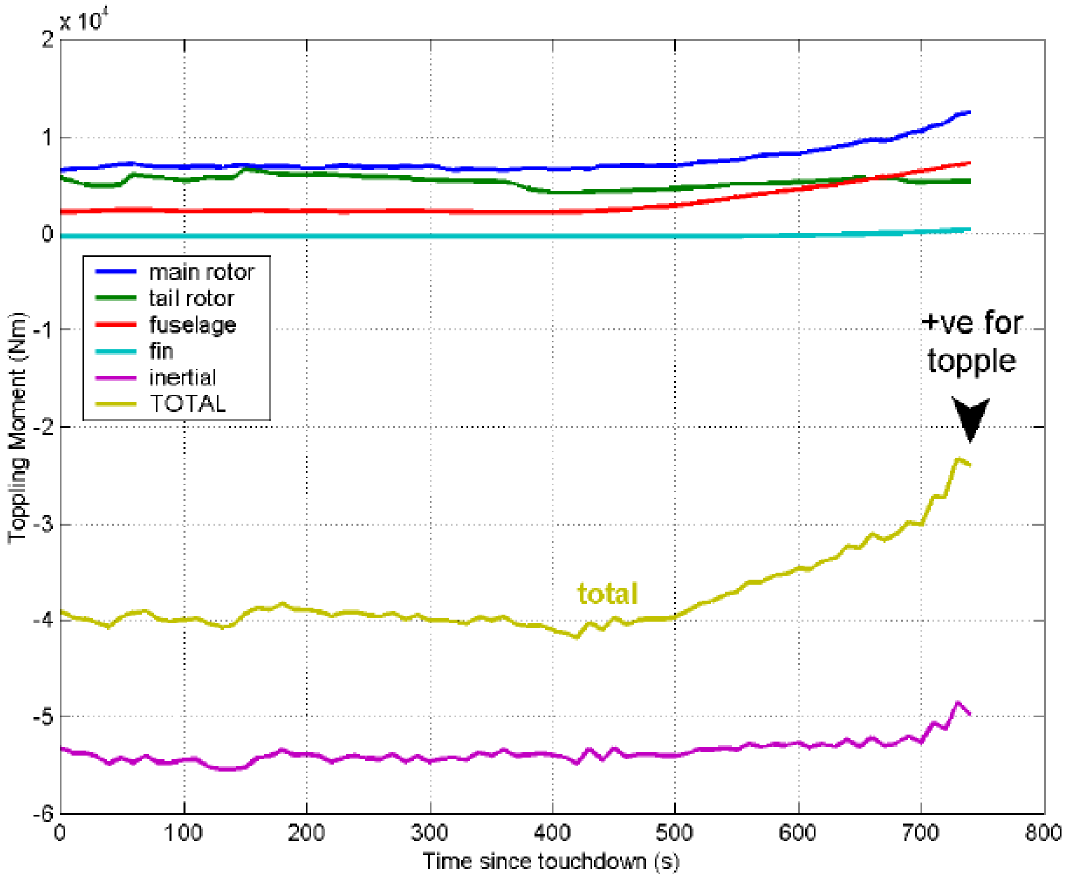


Figure 2. Toppling moments for wind vector of 276°/34 kt

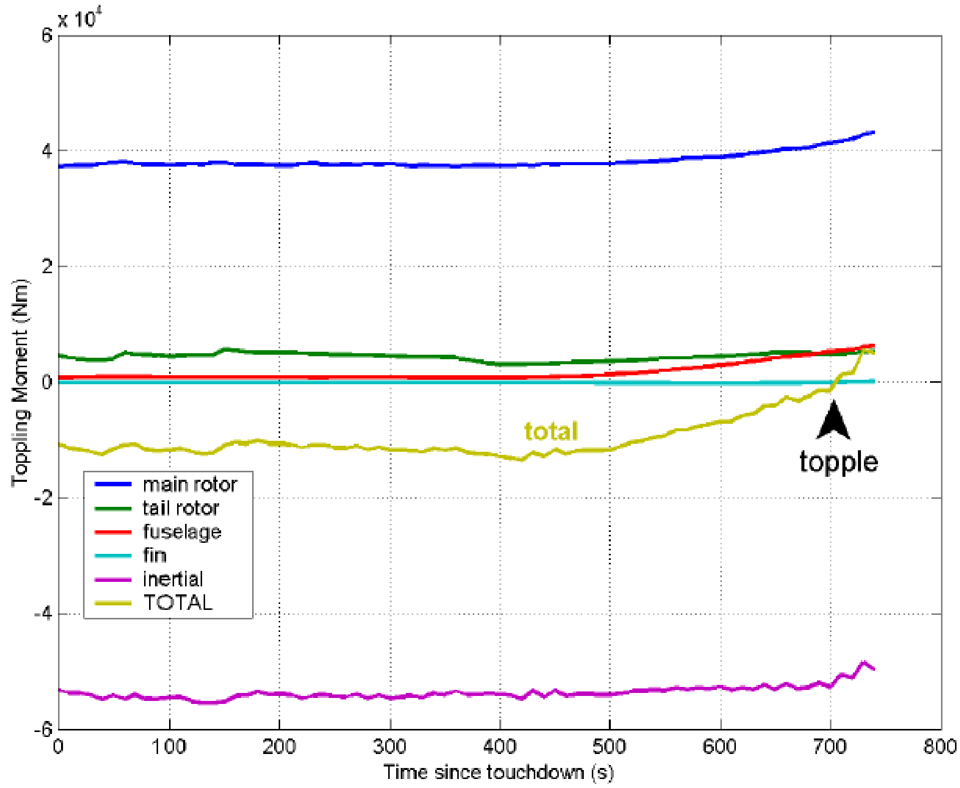


Figure 3. Toppling moments with rotor upwash due to deck heave and airwake

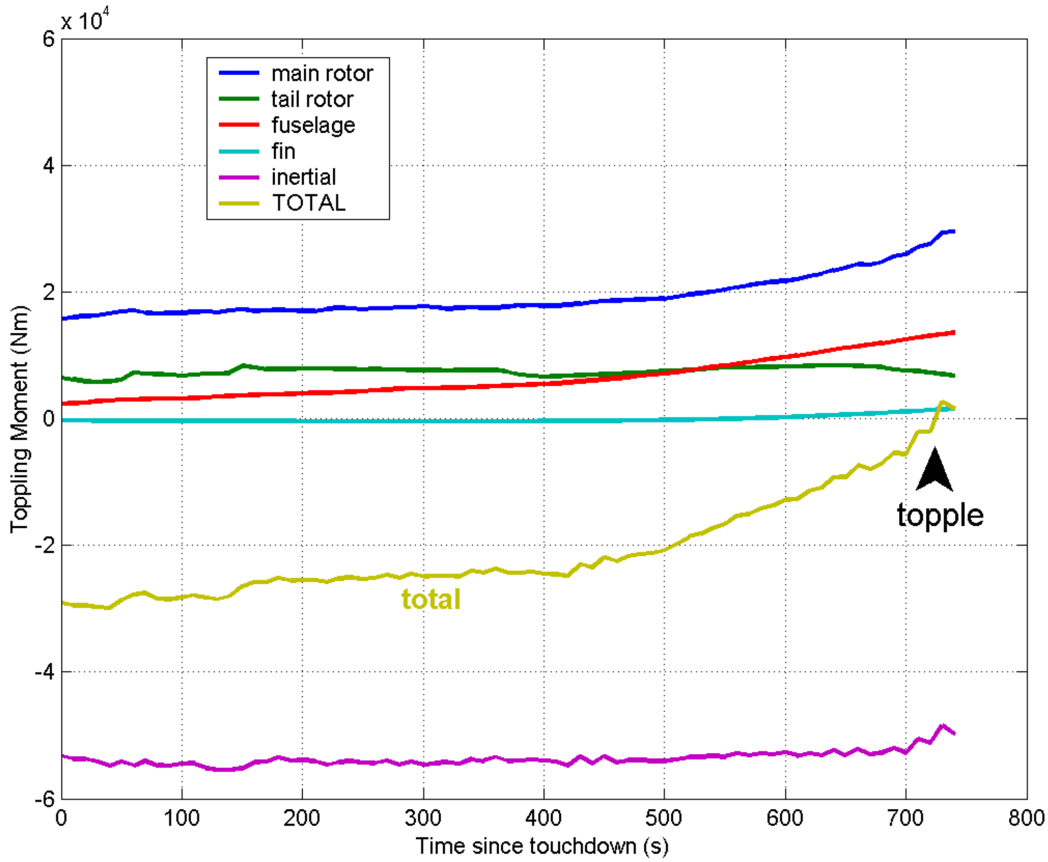


Figure 4. Toppling moments with wind of 42 kts, varying from 280° at landing to 260° immediately prior to accident

(4.5 m/s upwash through the door)

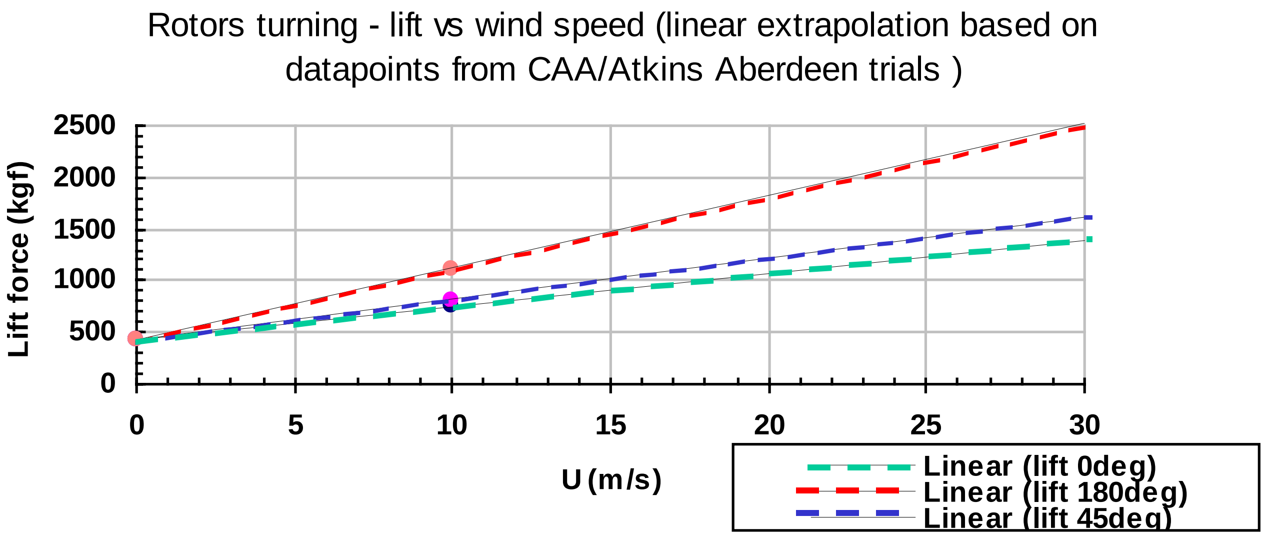


Figure 5. Main rotor lift variation with wind direction and speed at MPOG

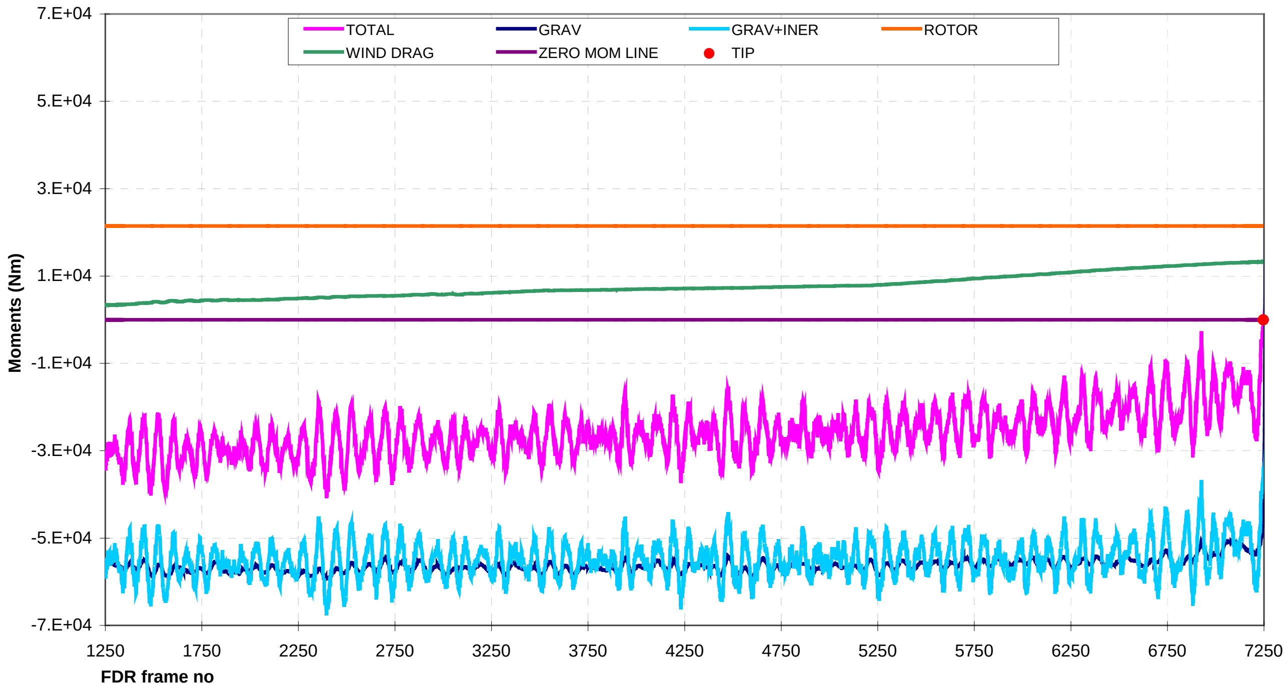


Figure 6. Total and individual moment contributions

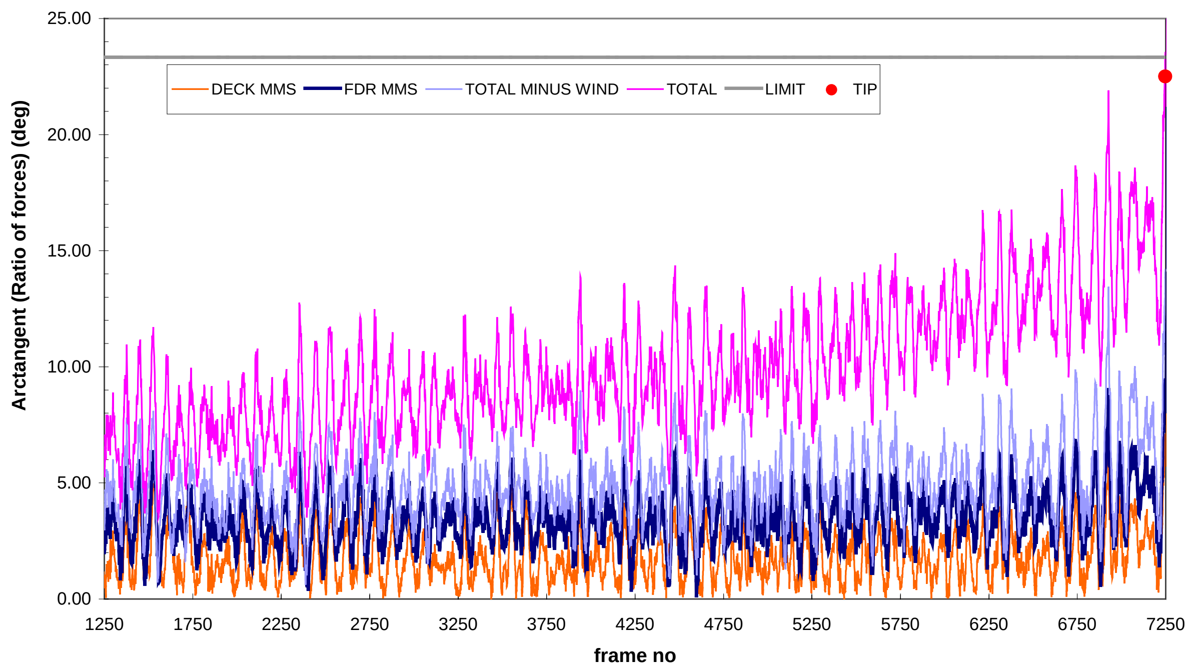


Figure 7. Ratio of horizontal to vertical forces (MMS)

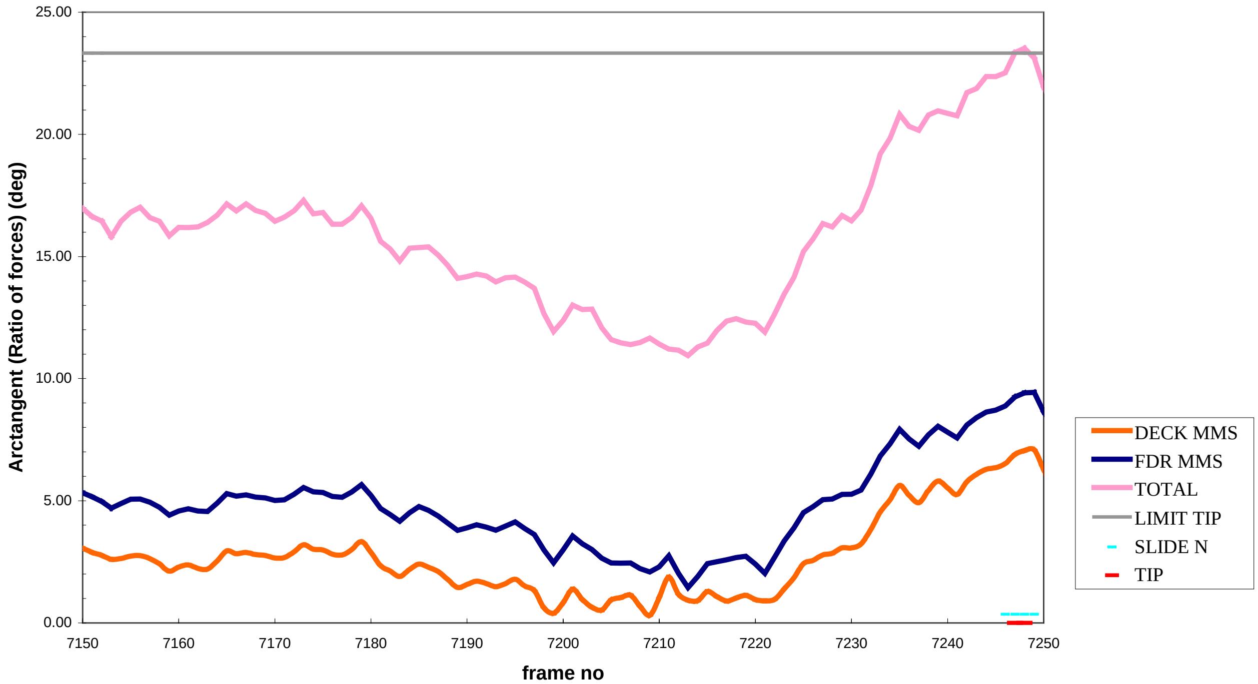


Figure 8. Onset of sliding and tipping