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Spatial Disorientation Analysis of AF Safety Center Mishap Data

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FOR THE DIRECTOR

//signed//

DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

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14. ABSTRACT
During the initial development of micro Analysis & Design's (MA&D's) Spatial Disorientation Analysis Toll (SDAT), we received seven mishap data sets from the Air Force Safety Center (AFSC). AFSC simply told us that five of the data sets were definitely SD related, and two were probably SD related; we received no other details about the data. Our goal was to use SDAT to analyze the data sets, report our results to AFSC, and then compare our findings to the Safety Investigation Board's (SIB's) conclusions. SDAT does not account for other sensory inputs to orientation. Even though it is know that the human visual system is the primary source of orientation information, there is nothing in the research literature that quantifies the contribution of visual inputs. SADT results assume that the pilot is not attending to visual attitude information (which is often the case when SD mishaps occur) or that such information is not available.

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1 Executive Summary

During the initial development of Micro Analysis & Design's (MA&D's) Spatial Disorientation Analysis Tool (SDAT), we received seven mishap data sets from the Air Force Safety Center (AFSC). AFSC simply told us that five of the data sets were definitely SD related, and two were probably SD related; we received no other details about the data. Our goal was to use SDAT to analyze the data sets, report our results to AFSC, and then compare our findings to the Safety Investigation Board's (SIB's) conclusions.

In analyzing flight data sets, SDAT uses four algorithms to calculate the difference between the actual attitude of the aircraft and what the pilot's vestibular system perceives the attitude to be:

1. Sub-threshold rotations that the vestibular system does not register, even though the aircraft moves. These sub-threshold rotations typically occur about the roll axis.
2. Sustained rotations that yield washout, so that the vestibular system stops sensing the rotation, even though the aircraft is still rotating. Washout typically occurs in the yaw or heading plane of aircraft motion.
3. After washout, a supra-threshold rotation (as occurs when rolling out from a sustained turn) yields illusory rotation. That is, the vestibular system perceives a turn in the opposite direction from the original turn. Eventually, there is washout from the illusory turn perception; this washout occurs at the same rate as washout from an actual turn.
4. Changes in airspeed yield perceptions of pitch changes. Decelerations feel like pitching down; accelerations feel like pitching up from the actual pitch angle.

SDAT does not account for other sensory inputs to orientation. Even though it is known that the human visual system is the primary source of orientation information, there is nothing in the research literature that quantifies the contribution of visual inputs. SDAT results assume that the pilot is not attending to visual attitude information (which is often the case when SD mishaps occur) or that such information is not available.

In the 7 data sets, SDAT found one probable pitch perception problem, several probable Leans events, and many probable Graveyard Spiral events. Of the 7 data sets, our SDAT analysis findings compared to the SIB's findings:

- Matched well for 2 mishap data sets;
- Did not match at all for 2 mishap data sets;
- Partially matched or were inconclusive for 2; and,
- No comparison was possible for 1 (due to data file problems).

In both cases where the SDAT conclusions did not match at all, detailed information about the flight conditions would likely have precluded using SDAT to determine if a vestibular-based illusion was a contributing factor.

In sum, we are pleased with the overall results from SDAT, and are extremely grateful to AFSC for sending us the data sets. We feel that SDAT is a useful tool for determining the likelihood that a vestibular-based SD may have contributed to a mishap; it is also useful for concluding that a vestibular illusion probably did not contribute to a mishap. During the remainder of the present research contract with AFRL, which ends 30 Sep 06, we would be delighted to assist with any other mishap data analyses at no cost to AFSC.

2 Introduction

Micro Analysis and Design (MA&D[1]) is a small Human Systems Integration consulting company headquartered in Boulder, Colorado. One of our specialties is the use of computer-based simulation software to model human performance. The Multisensory Integration for Pilot Spatial Orientation contract is a research project for AFRL/HECI funded by the SBIR program (contract # FA8650-04-C-6457). One focus of the research effort has been to develop models of pilot spatial disorientation (SD) in order to support a cockpit aiding system. The use of actual flight data has been extremely useful during the model development process. The AF Safety Center provided us with 7 flight data sets from actual or suspected SD mishaps. As part of obtaining these data sets, we agreed to provide an analysis based upon our SD models. It is our pleasure to provide this document containing our analysis.

The US military, US civilian, allied military and friendly nation pilots all stand to benefit from improvements to understanding SD. SD kills many pilots every year and has the enormous costs associated with lives lost, aircraft destroyed, property damage, and loss of mission capabilities. MA&D's development of an intelligent Spatial Orientation Aiding System (SOAS) for the cockpit is one part of a comprehensive approach to reducing the unacceptable costs of SD. SOAS is based upon the latest research into human physiology – reflected in its models of various SD illusions – as well as the most advanced pilot workload metrics and multisensory display technologies: head-down, head-up, and helmet-mounted visual displays and symbology; auditory cues and recovery commands; tactile cues; and, olfactory cues.

Spatial disorientation is the result of differences between the actual and perceived position or motion of the aircraft. The effort to model SD focuses on predicting these differences using a combination of aircraft angular accelerations and semi-circular canal research. A Mulder's Law algorithm and acceleration threshold values predict which aircraft movements will be perceived by the semi-circular canals. Decay calculations are used to predict the steady loss of the sense of rotation during washout. These calculations are used to predict the difference between the actual and perceived aircraft rotation at any point during a flight. These values are then combined with specific aircraft movement events to create models of common spatial disorientation sequences such as Leans and Graveyard Spiral. To date, these calculations and models have detected potential spatial disorientation problems in flight data sets from actual SD mishaps, as this document describes in detail.

In addition to the cockpit system, MA&D has applied the attitude perception models to an SD analysis system. The Spatial Disorientation Analysis Tool (SDAT) supports accident investigators by detecting potential SD problems within flight data sets. Given common flight dynamics information from data recorders, SDAT can predict differences in angular rotation perception and pitch angles and detect instances of the Leans and Graveyard Spiral SD illusions.

3 SDAT Analysis Summary

The following is a summary of the SDAT analysis of the seven flight data sets provided to us by the AF Safety Center. The use of these data sets proved to be an invaluable aid to the work on

[1] See section 11, Appendix C, page 81 for acronym definitions.

this project. It is with great pleasure that we present our analysis of these data sets to the safety center and look forward to continued interactions with their staff.

The data sets were provided to us without any additional information related to the types of aircraft involved, mission, phase of flight, or visual environment. We were told that 5 of the data sets were considered SD mishaps and 2 were suspected to be SD related. Our SD modeling assumes that the pilot is not attending to attitude information (i.e., horizon, attitude indicator, HUD), or that such information is absent due to a system malfunction combined with an obscured horizon. As such, our results represent the information provided to the pilot by the vestibular system alone. Therefore, our conclusions about how SD may or may not have affected a specific flight need to be combined with information related to the visual and attentional environment. If it can be determined that the pilot had a sufficient visual horizon, it may be unlikely that our conclusions will be valid. However, it should be emphasized that vestibular-based SD can still occur in a visual environment due to inattention by the pilot.

The following table provides the summary conclusions of our analysis. The reader should refer to Section 7 of this document for the analysis process, detailed SD detection records, and complete analysis.

Data Set	Summary Conclusion
A*	There were no attitude perception deltas or illusions detected in this data set. It is unlikely that a vestibular-based spatial disorientation contributed to this mishap.
B*	One Leans event and two Graveyard Spiral events were detected in this data set. However, none of the three represents a strong or persistent indication of a perception problem. The SD events occur near the end of the data set and may represent an increasing attitude perception problem. It is possible that a vestibular-based perception problem contributed to this mishap.
C	A number of Leans and Graveyard Spiral events were detected in this data set. In addition, there seem to be two instances of a common flight dynamics and illusion detection pattern. These patterns suggest that two similar activities occurred during this flight sequence and that both may have resulted in perceptual problems for the pilot. The second ended in an apparent ground impact. As such, it seems likely that a vestibular-based attitude perception problem contributed to this mishap.
D	A few Leans events and a high number of significant Graveyard Spiral sequences were detected in this data set. It appears that the frequency of the illusions increases across the data set which may indicate an increasing perception difficulty for the pilot. This apparent difficulty, combined with the highly active maneuvers, indicates the potential for vestibular fatigue. However, there are no illusions detected within 40 seconds of the end of the data set. While it appears that vestibular-based perception problems were occurring during this flight and may have contributed to attitude awareness and control problems, it is difficult to determine that one was directly involved with the apparent ground impact.
E	Due to inconsistencies within the data, we split this data set into two parts. Also, the flight sequence does not seem to end in a ground impact. However, we did detect several Leans and Graveyard Spiral sequences in this data set. As such, it is possible that a vestibular-based awareness problem caused attitude problems for this pilot.

F	A large number of Leans and Graveyard Spiral sequences were detected in this data set. This seems to indicate that there may have been an ongoing problem with attitude perception. The largest lost of altitude is concurrent with four different illusion detections. The final graveyard spiral detection is closely timed with the end of the data set. It is likely that a rotation perception problem contributed to this mishap.
G	This data set contains very few sub-threshold roll movements and the two yaw rotation perception sequences occur one and two minutes prior to the end of the data set. While the pitch perception anomaly near the end of the set may have masked the progressive pitch down attitude, it is unlikely to have caused a loss of control. It is unlikely that any vestibular based attitude detections contributed to this mishap.

* Data sets provided as, "maybe_SDO"; all others as "definitely_SDO".

We were fortunate to be able to do a basic comparison between our results and the conclusions determined by the official Safety Investigation Board (SIB). This comparison was done after our analysis was complete. We have not modified our results based on the SIB conclusions. The purpose of the comparison is simply to see what matched and what did not. Certainly a better use of SDAT would be to work within a full analysis process rather than in isolation as was done here. While we cannot present the conclusions of the SIB in this document we can provide a comparison summary. Of the seven data sets, the SDAT conclusions:

- Matched well for 2;
- Did not match at all for 2;
- Partially matched or was inconclusive for 2; and,
- No comparison was possible for 1

In both cases where the SDAT conclusions did not match at all, detailed information about the flights would have likely precluded using SDAT to determine if a vestibular-based illusion was a contributing factor.

4 Spatial Disorientation

The eyes, the most important source of motion information to the human brain, send information to the pilot's brain about the aircraft's position, velocity, and attitude relative to the ground. The overwhelming reliance on visual cues over those from other senses, when there are sufficient visual cues, is called *visual dominance*. Visual cues are ideal for spatial orientation on clear days in VFR conditions with a well-defined horizon. But, when visibility is poor (e.g., during night flying, or in IMC), pilots can experience SD illusions. Even on a clear VFR day, the eyes can "play tricks" (e.g., runway and approach illusions).

The inability of pilots to accurately and intuitively perceive aircraft position without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Maintaining spatial orientation cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature, so continuous attention to one's spatial orientation cannot be maintained using current visual displays. Furthermore, attention can also be diverted to non-visual sources as well (Wickens, 2002), for example the distraction of voice communications or problem solving. Holmes et al. (2003) identify "distraction/task saturation" as an important factor in their list of causes of spatial disorientation. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body (vestibular) cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of SD in flight is not caused merely by attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive, subconscious tendency to rely upon vestibular orientation cues. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored (McGrath, 2000).

4.1 Vestibular System

The parts of the vestibular system that we focus on are the semicircular canals, and the otoliths or vestibular sacs in the inner ear (Figure 1). The semicircular canals are filled with fluid that indicates bi-directional rotation in the pitch, roll, and yaw axes via the cilia, or hair cells, within each canal. The canals are actually accelerometers that sense changes in velocity. Figure 2 shows the role of the semicircular canals in the three dimensions of flight. The otoliths, connected to the base of each semicircular canal, respond to linear accelerations and decelerations.

As rotational motion occurs, the cilia (hair cells) in the canals bend in response to the relative motion between the canal walls, to which the cilia are attached, and the fluid within the canal. The fluid's inertia provides initial resistance and bends the cilia, which informs the brain of the acceleration axis and the magnitude of angular acceleration. After undergoing sustained and constant angular motion, however (e.g., continuous yaw in a standard rate turn), the fluid within the canals begins to rotate at a velocity corresponding to the body and head. As a consequence, there is no longer relative motion between the cilia and the fluid within the canals, the cilia are not bent, and so no sensation of motion is sent to the brain. This phenomenon is called "washout" and has important implications for spatial disorientation. This washout occurs after approximately 10-15 seconds of sustained rotary acceleration (Gillingham & Previc, 1993).

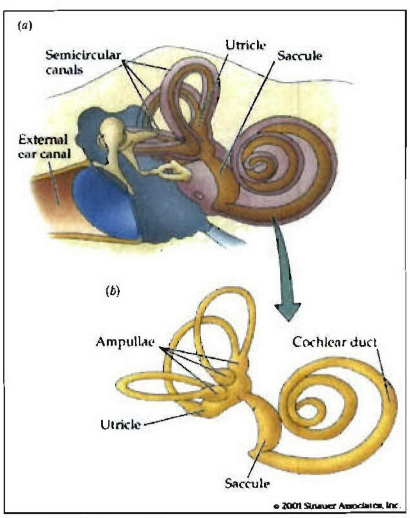

Figure 1. The structure of the outer, middle and inner ears showing the location of the semicircular canals (Rosenzweig et al., 2002, pg 67).

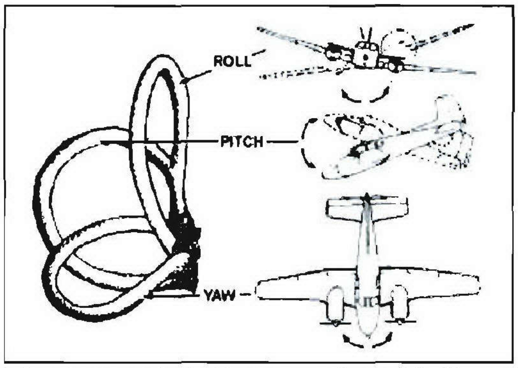

Figure 2. The role of the semicircular canals in the perception of 3-dimensional motion (US Army Field Manual, 2000).

Another important term to SD research is Mulder's Law (DeHart & Davis, 2002), which describes a threshold (called Mulder's Constant) below which accelerations are not sensed by the human vestibular system. For an angular acceleration to be perceived, the product of the intensity or magnitude of acceleration (deg/s2) and time (seconds) of application must reach a threshold value. The best way to illustrate the meaning of Mulder's Law is with a few examples:

1. If a person experiences an acceleration of 1°/sec^2 for 1 sec, he or she will probably not sense that acceleration because the product (1°/sec) does not exceed Mulder's constant.
2. If the same acceleration occurs for 3 sec, however, it will likely be detected (because the product, 3°/sec, exceeds Mulder's constant).
3. Even a large acceleration of 10°/sec^2 will not be felt, if its duration is less than 0.2 sec. The same acceleration will be felt, if its duration is 0.2 sec or greater.

It is important to note that not all humans have identical thresholds and various researchers have determined slightly different threshold values. The following is a list of the most commonly accepted threshold values:

- Mulder's
  - 2.5°/sec for all three axes
- Stapleford, 1968
  - 3.2°/sec for roll
  - 2.6°/sec for pitch
  - 1.1°/sec for yaw
- Oman, 2005
  - 1.5°/sec for all three axes

While the semicircular canals sense rotary motion, the otolith organs sense linear acceleration. Here, in the presence of linear acceleration, the cilia within the linear otolith organs will bend backward, opposite to the direction of acceleration. This angle of bend, relative to the orientation of the organ, signals the degree of acceleration. The orientation of the cilia is as affected by gravitational force as well as by accelerations (Howard, 1986). Hence a linear forward acceleration will produce the same vestibular sensation as a tilt backward, producing the phenomenon of the *somatogravic illusion* (Gillingham & Previc, 1993; Tokumaru et al., 1998), in which pilots who execute a rapid acceleration (for example, on a missed approach) may incorrectly perceive a pitch-up motion.

5 Vestibular Model

The purpose of the vestibular model is to predict the attitude cues provided to the pilot by the vestibular system in the absence of visual orientation cues. The model uses basic aircraft flight dynamic data and the associated responses of the vestibular system. The angular rotation model uses Mulder's Law and perception threshold values to determine which angular accelerations are perceived by the pilot. The concept of washout is used to predict the loss of the sense of rotation. The pitch perception model uses linear accelerations to calculate the pitch information provided by the otoliths.

5.1 Angular Rotation Perception Model

The angular rotation perception model uses the properties of the semi-circular canals to predict the attitude perception information provided to the pilot in the yaw and roll planes. For the purpose of this model, yaw is the rotation of the nose of the aircraft as heading changes. For each time period of a flight data set, the yaw rate is calculated as the change in heading over the duration of the time period. Once the yaw rate has been calculated for two time periods, the yaw acceleration is calculated as the change in yaw rate over the duration of the time period.

At the beginning of the data set, the perceived yaw values will be the same as the actual yaw values. For each calculated yaw acceleration, the model determines if the motion is above or below the perception threshold value using Mulder's Law (see Appendix B for a detailed description of the Mulder's Law calculation).

The effect of washout is modeled by an exponential decay curve. Figure 3 shows an example of exponential decay washout. In the example, the perceived rotation value has reached 5 deg/sec. After about 2.5 seconds, the perceive rotation rate is down to 2 deg/sec and is completely lost by about 8 seconds.

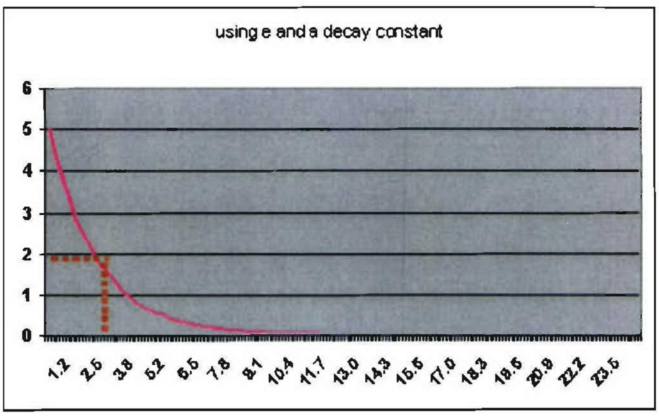

Figure 3. Exponential rotation perception decay example

Figure 4 shows the analysis sequence for the semi-circular canal model for the perception of rotation in yaw and roll. In the case of motion in the yaw plane (heading), if a specific acceleration is above threshold then the same velocity change applied to the aircraft is applied to the perceived rotation value (i.e., it is noticed). If a specific acceleration is below threshold then the associated small change to the AC velocity is not applied to the perceived velocity value resulting in a difference between actual AC yaw (or roll) rotation rate and the perception of that rotation. For any below threshold change we then apply the washout calculation to predict how much of the sense of rotation is lost for the given time period. For each time period, the model then calculates the delta between the actual and perceived attitude.

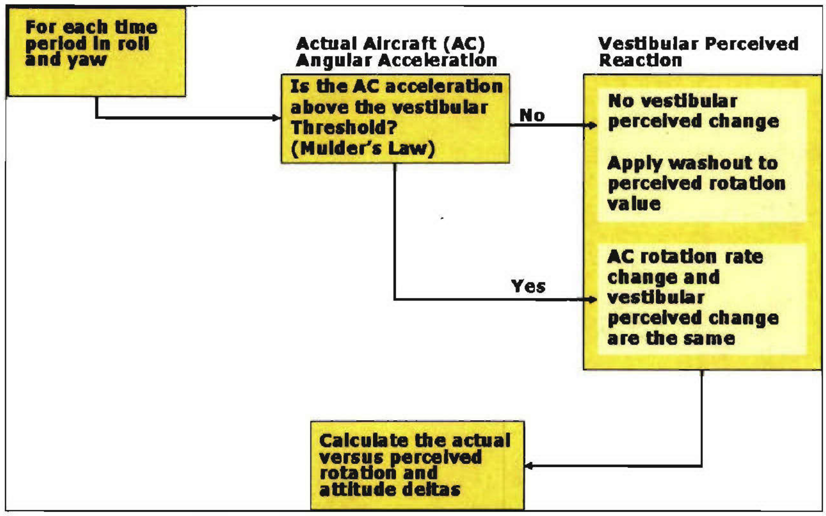

Figure 4. Perceived attitude sequence

The research of angular acceleration thresholds seems to have all been applied from the point of zero rotation. A stationary subject is accelerated in a specific angular plane at different rates and the threshold at which they sense the rotation is recorded. We know of no study that tried to determine detection thresholds for participants who start from a non-zero angular velocity. It is possible that threshold perception values could be different when already rotating as apposed to starting from zero rotation. Our assumption is that we can use the same threshold values to apply velocity changes to perceived values whether or not the pilot is already sensing rotation. The extension to that assumption is that the velocity change associated with a perceived acceleration is additive to the current perceived value.

5.1.1 Actual versus Perceived Rotation Delta Examples

The following two examples show how the vestibular model can be used to predict the delta between actual and perceived rotation during flight. Remember that the perceived rotation value is based on the information provided by the vestibular system without any visual information.

The graph in Figure 5 shows an example of actual versus perceived rotation as calculated by the vestibular model. The data set is approximately three minutes long and shows a long left turn. The blue line in the figure show that the yaw rotation rate (heading change) reaches a maximum of about -5 deg/sec. Part way through the turn the rotation drops to zero before increasing again. The rate of change of the rotation is slow enough to be below the perception threshold value for nearly the whole data set. The red line shows the rotation rate as perceived by the vestibular system. Since the accelerations are below threshold, there is almost no perception of the turn as it occurs. The only above threshold movement is at about time 125 when the rotation rate is quickly reduced by about 2 deg/sec. The movement is above the vestibular perception threshold and the pilot would feel approximately 2 deg/sec of rotation to the right (illusory rotation). The movement back to -5 deg/sec rotation is below threshold so it is not perceived by the pilot. So it is the decay (washout) of the sense of illusory rotation that brings the perception of rotation back to zero.

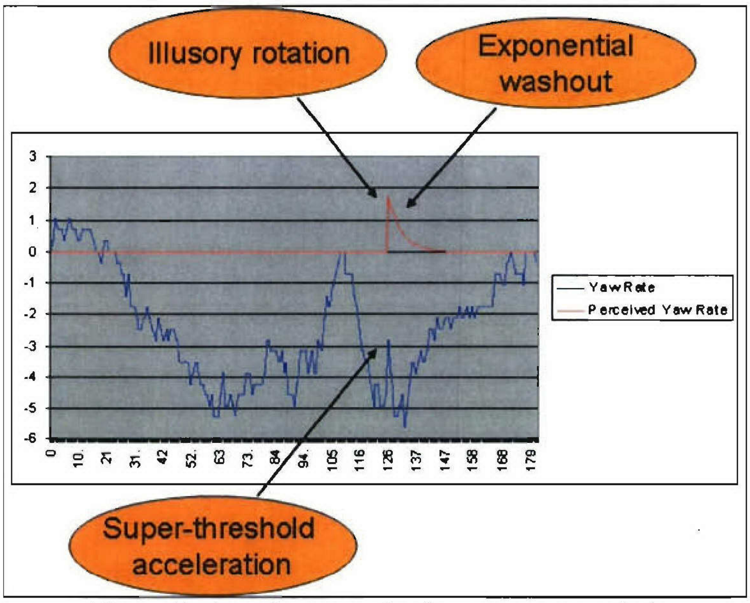

Figure 5. Actual vs. perceived yaw rate example 1

Figure 6 shows another example of actual versus perceived yaw rotation. Over about 2 minutes, the blue line shows a series of three right hand turns. The rotation rate of the first turn is maintained at about 2 deg/sec. The red line, representing the perceived rotation rate, shows that the initial acceleration at about time 23 is perceived but then washes out to zero perceived rotation by about time 46. The second turn is at a maximum of about 8 deg/sec rotation and again the perception of rotation is gradually lost during the turn. When the actual rotation returns to zero (rolling out of the turn) the rotational deceleration is above threshold resulting in over -6 deg/sec of illusory rotation in the opposite direction.

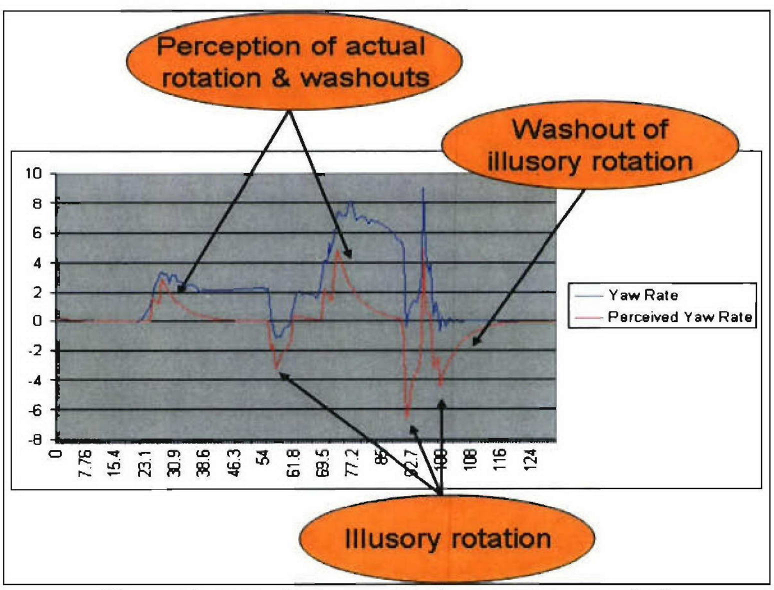

Figure 6. Actual vs. perceived yaw rate example 2

5.2 Pitch Perception Model

Otoliths are another of the organs of the vestibular system. Unlike the semi-circular canals, otoliths respond to G forces – they sense where 'down' is. In normal ground activity, this sense is dominated by acceleration to gravity since most human motion is way less than 1 G. Aircraft, however, can create both linear and rotational accelerations that are much higher. The otoliths essentially respond the acceleration vectors. The combination of AC acceleration and gravitational vectors can cause the otoliths to create an incorrect perception of 'down'. This is most apparent in the sensation of pitch. A combination of 1 G gravitational vector (Gz - down) and 1 G linear acceleration vector (Gx - forward) can result in the perception of a 45 degree pitch up angle.

The SD system currently uses a model of Otolith sensation to predict the perceived pitch angle. Vector analysis is used to combine the linear acceleration with acceleration to gravity to arrive at the perceived pitch angle. The formula:

$$\text{Perceived Pitch} = \text{Actual Pitch} + \text{ArcTangent}(Gx/Gz)$$

Gx is linear acceleration calculated from the change in airspeed and converted to G. Gz is taken from the Normal Load Factor value in the data sets and is assumed to be 90 degrees from the linear acceleration vector. Figure 7 shows an example of actual versus perceived rotation based on the model calculation. This data set starts with a take-off so the actual pitch is 0 until above time 120 then changes quickly to about 12 degrees. The high linear acceleration associated with take off causes a feeling of even greater pitch up during that time period. While the rest of the data set shows a few smaller sustained differences and the occasional high spike, none are as great as the take-off at the beginning.

This calculation is only accurate when the AC is banked at 30 deg or less. More than that and the perception of 'down' is combined with the bank to the side and the pure pitch calculation may no longer valid. As such, this prediction of perceived pitch is only valid for time periods at which the AC is banked less than 30 deg.

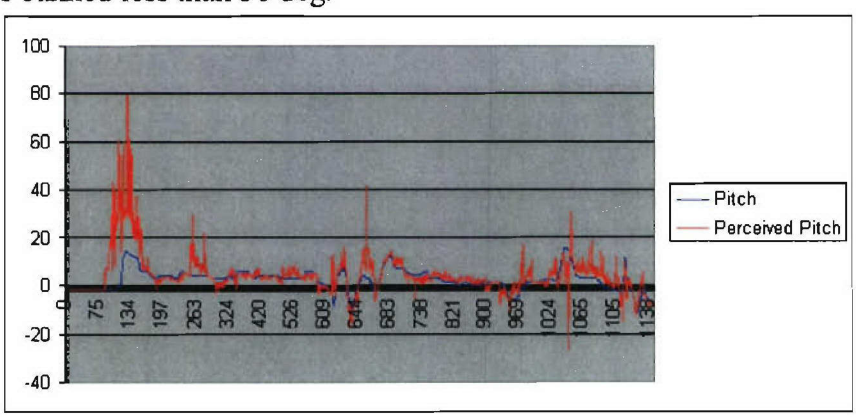

Figure 7. Actual vs. perceived pitch example

5.3 Spatial Disorientation Illusion Sequence Models

We know of no way to determine the actual intentions or perceptions of the pilot. As such it is difficult to determine if a specific SD illusion was experienced based only of flight dynamics.

However, looking for specific sequences within that data and combining that with the perception predictions from the vestibular model can give us a general indication that an SD problem might be occurring. Two illusion models are currently used to look for such sequences. They assume that there is not or little visual information available to the pilot. The models are designed as a sequence of events that must occur in a specific order with specific values and time periods. As each event occurs the certainty of SD increases.

5.3.1 The Leans Illusion Model

The most common SD illusion in flight is *the Leans* (Holmes et al., 2003; Benson, 1988), which entails an erroneous feeling of roll. A typical case occurs in the following scenario (Gillingham & Previc, 1993): In IMC, the pilot has very slowly entered a turn, perhaps unknowingly, at a sub-threshold rate so that the semicircular canals provide no sense of rotation. If the pilot then becomes consciously aware of the aircraft's bank angle (e.g., by looking at the instruments), and intentionally returns the bank to the true level attitude, he or she will now receive a vestibular sensation of an opposite bank. If the pilot continues to rely upon flight instruments to maintain a level attitude, he or she may also *lean* in the orientation of the incorrectly perceived upright (hence the illusion's name). If the pilot does not rely upon the instruments at this point, but rather the intuitive (vestibular) signal of upright, he or she will return the aircraft to its original bank angle. Without awareness and conscious correction, the bank can lead to a gradual pitch down attitude, a loss of altitude, and an increase in airspeed. This side-to-side seesawing process of correction and re-entry may continue until the pilot is so disoriented that recovery to straight-and-level flight is difficult, if not impossible.

The model of the Leans is expressed as a timed sequence of events with the certainty of the assessment of the disorientation increasing with each successive event as shown in Figure 8. The first event is the initiation of a roll at a rate below the vestibular threshold starting from a specified roll angle and rate. The second event is a roll angle change of at least 5 degrees that lasts at least 5 seconds that is reached through continuous sub-threshold movements. If these two events occur in sequence, it is possible that the pilot has not noticed the ensuing roll angle and that there is a difference between the pilot's perceived attitude and the true attitude of the aircraft. As such, the model indicates a possibility of SD but only at a very low confidence level. The third event is the loss of altitude as measured by negative vertical velocity. If this event follows the first two, it is possible that the pilot has also not noticed the loss of altitude and the model represents an increased confidence in its assessment of the Leans. The fourth event is a roll well above the vestibular threshold (i.e., greater than 5deg/sec). If this occurs following the first three events, it is possible that the pilot has now noticed the roll angle and has quickly corrected back toward level. When this occurs, the pilot's vestibular system will register a roll in the opposite direction, again resulting in a difference between the perceived attitude and the actual attitude of the aircraft. At this point the model represents a high level of SD certainty. The final event in the model is the tilt of the pilot's head opposite the perceived roll angle. If this occurs following the other four events, it is likely that the pilot is experiencing the Leans and the model represents an even higher level of SD certainty.

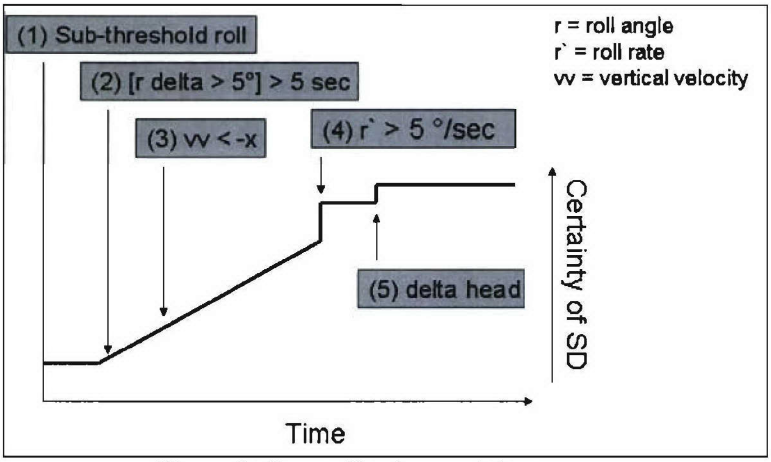

Figure 8. Leans Illusion model sequence

The current version of the Leans Illusion model allows the user to vary the starting position, roll delta and duration values, negative vertical velocity and final roll rate. This allows the user to detect Leans-type sequences that vary from the standard version. A detailed description of these values and the process for changing them is included in section 6.3 of this document.

5.3.2 Graveyard Spiral

A somatogyral illusion is "any discrepancy between actual and perceived rate of self-rotation that results from an abnormal angular acceleratory stimulus pattern." One such illusion is the Graveyard Spiral in which a misperception of a turn results in a descending and often tightening spiral. The common sequence involves a turn that is held long enough to loose (washout) the sense of rotation. The attempt to roll level then feels like a turn in the opposite direction. The pilot then erroneously attempts to reduce the sense of rotation by rolling back into the original turn. If they then attempt to arrest the loss of altitude by pulling back on the stick, the turn can tighten and result in a descending spiral that is not felt by the pilot.

The Graveyard Spiral Illusion model focuses on the delta between perceived yaw rotation as calculated by the vestibular model and actual yaw rotation. Figure 9 shows the model event sequence. Event 1 looks for a perceived yaw rotation that is less than the actual yaw rotation by a specified delta (5 deg/sec). When this situation exists it is indicative of either washout or sub-threshold yaw rotation. For the next two events, any reduction in the rotational delta interrupts the sequence and is indicative of more accurate rotational perception on the part of the pilot. Event 2 looks for a perceived yaw rotation that is greater than the actual provided the rotation delta is maintained. This indicates that the pilot has reduced the actual rotation and is experiencing illusory rotation. Event 3 looks for a perceived yaw rotation that is less than the actual provided the rotation delta was maintained. This indicates that the pilot increased actual yaw rotation but doesn't perceive much or any of it. This is indicative of an erroneous roll back to yaw rotation in order to reduce the sense of illusory rotation. Event 4 is designed to indicate a loss of control following the other events by a combination of high bank angle and negative vertical velocity. Event 5 looks for the pitch up command that could tighten the spiral.

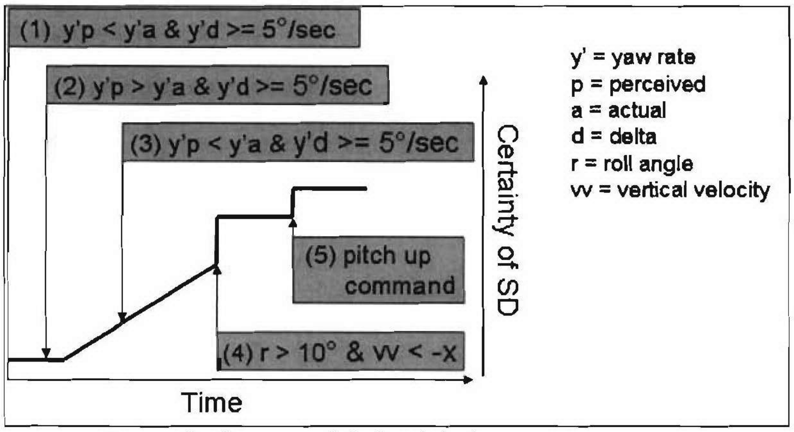

Figure 9. Graveyard Spiral Illusion model sequence

The current version of the Graveyard Spiral Illusion model allows the user to vary the rotation perception deltas of the first three events. This allow the user to detect illusions of lesser or greater magnitude. They can also vary the values of Event 4. A detailed description of these values and the process for changing them is included in section 6.4 of this document.

6 Spatial Disorientation Analysis Tool (SDAT)

This section describes the SDAT tool screens used to setup an analysis. It describes the following tabs in detail:

- Analysis Setup tab
- Vestibular sub-tab
- Leans sub-tab
- Graveyard Spiral sub-tab

The focus is on those settings that were used in the analysis of the flight data sets provided by the AF. The function and use of additional SDAT tabs are not described here (the reader should see the *SDAT User Guide* for more detailed information).

6.1 Analysis Setup Tab

The Analysis Setup tab is the first screen shown when running the SDAT tool (Figure 10). It includes the Create New Analysis pain on the left and the sub-tab pain on the right. The Analysis Setup tab allows the user to enter the basic settings for analysis. Each time the tool is started the default settings are used. The tab allows the user to:

- Select the data file to analyze
- Select the illusion type to search for
- Set the values for data rounding and sampling rate

<u>Select Flight Data File</u>

The tool allows the user to browse for and select a data file to load in the tool and analyze for spatial disorientation events. The data needs to be in an Excel file with the format described in Appendix A.

Select Illusion Type
The tool allows the user to select which type of SD illusion sequence to search for within the flight data set. The tool currently has three options; Coriolis, Graveyard Spiral, and Leans. The Coriolis model will only function properly if the data set includes pilot head position data. To date, we have no actual or simulated flight data sets containing this information.

Data Rounding
Many flight data values are listed out to five or six decimal places. It is unlikely that human perception can distinguish variations at such high precision (e.g. thousandths of a degree of roll). The tool allows the user to round data values down as desired. The default is currently set at 2 decimal places.

Data Sampling Rate
The frequency of data varies in different sampling rates. Some data sets might include values for each second (1 Hz) while others may include data every 10^{th} of a second (10 Hz). The tool allows the user to vary the rate at which the tool samples the data from the file. The default is set to use all the data available in the file.

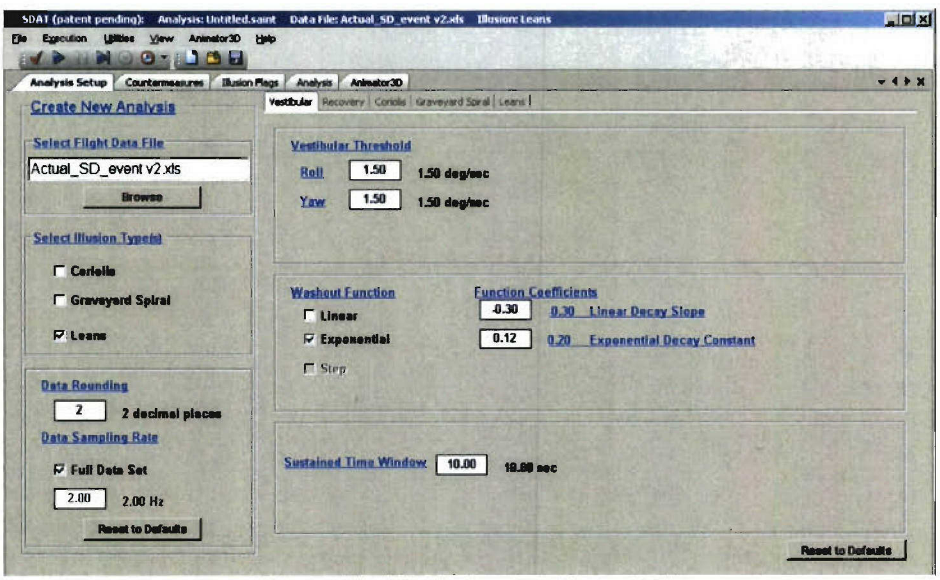

Figure 10. SDAT Analysis Setup Tab

6.2 Vestibular Sub-tab

The Vestibular sub-tab is the first shown on the right pain of the Analysis Setup tab. The vestibular sub tab allows the user to:

- Set the threshold values for the roll and yaw planes
- Select the washout function type and set the associated decay values
- Select the duration of the Sustained Time Window

Vestibular Threshold
The tool allows the user to vary the perception threshold value for the roll and yaw planes. The defaults are both set at 1.5. The most common ranges for these values, as derived from the research, are described in Section 6.5.

Washout Function
The tool allows the user to vary the decay function used to model the effect of washout. Currently the tool contains both linear and exponential decay functions. Currently the exponential decay function is most commonly used and a value of 0.12 for the decay constant is being used based on experimental calibration.

Sustained Time Window
The tool allows the user to vary the duration of the sustained time window. This duration relates to the definition of Mulder's Law and the methodology used in its implementation (see Appendix C for details). The current default and most often used value is 10 seconds.

6.3 Leans Illusion Sub-tab

The Leans Illusion Sub-tab (Figure 11) allows the user to alter the illusion sequence detection values. The default values represent a commonly accepted illusion sequence. Changing the values allows the user to search for non-standard leans-type sequences within the flight data set. The Event 1 values include the starting conditions for which the tool looks for sub-threshold roll changes. The default values refer to nearly straight and level flight at a maximum +- 1 degree of roll and +- 1 deg/sec of roll rotation. These can be varied to look for sub-threshold roll changes starting from higher roll angles to rotation values. The Event 2 values are focused on the amount and duration of change that occurs during sustained sub-threshold roll actions. The default value for roll delta is 5 degrees and the default duration is 5 seconds. These can be varied to look for smaller or large delta and durations of roll changes. Event 3 refers to the potential loss of control by looking for negative vertical velocity. The value can be altered based on aircraft type and/or phase of flight. Event 4 looks for high roll velocity that could occur following the unnoticed sub-threshold changes. This is often the first in a series of roll oscillations.

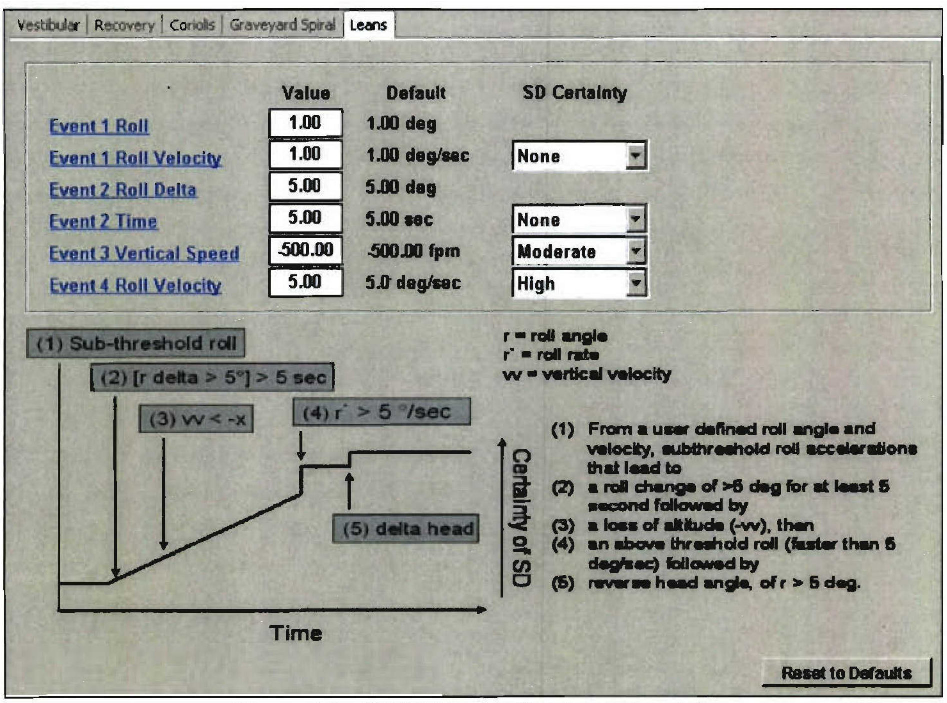

Figure 11. SDAT Leans Illusion setup tab

6.4 Graveyard Spiral Sub-tab

The Graveyard Spiral Illusion Sub-tab (Figure 12) allows the user to alter the illusion sequence detection values. The default values represent an illusion sequence of a particular magnitude of perception delta. Changing the values allows the user to search for illusion sequences of less or greater deltas. Each of the first three events represents the yaw velocity delta between the actual and perceived yaw rotation rates. Event 1 represents the level of washout. The default value would indicate the aircraft is rotation 5 deg/sec faster than the rotation value perceived by the pilot. Event 2 represents the level of illusory counter rotation. The default value would indicate that the pilot is perceiving 5 deg/sec more rotation than the actual aircraft value. Event 3 represents that erroneous counteraction by the pilot opposite the direction of the illusory rotation such that the aircraft is once again rotation faster than the pilot perceives. These three values can be altered together or separately to look for different levels of rotation perception delta magnitudes. Event 4 represents a two part indication of loss of control with a minimum roll angle and negative vertical velocity. Event 5 looks for the pitch up command that would erroneously tighten the descending turn of the classical graveyard spiral sequence. To date, we do not have data sets with sufficient stick control information for this event.

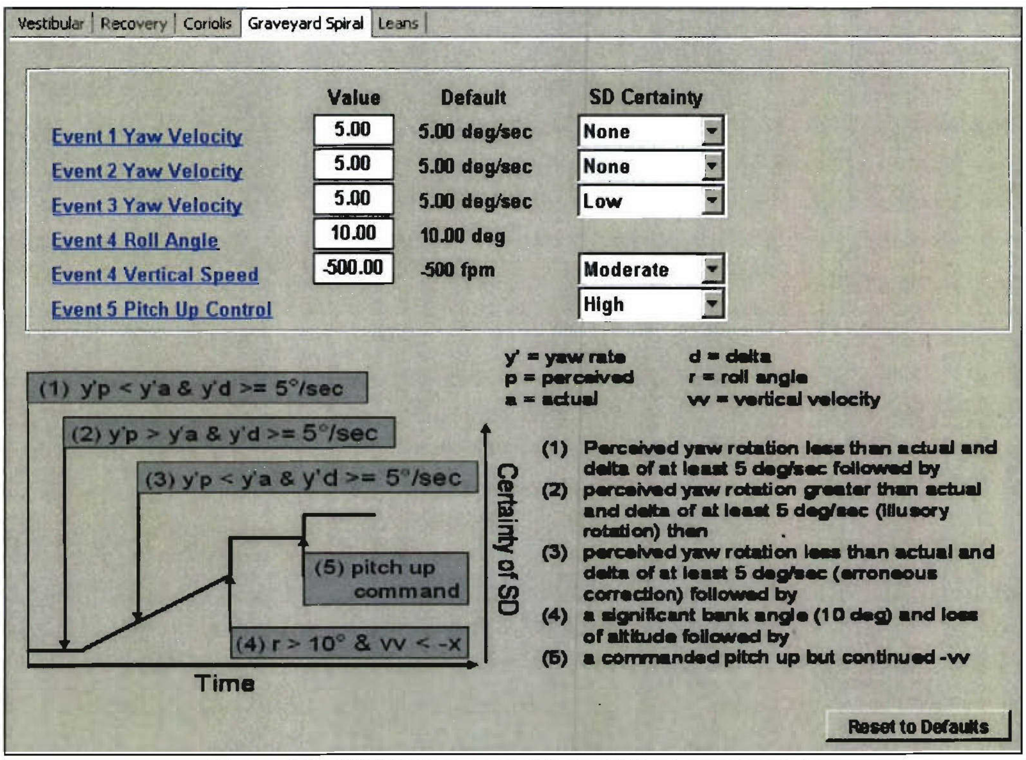

Figure 12. SDAT Graveyard Spiral Illusion setup tab

6.5 Tool Settings & Analysis Ranges

Table 1 lists the data types, default values and common ranges used for the analysis of the AF Safety Center flight data sets. The default values and ranges are either provided by research results or expert estimation. The provided ranges can be used as guidelines during an analysis but it has been common in many cases to range outside of some of these values depending on the dynamics of the flight data.

Table 1. SDAT settings default values and common ranges

Data Type or Event	Default	Common Ranges and Values
Data		
Rounding	2 decimal places	None
Sampling Rate	Full data set	>= 2 Hz
Vestibular Model		
Roll Threshold	1.5	1.1, 2.5, 3.2
Yaw Threshold	1.5	1.1, 2.5
Washout Decay Function	Exponential Decay Constant 0.12	.1 to .2
Leans Illusion		
Event 1 Roll Angle	1 deg	1 to 60
Event 1 Roll Velocity	1 deg/sec	1 to 2
Event 2 Roll Change	5 deg	3 to 7
Event 2 Time Duration	5 seconds	3 to 7
Event 3 Vertical Speed	-500 fpm	-500, -1000
Event 4 Roll Velocity	5 deg/sec	> 5 deg/sec
Graveyard Spiral		
Event 1 Yaw Velocity	5 deg/sec	3 to 7
Event 2 Yaw Velocity	5 deg/sec	3 to 7
Event 3 Yaw Velocity	5 deg/sec	3 to 7
Event 4 Roll Angle	10 deg	> 10 deg
Event 4 Vertical Speed	-500 fpm	-500, -1000

7 Analysis Results

This section provides the results of using SDAT to analysis the seven flight data sets provided to use by the AF Flight Safety Center. The use of these data sets proved to be an invaluable aid to the work on this project. Specifically the use of actual flight dynamics rather than simulated data allowed us to locate problems within the vestibular and illusion models. It is with great pleasure that we present our analysis of these data sets to the flight safety center and look forward to continued interaction with their personnel.

The data sets were provided to us without any additional information. That is, we didn't know anything about the types of aircraft involved, mission, phase of flight, or visual environment. It is clear in most of the data sets based on data values like pitch, altitude and vertical velocity that the end of each set represents a ground impact. We were told that 5 of the data sets were considered SD mishaps and 2 were suspected to be SD related. We were given no information about the type of SD that was suspected. As such, our analysis was done in isolation. All our SD modeling is based on the assumption that the pilot is either not attending to or is without sufficient visual cues to maintain attitude awareness. Therefore, our conclusions about how SD may or may not have affected a specific flight need to be combined with information related to the visual environment. If it can be determined that during a specific data set the pilot had a sufficient visual horizon, it is unlikely that our conclusions will be valid.

7.1 Analysis process

When we received the data sets from AFSC, we examined them to determine which parameters were in each data set. We re-arranged the parameter columns into the format we need for SDAT (see Appendix A), and then looked for gaps in the data. We found that all the data sets contained significant data gaps, some lasting several seconds. Not knowing why these gaps occur or how the flight recorders functioned, we chose to fill the gaps using Excel's "Fill...Series" linear interpolation. That is, if the gap was 4 lines long, and the data elements were 1 before the gap and then 6 at the end of the gap, the Excel function filled the gap with 2, 3, 4, 5. We did this for all observed gaps in the data. Naturally, we had to modify this process for data values such as heading because the linear trending function would not correctly interpret the change from a heading of 358 degrees to 2 degrees.

In addition, we often had to calculate key data that was occasionally missing. For example, if vertical speed indicated was not included, we calculated it based on altitude rate of change in feet per minute. Both the linear interpolation and the data calculation processes may have introduced errors into the data sets.

The next step in our analysis process involved a general review of the flight sequence. We plotted the values for Alt, RAlt, pitch & roll, CAS, VSI, Gz over time to determine nature of flight (e.g., aircraft type, landing, takeoff). The results for each data set includes our basic description of the flight sequence as we understood it.

The analysis process using the SDAT system took several steps. For each data set, we ran it through the tool and plotted the actual versus perceived pitch to look for any sustained pitch anomalies. We currently do not have an otolith-based illusion sequence model so our pitch anomaly analysis is purely based on the comparison of actual to perceived values.

Each data set was then run using first the Leans model and then the Graveyard Spiral model. Multiple runs were done for each model as we varied the data values to detect different instances of the illusion sequence and determine its level of persistence. Assuming that individual differences in semi-circular canal threshold values exist and assuming that the range of thresholds from the research generally covers the population, we make a distinction between events detected across the threshold values. If an event occurs for only one threshold value then our assumption is that of a low probability that the event was indicative of a perception problem for the pilot. Events persisting across more than one threshold value are assumed to have a higher probability of indicating a perception problem.

Finally, we combined the results of the flight dynamics review, pitch anomaly analysis, Leans and Graveyard Spiral into a single graphical figure. This allowed us to look for patterns in the detected SD sequences within the flight sequence. The complete results and our conclusions are included in the rest of this section.

7.2 Data Set A

This data set lasts 600 seconds (10 minutes) and describes an aircraft in a near-steady descent from 15,000' MSL to about 5,000' MSL. During that time, Radio altitude is level at 5,000' AGL (its maximum), then drops to about 2,000' AGL, climbs to about 4,000' AGL, and then descends to ground impact (Figure 13). This is clearly an approach and landing.

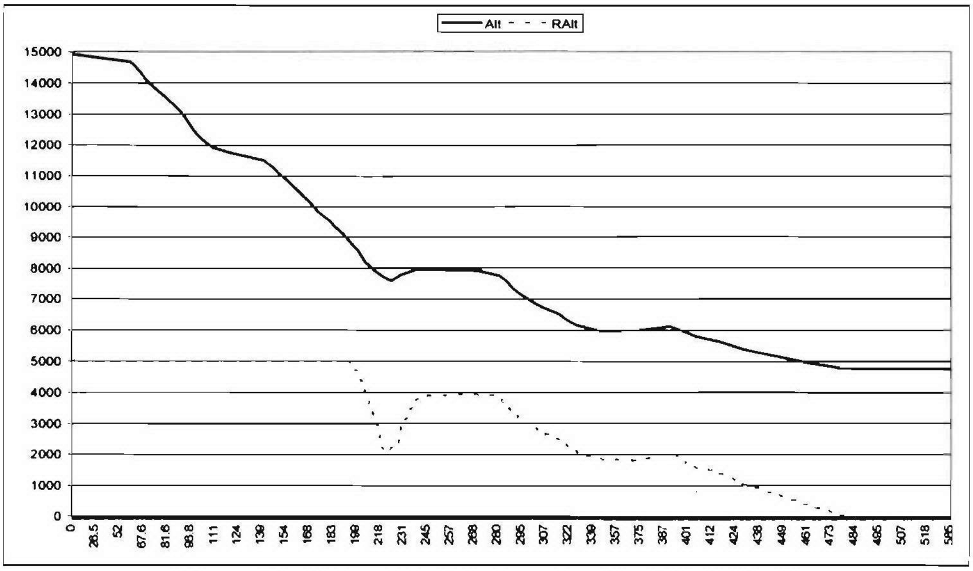

Figure 13. Data set A altitude and radio altitude (feet)

The reader should note that pitch does not reach extreme values and is mostly nose up (Figure 14). Roll is much more erratic and varies from about right 40° to about left 50°. At the time of touch down (about 480) the aircraft is in a 15 degree left bank. The landing is clearly hard as the vertical G's at the time were about 2.9 (Figure 17). Following the hard banked landing, the aircraft remains banked to the left possibly indicating a collapse of the left landing gear.

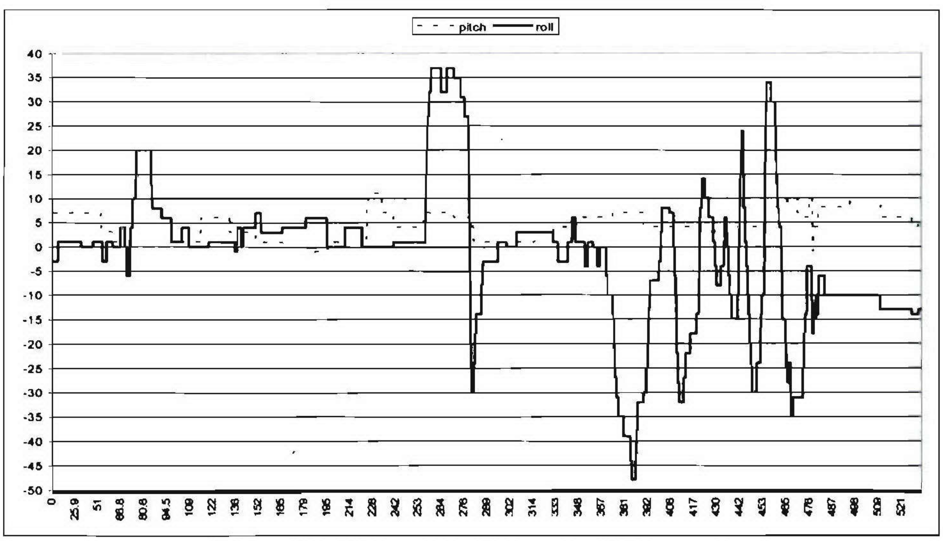

Figure 14. Data set A pitch and roll (degrees)

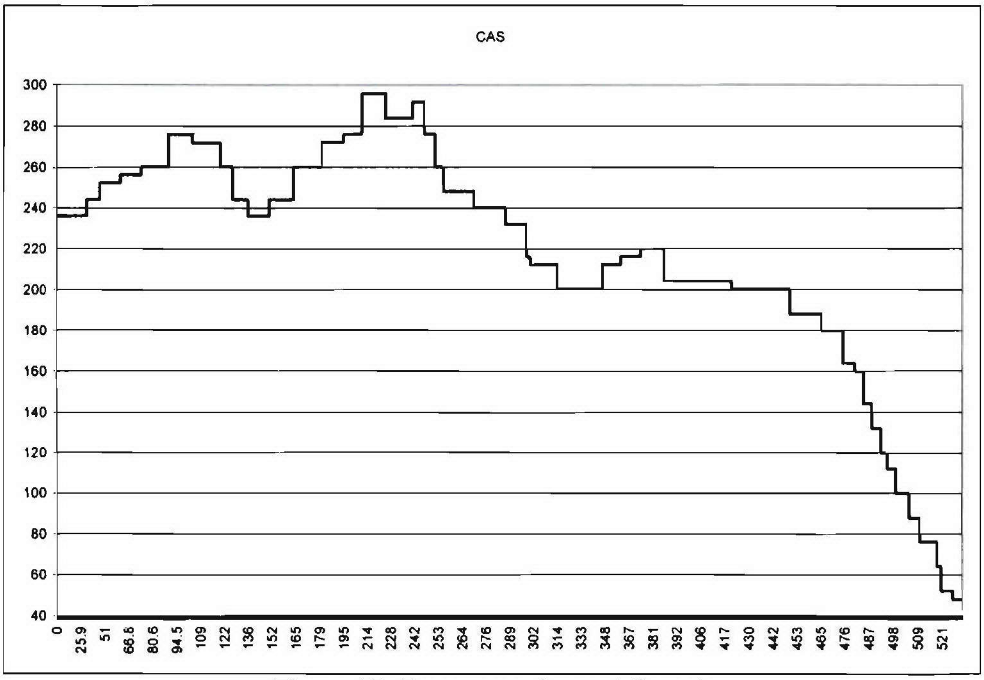

Figure 15. Data set A airspeed (knots)

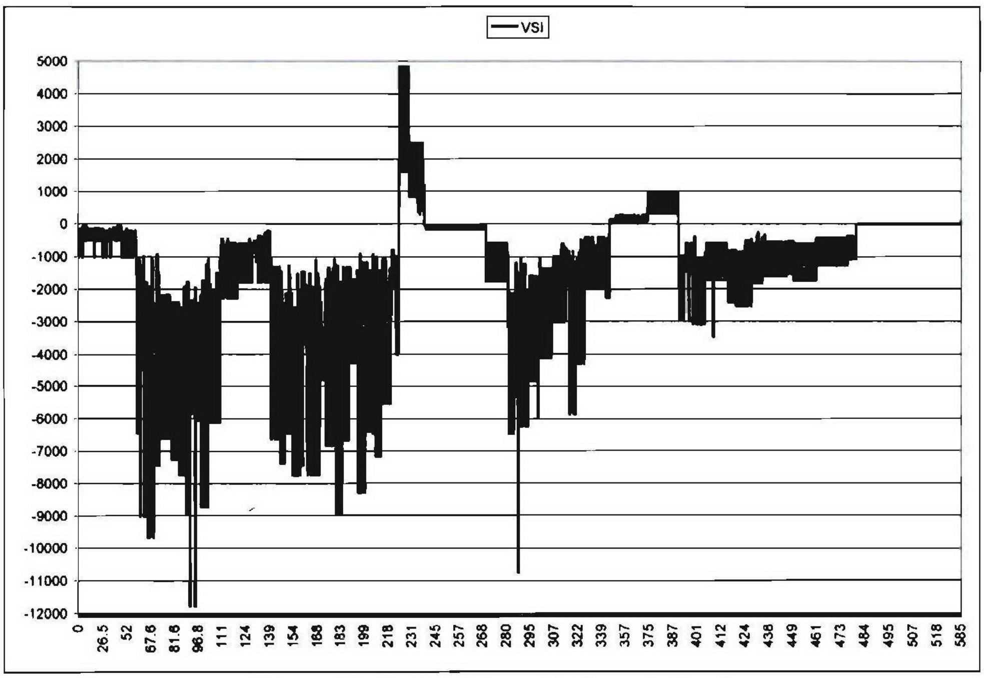

Figure 16. Data set A vertical speed (fpm)

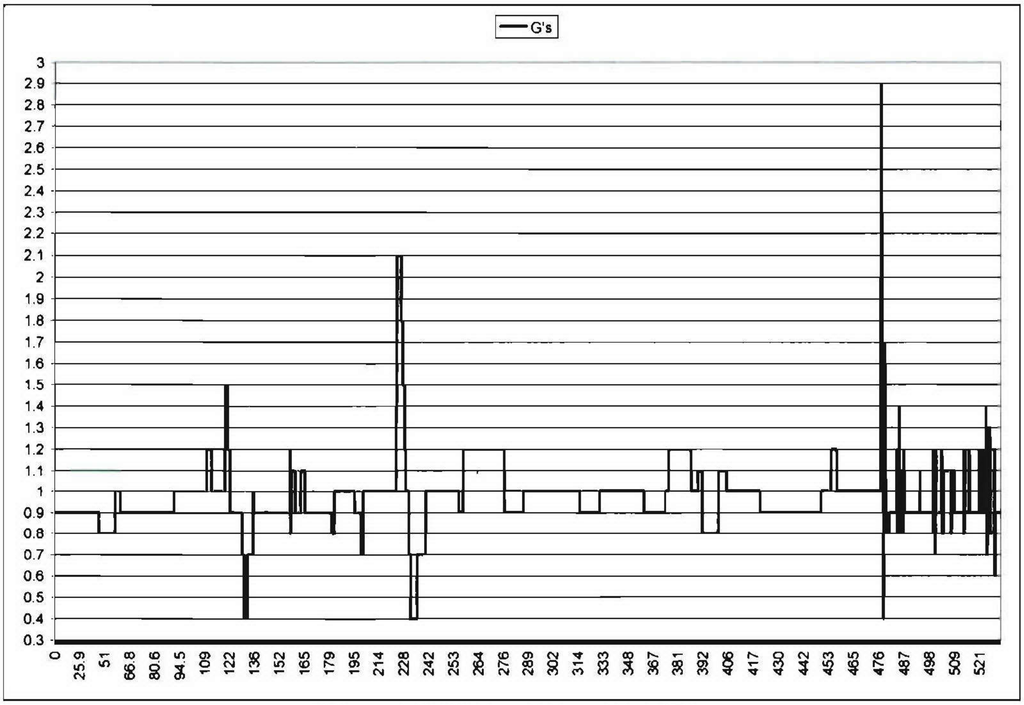

Figure 17. Data set A vertical G's

Pitch Analysis

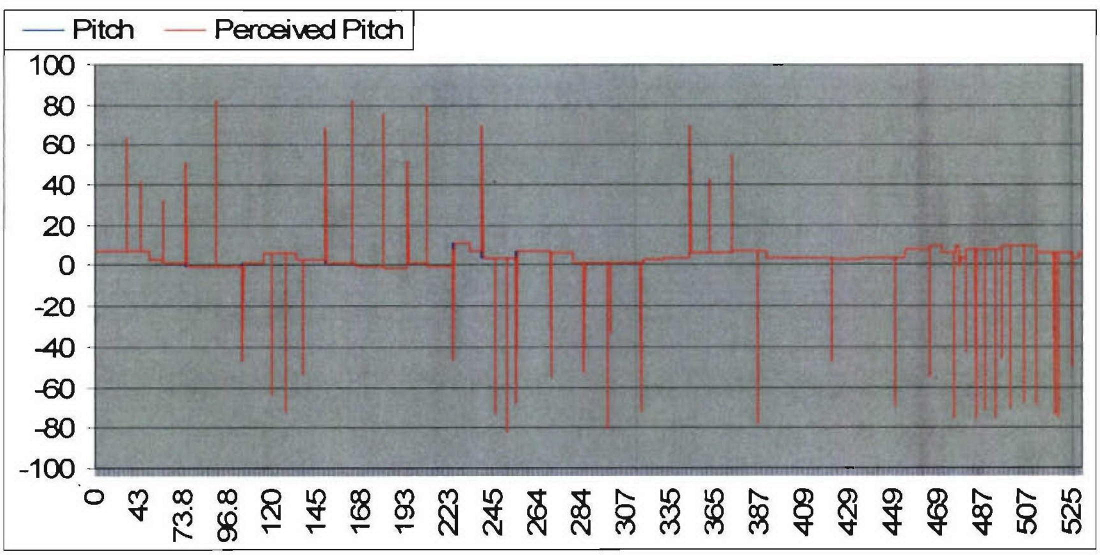

Figure 18. Data set A actual and perceived pitch

The strange blockiness of the values in this data set makes the calculations of perceived pitch questionable. The actual pitch value is identical to the perceived pitch in the graph (Figure 18) except for the instantaneous large deviations which are due to sudden changes in the blocky data set. The aircraft on approach general keeps the nose just a little above horizontal. The changes in perceived pitch are primarily due to changes in airspeed as the pilot stays on the desired glide slope (small accelerations and decelerations). The only consistent perceived pitch delta is after the touch down at time 480 as the aircraft decelerates on the runway. It is unlikely that a pitch perception problem contributed to this mishap.

Leans Analysis

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default settings	Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: default Event 2: • 3 degrees • 3 seconds	Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: • 20 degrees • 2 deg/sec Event 2: • 3 degrees • 3 seconds	Event 2: none

Table 2. Leans illusion identification and sensitivity analysis results

No standard or non-standard Leans events were detected in this data set. While there are sub-threshold roll movements (Leans Event 1), they never result in a change in bank angle that lasts for more than a few seconds. Most of the roll actions are above the threshold value and, as such, are likely perceived by the pilot. It is unlikely that a sub-threshold roll perception problem contributed to this mishap.

Graveyard Spiral Analysis

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1, 1.5, 2.5 Full data set, 2 Hz sampling rate	Defaults	Event 1: none
1.1, 1.5, 2.5 Full data set, 2 Hz sampling rate	Event 1: 3 deg/sec Event 2: 3 deg/sec Event 3: 3 deg/sec	Event 1: none

Table 3. Illusion ID and Sensitivity Analysis

There were no illusion events detected. The blockiness of the data set causes calculations of very large (unrealistic) yaw accelerations. Also, there is very little heading change during this suspected approach and landing. It is unlikely that a yaw rate perception problem contributed to this mishap.

Conclusion

There were no attitude perception deltas or illusions detected in this data set. It is unlikely that a vestibular-based spatial disorientation contributed to this mishap.

7.3 Data Set B

This data set lasts about 8 minutes (468 seconds). It was described to us a 'possibly SD'. The final dive to the ground is fairly precipitous, taking about 20 seconds to descend from 20,000' MSL (Figure 19).

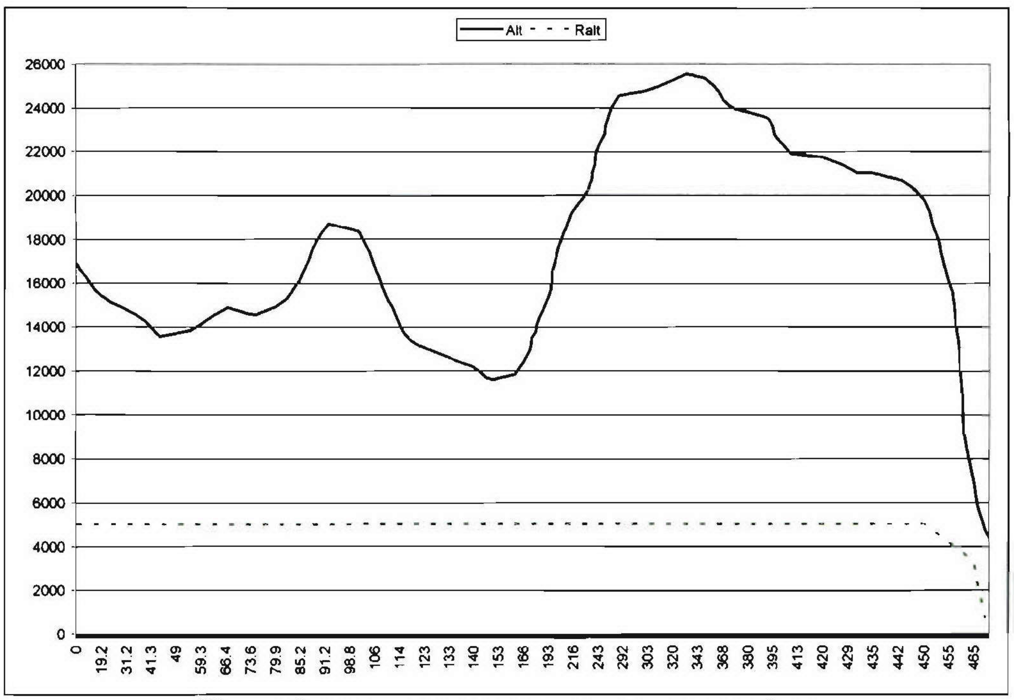

Figure 19. Data set B altitude and radio altitude (feet)

Pitch is unusual in that it goes from 60° nose up to 80° nose down in about 20 seconds at about time 85. Just prior to that, the roll goes inverted (probably a full aileron roll at about time 70) and is fairly erratic throughout the data set (Figure 20). The aircraft is inverted within about 20 seconds of the end of the data set. However, such maneuvers may not be that unusual because the aircraft is undoubtedly a fighter-type jet, given the airspeeds shown in Figure 21. Also, the airspeed seems to indicate a stall during the large pitch-up mentioned above at about time 83-90. The extreme nose down pitch may be a stall recovery, since airspeed builds after that maneuver.

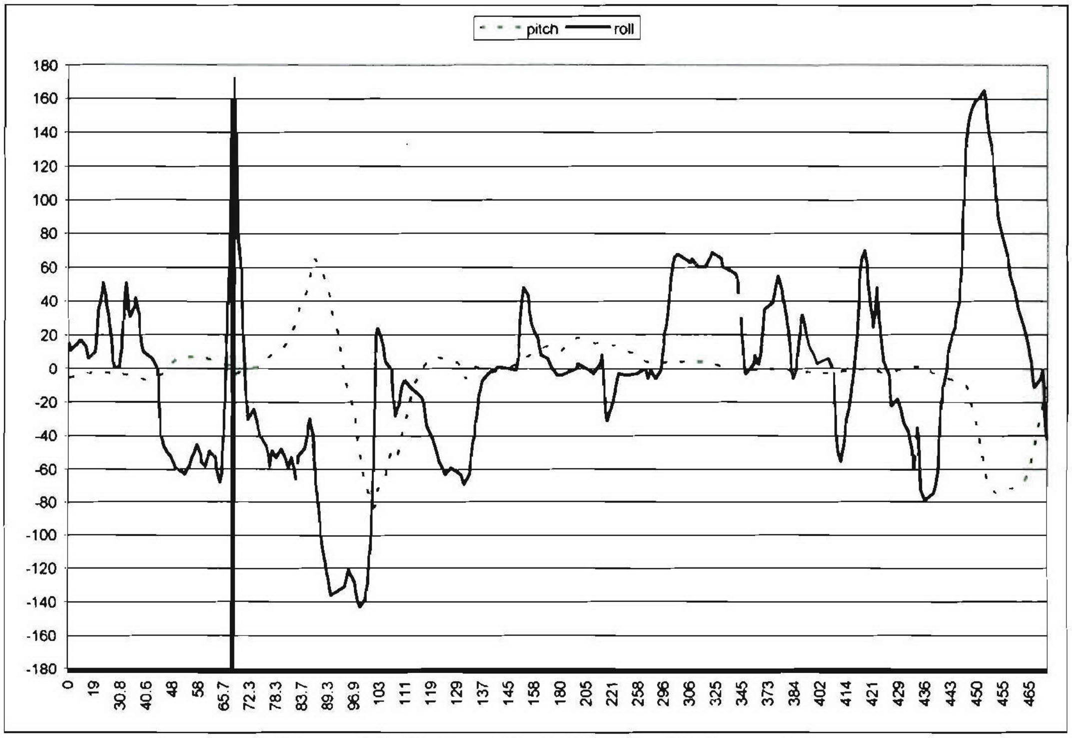

Figure 20. Data set B pitch and roll (degrees)

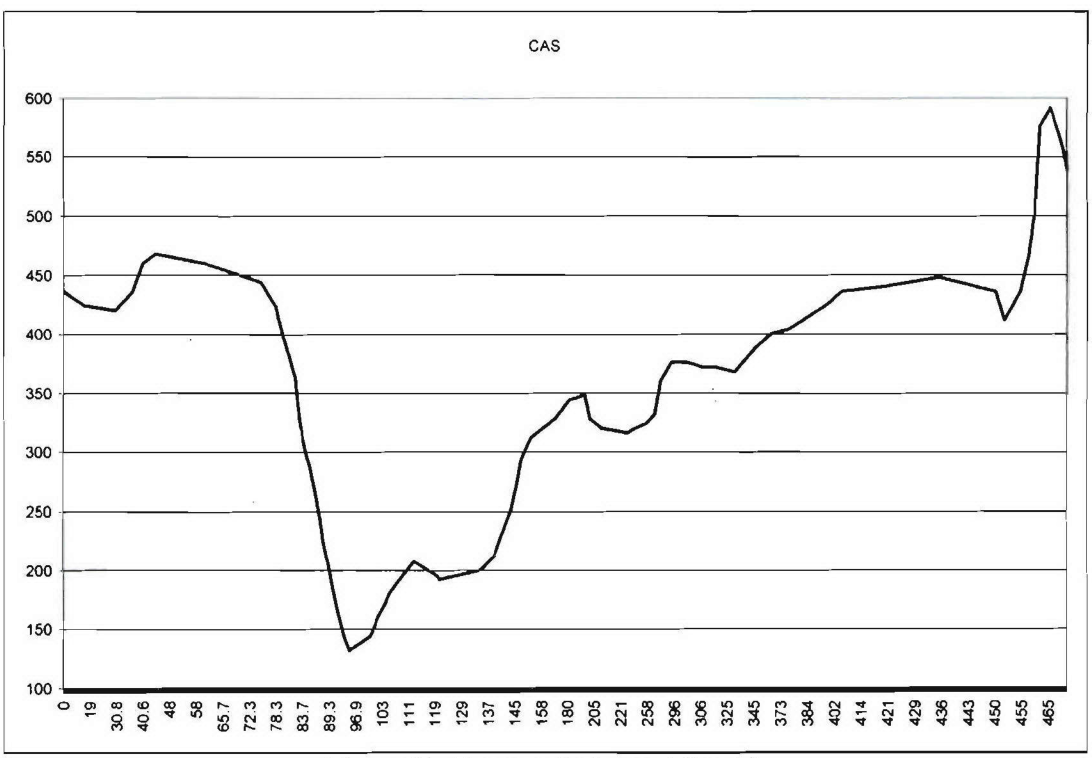

Figure 21. Data set B airspeed (knots)

Vertical speed seems unusual, even for a fighter-type aircraft, with extremes of 50,000 fpm – both positive (climb) and negative (dive) – numerous times (Figure 22).

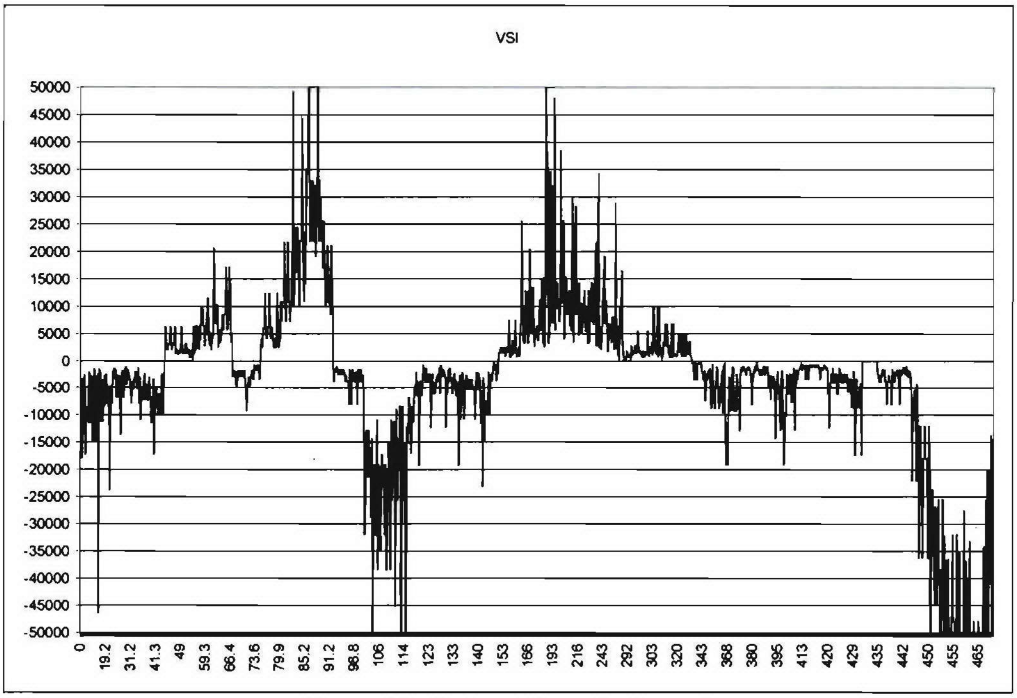

Figure 22. Data set B vertical speed

Lastly, vertical G's seem reasonable for a fighter-type jet, except for the 8g pull-up near the end, which may indicate an attempt to avoid ground impact (Figure 23).

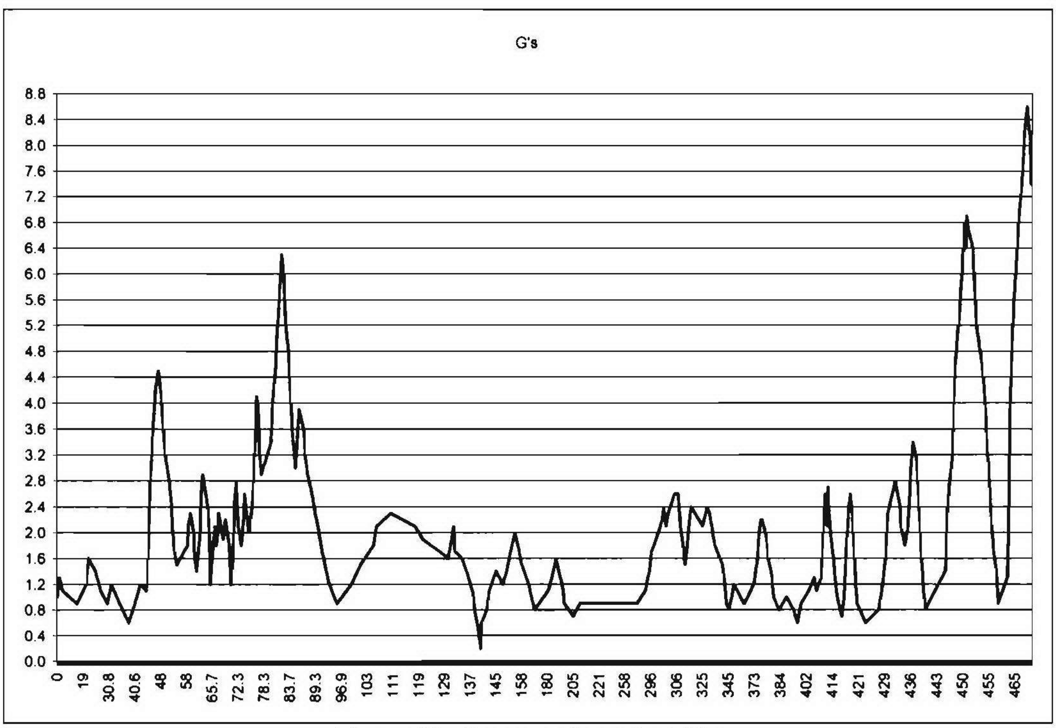

Figure 23. Data set B vertical G's

Pitch Analysis

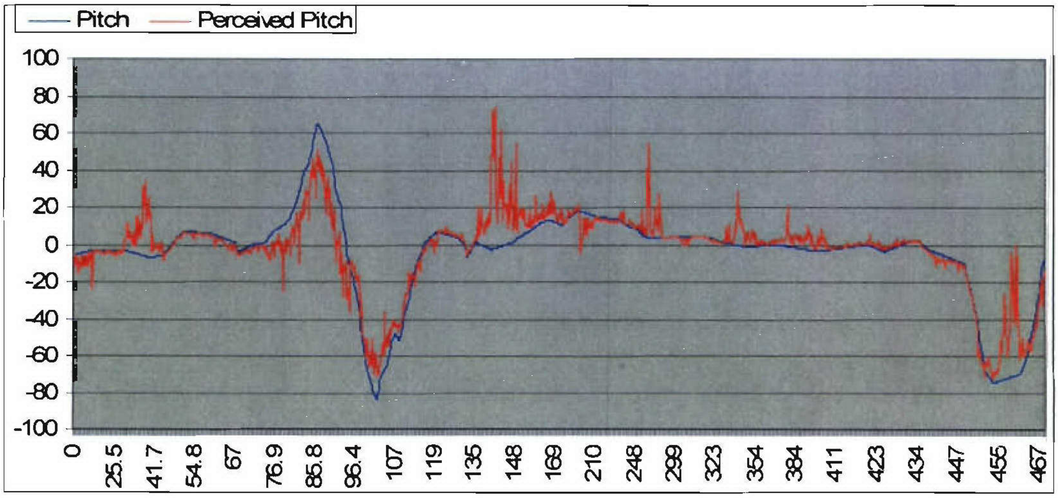

Figure 24. Data set B actual and perceived pitch

Table 4. Pitch perception anomalies

Time	Description
135-160	• 70 degree maximum perceived pitch • 15-20 degree sustained perceived pitch • 0-10 actual pitch • Very little bank angle for most of the time period
458-464	• 0 degree minimum perceived pitch • -75 degree maximum actual pitch • Very high bank angle

The perceived pitch calculation follows the actual pitch as the aircraft completes the full pitch over starting about time 80 (Figure 24). The first anomaly occurs after the pitch over as the aircraft is level but there is a high sustained perceived pitch. The second anomaly occurs near the end of the data set. The perceived pitch calculation follows the dramatic pitch down attitude but then shows a lesser perceived pitch all the way back to zero before again matching the actual pitch down value and again following as the nose is brought back up. During the period of the anomaly, the aircraft is in a high bank angle reaching about 160 degrees. As such it is not possible to rely on the perceived pitch calculation. It is unlikely that a pitch perception problem contributed to this mishap.

Leans Analysis

Table 5. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	

1.1, 1.5, 2.5, 3.2	Default	Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: Default settings Event 2: • 3 deg roll • 3 sec duration	Event 2: 199-200 (only at 2.5 & 3.2 roll threshold, and 2 Hz sampling rate) Event 3: none
1.1, 1.5, 2.5, 3.2	Event 1: • 20 deg roll • 2 deg/sec roll rate Event 2: • 3 deg roll • 3 sec duration	Event 2: 199-206 (only at 2.5 & 3.2 roll threshold & 2 Hz sampling rate) 396 - end Event 3: 396 – end (intermittent) (only at 3.2 roll threshold & 2 Hz sampling rate) Event 4: 411-end

Table 6. Leans illusion detection descriptions

Leans Illusion #	Illusion Timing (seconds)	Description
1	199-206	This is a standard leans sequence starting with a just negative bank angle and resulting in about 3 deg of roll difference lasting at least 3 seconds resulting in an actual bank angle of about 3 deg. It is detected at the two higher threshold values and a the 2 Hz sampling rate. There is no concurrent negative vertical velocity.
2	396-end	This is a non-standard leans sequence. Sub-threshold changes in roll begin at an elapsed time of about 390 and a starting bank angle of 11 degrees. The sub-threshold roll to the left results in a bank angle of about 3 degrees. This attitude is maintained for about 10 seconds and is concurrent with a vertical velocity of greater than -500 ft/min. This is followed by an above threshold roll in the same direction to about -50 degrees then larger roll oscillations with increasing negative vertical speed. This illusion is only detected at the high threshold value of 3.2 and at a reduce data sampling rate.

Neither of the leans sequences detected in this data set is persistent across the sensitivity analysis. Each one shows up only at one or two of the highest threshold values and only at the 2 Hz sampling rate. As such, they may not represent a roll perception problem to the pilot. The first sequence represents a very small change around the zero bank angle and is followed by a prolonged period of seemingly level and controlled flight. The second sequence represents a potential bank angle perception delta of up to 8 degrees. It is a non-standard leans sequence because it starts from a higher bank and 'drifts' sub-threshold towards level rather than away. However, it is concurrent with a large and increasing negative vertical velocity. It is followed by large roll oscillations that directly precede the end of the data set and apparent ground impact of the aircraft. As such, it is possible that a sub-threshold roll perception problem contributed to this mishap.

Graveyard Spiral Analysis

Table 7. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1, 1.5	Defaults	Event 2: 96-140 Event 3: 99-140 Event 4: 99-140
2.5	Defaults	Event 2: 126-147, 322-324, Event 3: 126-147, 323-325 Event 4: 126-147 both are increased using the 2 Hz sampling rate
1.5	Events 1, 2, 3 • 3 deg/sec yaw rotation deltas	Event 2: 54-70 (int), 96-147, 462, Event 3: 54-56, 97-147, 462, Event 4: 97-147, 462,
1.5, 2 Hz	Events 1, 2, 3 • 3 deg/sec yaw rotation deltas	In addition to above: Event 2: 337-383, 437-441 Event 3: 338-383 Event 4: 338-383
1.1	Events 1, 2, 3 • 3 deg/sec yaw rotation deltas	Event 2: 96-147, 437 Event 3: 96-147, Event 4: 96-147, Increased duration of the first with 2 Hz sampling rate
2.5	Events 1, 2, 3 • 3 deg/sec yaw rotation deltas	Event 2: 57-60, 126-148, 314-330 Event 3: 57-60, 126-151, 314-330 Event 4: 126-151, 332-383 (at 2 Hz) Increased duration with 2 Hz sampling rate

Table 8. Graveyard spiral detection descriptions

Graveyard Illusion #	Illusion Timing (seconds)	Description
1	54-70	This event sequence includes washout, illusory rotation and a rotation back all while maintaining at least 3 deg/sec perceived rotational delta. While there is also a high bank angle, there is no concurrent negative vertical velocity. The sequence shows up at two of the three threshold values. It is possible that this sequence represented some yaw rotation perception problems for the pilot.
2	96-148	This event sequence occurs at the same time that the aircraft is pitching over in a full loop. This dynamic causes an erroneous yaw rate (heading change) calculation within the tool. As such, it is not possible, at this point, to determine if this is a real event sequence.

3	314-325 (380)	This event sequence includes washout, illusory rotation, and a rotation back all while maintaining at least 5 deg/sec perceived rotational delta. While there is also a high bank angle, there is not concurrent negative vertical velocity. The sequence shows up only at the highest threshold value. At the 2 Hz sampling rate, the event sequence extends out to about 380 and includes negative vertical velocities and higher bank angles. It also shows up at one of the other threshold values. It is possible that this sequence represented a perception problem for the pilot. Given how late it occurs in the data set, it is possible that it was a precursor or in some other way contributed to the subsequent ground impact.
4	437-441	This event sequence includes washout and illusory rotation with at least 3 deg/sec perception delta. While there are concurrent high bank angles and negative vertical velocity, there is not rotation back against the direction of the illusory rotation while maintaining the perception delta. The event shows up only at the middle threshold value at the 2 Hz sampling rate and partially at the lower threshold value. The lack of persistence and duration seem to indicate that this sequence was not a problem for the pilot but it occurs very near the apparent ground impact.

Event 1 occurs very early in the data set and cannot have contributed to the eventual loss of control. Event 2 may be an erroneous detection associated with the complete loop that occurs early in the data set. As the nose of the aircraft passes through the vertical, the heading changes dramatically. Since our yaw rotation calculations are based on heading change, this causes an erroneously large rotation rate. Events 3 and 4 are much closer to the end of the data set and may indicate an ongoing problem prior to the apparent ground impact.

Combined Analysis

Figure 25 shows three graphs combined with the timing up the detected leans and graveyard spiral illusion events. Note that the yaw rate graph shows the erroneously calculated high rate caused by the dramatic heading change associated with the pitch over maneuver. It is also interesting to note that no vestibular based-based perception problems were detected concurrent with the high roll followed by high pitch maneuvering early in the data set. None of the three illusion events shown represents a strong or persistent indication of a perception problem. However, they occur near the end of the data set and my represent in increasing attitude perception problem. It is possible that a vestibular-based perception problem contributed to this mishap.

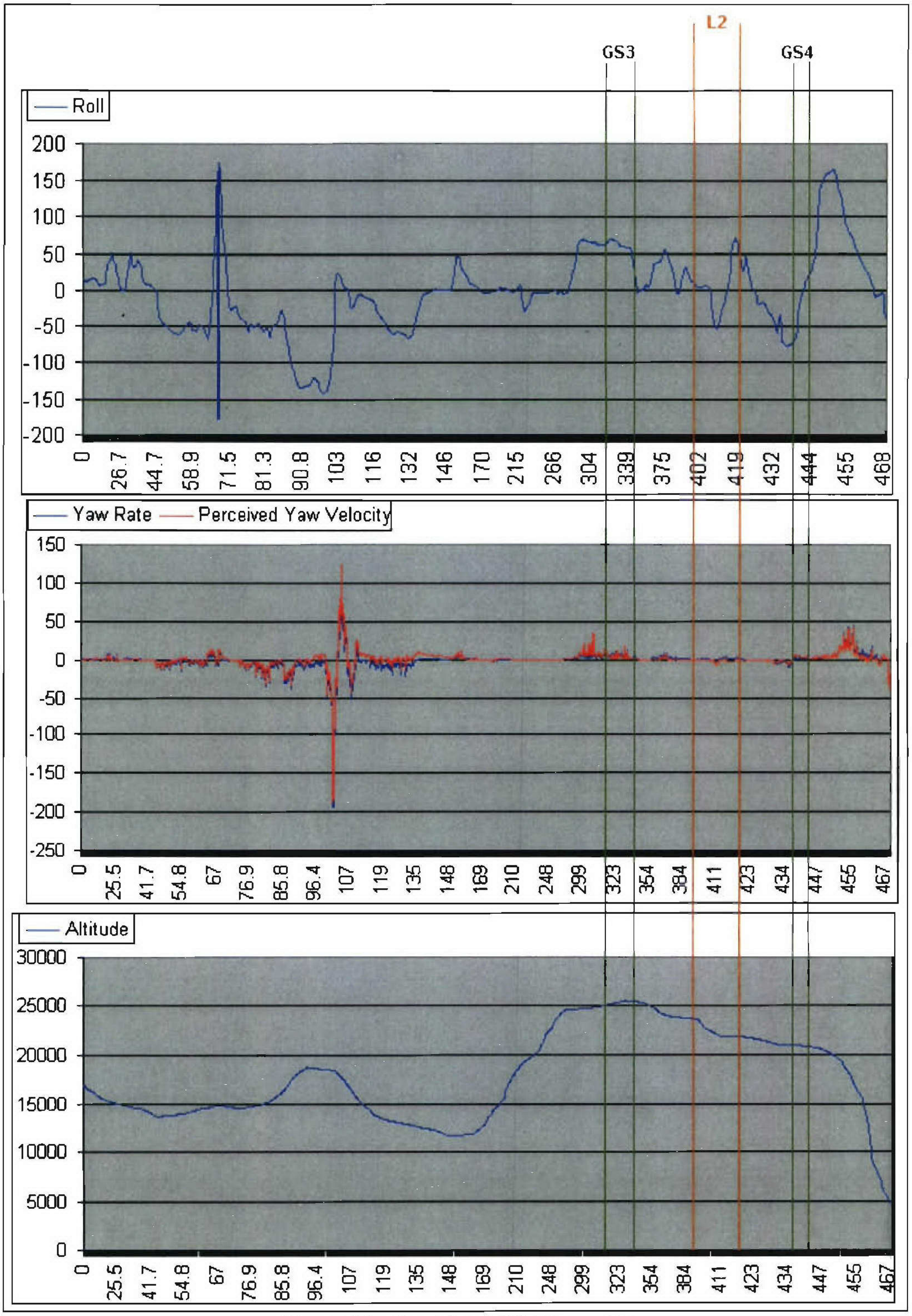

Figure 25. Combined SDAT results

7.4 Data Set C

This data set lasts almost 14 minutes (816 seconds), but does not appear too unusual until the precipitous dive at the end. Airspeeds, as well as pitch and roll values, indicate a fighter-type aircraft. If this is the same data set we received in Phase I (21 Nov 03), then we also suspect that the pilot ejected shortly before ground impact. That Phase I data set had several additional parameters that were not in the recent delivery.

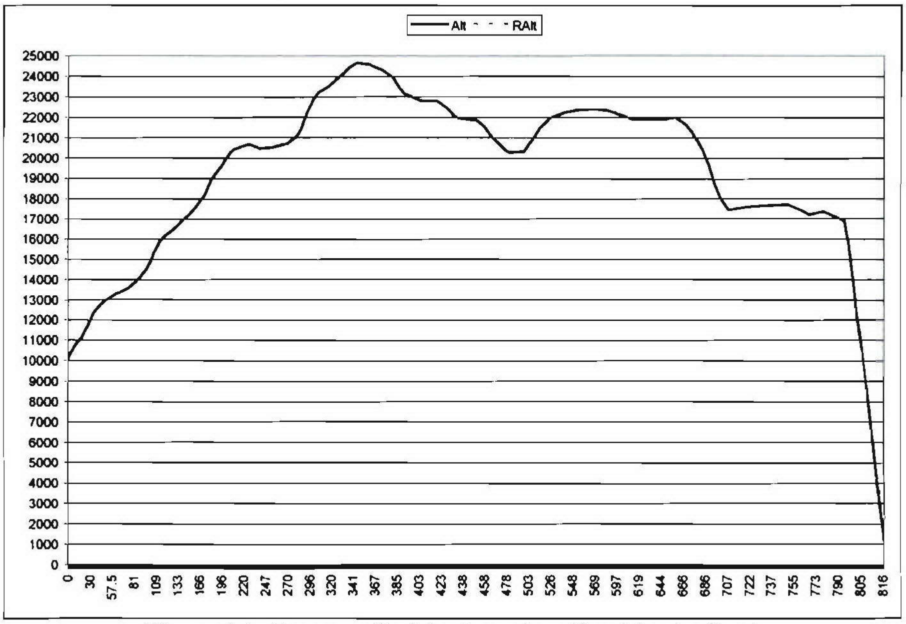

Figure 26. Data set C altitude and radio altitude (feet)

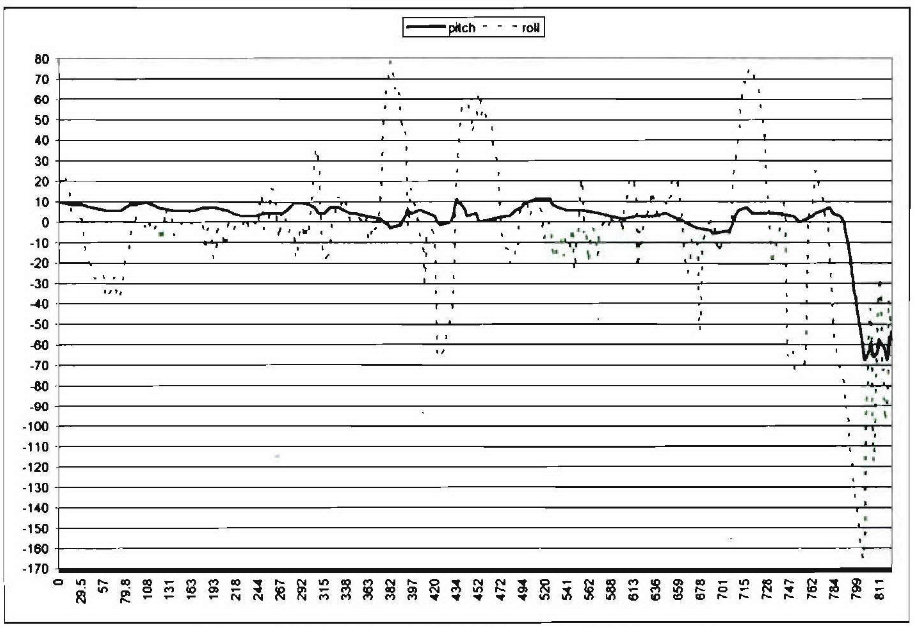

Figure 27. Data set C pitch and roll (degrees)

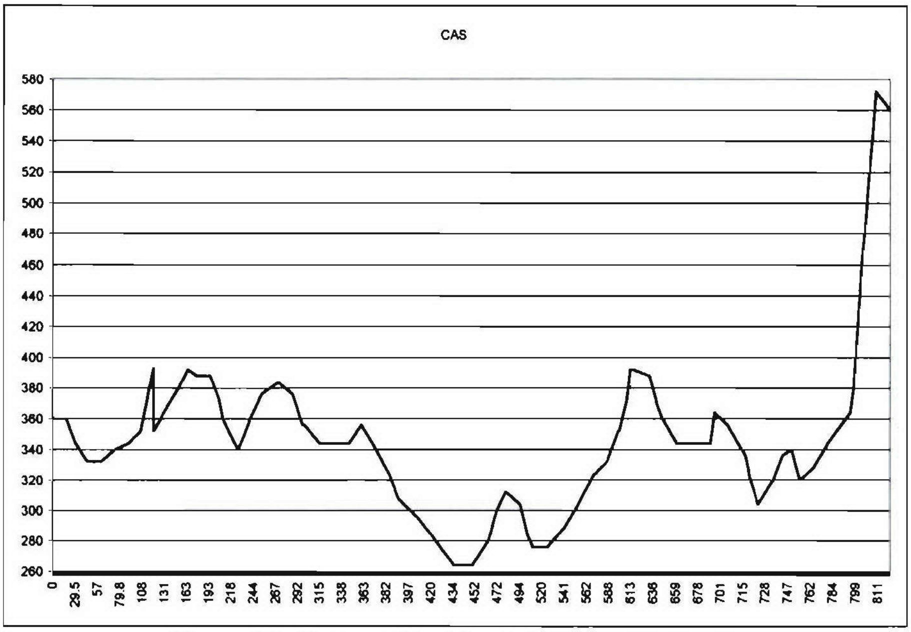

Figure 28. Data set C calibrated airspeed in knots

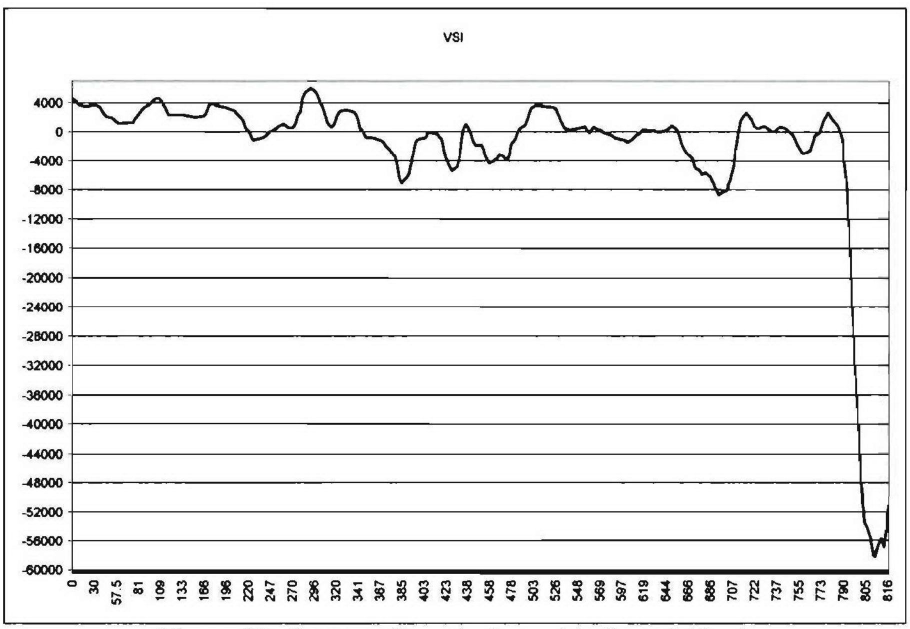

Figure 29. Data set C vertical speed indicated (fpm)

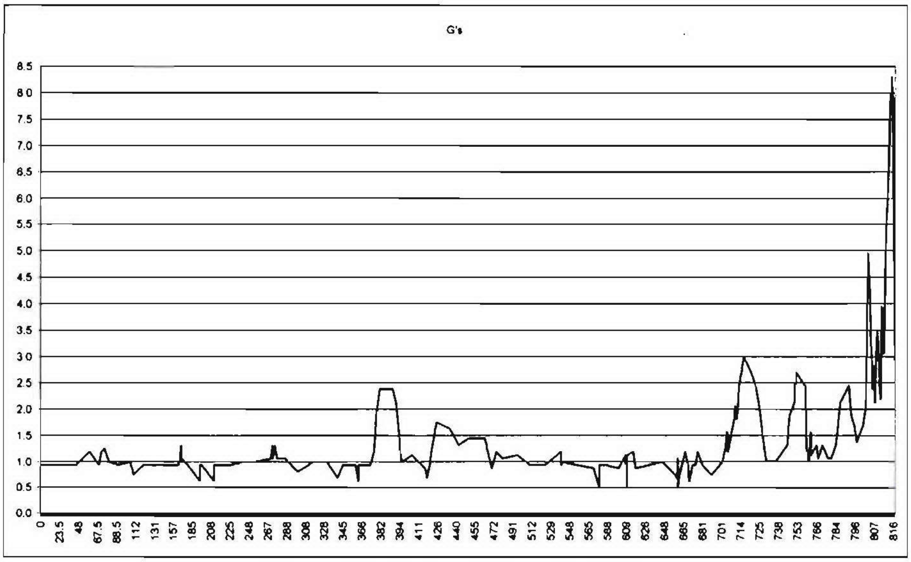

Figure 30. Data set C vertical G's

Pitch Analysis

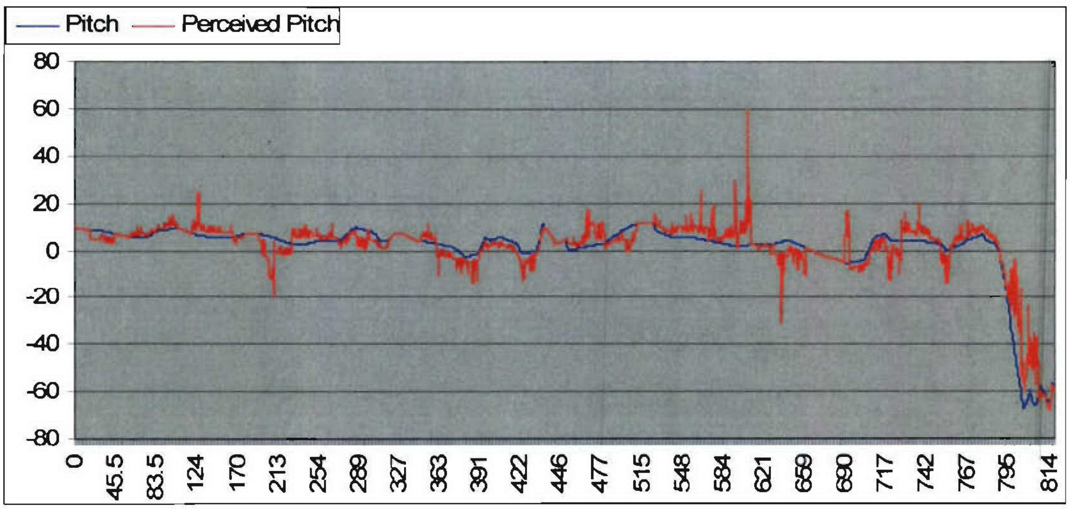

Figure 31. Data set C actual and perceived pitch

Table 9. Pitch perception anomalies

Time	Description
609	• 60 degree perceived pitch • 2 degree actual pitch • > 50 degree pitch perception delta • 20 degree bank angle
640	• -30 degree perceived pitch • 3 degree actual pitch • > 30 degree pitch perception delta • 3 degree bank angle

The two pitch perception anomalies in the table are the two largest calculated for the data set. There are others of up to 20 degrees of difference. These two are nearly instantaneous and there is no following sudden change in actual pitch. The perceived pitch calculation shows that the pitch over associated with the end of the data set was probably perceived by the pilot. It is unlikely that a pitch perception problem contributed to this mishap.

Leans Analysis

Table 10. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default	Event 1: numerous Event 2: none
1.5, 3.2, 1.1	Event 1 (default) Event 2 • 3 deg roll delta • 3 second duration	Event 1: numerous Event 2: none at 1.5, 1.1 Event 2: 113-116 (3.2 & 2 Hz)
1.5, 1.1, 3.2	Event 1 • Roll angle < 3 deg • Roll rate < 1 deg/sec Event 2 • 4 deg roll delta • 4 seconds	Event 2: 236-242 Event 3: 236-244 (1.5 roll threshold and 2 Hz sampling rate) (3.2 roll threshold and full sampling) (nothing at 1.1 roll threshold)
1.5	Event 1 • Roll angle < 12 deg • Roll rate 1 deg/sec Event 2 • 4 deg roll delta • 3 seconds	Event 2: numerous but only one sequence continued. Event 2: 706 – 730 Event 3: 706 – 712 Event 4: 706.5
3.2	Same as previous	Event 2: 235-238, 341-351, 706 Event 3: 235-238, 351, 706

Table 11. Leans illusion detection description

Illusion #	Illusion Timing (seconds)	Description
1	234-238	This sequence starts with a roll angle of about -3 deg. The sub-threshold change in roll results in a roll angle of about 1 deg over 8 seconds. It is concurrent with a negative vertical velocity. This illusion showed up again at a higher threshold value. The rolls starts at nearly 3 deg and rolls left to at least -3 degrees. While this sub-threshold roll event was somewhat persistent and may not have been perceived by the pilot, it occurred across the zero roll angle and probably didn't represent a control problem.

2	341-351	This is a non-standard leans sequence starting at a roll angle of between 11-12 deg and using a roll threshold value of 3.2. The sub-threshold change in roll results in a roll angle change of at least 4 deg and lasts for at least 3 seconds. It is concurrent with a negative vertical velocity. This illusion is very sensitive to the roll threshold value showing up only at the high 3.2 value.
3	706 - 730	This is a non-standard leans sequence starting at a roll angle -11 deg. It occurs across a range of roll threshold values from 1.5 to 3.2 in various forms. The sub-threshold change in roll results in a roll angle change of about 10 degrees over 6 seconds. It is concurrent with a negative vertical velocity and is followed by a high rate of roll but it is in the same direction as the sub-threshold change. This illusion is not very sensitive to threshold value variations. It is possible that this sequence represents a roll rate perception problem for the pilot and could have been a contributing factor to the mishap.

There were no standard Leans Illusion sequenced detected in this data set. That is, there do not appear to be any sub-threshold roll actions starting from straight and level flight that result in a roll change of more than 3 degrees lasting for more than 3 seconds. There are three instances where sub-threshold roll activities starting from higher bank angles did result in roll changes of 3-4 degrees lasting about 3 seconds. Illusion sequences 1 and 2 both included negative vertical velocity events. Number 1 persists across the higher roll threshold values while 2 only shows up at 3.2. Illusion sequence 3 includes negative vertical velocity and persists across the higher threshold values. Sequence 3 also occurs just prior to the large pitch oscillations that precede the end of the data set and apparent crash. It is possible that a sub-threshold roll rate perception problem contributed to this mishap.

Graveyard Spiral Analysis

Table 12. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1, 1.5	Default	Event 2: 809 No occurrence at 2 Hz sampling rate
2.5	Default	Event 2: 380-404, 456-489, 723-724, 758, 815 Event 3: 380-404, 457-489, 724-724 Event 4: 380-404, 457-489, At 2 Hz sampling: 712-726 extends but not to event 4 758 still occurs None of the others
1.1	3 deg/sec deltas	Event 2: 72-74, 465-489, 724, 758-759, 789-end Event 3: 72-74, 465-489, 789-end Event 4: 465-489, 789-end

1.5	3 deg/sec deltas	Event 2: 65, 391-393, 724, 758, 806-end Event 3: 65, 806-end Event 4: 806-end
2.5	3 deg/sec deltas	Essentially the same detections as default illusion settings for 2.5 threshold value

Table 13. Graveyard spiral detection description

Illusion #	Illusion Timing (seconds)	Description
1	65-74	This sequence includes washout, illusory rotation and a counter rotation opposite the direction of the illusory motion while maintaining up to 3 deg/sec rotational delta. While there are higher bank angles at the time, there is no concurrent negative vertical velocity. The illusion is small, very brief and shows up at two of the three threshold values. While it may have represented a small perceptual problem for the pilot, there is no indication that it resulted in a control problem
2	380-404	This sequence includes washout, illusory rotation and a counter rotation opposite the direction of the illusory motion while maintaining up to 5 deg/sec rotational delta. High bank angles and high negative vertical velocities are concurrent with the sequence. It occurs at the higher threshold value and reoccurs with lower rotation deltas at the middle threshold value. While there is very little loss in elevation and no indication of loss of control, it is likely that this sequence represented a yaw rate perception problem for the pilot.
3	456-489	This sequence includes washout, illusory rotation and a counter rotation opposite the direction of the illusory motion while maintaining up to 5 deg/sec rotational delta. High bank angles and high negative vertical velocities are concurrent with the sequence. It occurs at the higher threshold value and reoccurs with lower rotation deltas at another threshold value. While there is very little loss in elevation and no indication of loss of control, it is likely that this sequence represented a yaw rate perception problem for the pilot.
4	723-724	This sequence includes washout and illusory rotation at up to 5 deg/sec perception delta but no rotation opposite the direction of the illusory motion. While there are high bank angles, there is no concurrent negative vertical velocity. This sequence occurs at the highest threshold value and partially occurs at the other two threshold values at lower perception deltas. This sequence is very short and only partially persistent but does occur very near the final loss of control. It is possible that this event was a precursor to the mishap.
5	758	This sequence includes washout and illusory rotation at up to 5 deg/sec perception delta but no rotation opposite the direction of the illusory motion. There are high bank angles and negative vertical velocity concurrent with the event. The event occurs at differing

		delta levels across all the threshold values. Even though very short, it is possible that this indicates a perception problem for the pilot
6	789-end	This sequence includes washout, illusory rotation and rotation opposite the direction of the illusory motion at up to 3 deg/sec perception delta. High bank angles and negative vertical velocity are concurrent with the event. It occurs, with variations, at all the threshold levels. The even is very close to the end of the data set. While the perception delta is small, the persistence is reasonably high. It is possible that this event contributed to the apparent ground impact.

Event 1 occurs very early in the data set. While it may have caused some difficulty to the pilot, it doesn't seem to have resulted in any loss of control. Events 2 and 3 closer follow each other and while there doesn't appear to be any loss of control they may indicate an increasing perception problem for the pilot. Events 4, 5 & 6 occur just prior and during the final descent. They are only short duration events but seem to indicate an ongoing perceptual problem associated with the loss of control. It is possible that a graveyard spiral type sequence contributed to this mishap.

Combined Analysis

Figure 32 shows three graphs combined with the timing of the detected leans and graveyard spiral events. Notice that there appear to be two common sequences both starting with a leans event and followed by two or three graveyard spiral events. These two patterns are also represented by similar patters of roll sequence and magnitude. These patterns suggest that two similar activities occurred during this flight sequence, both may have resulted in perceptual problems for the pilot and the second ended in an apparent ground impact.

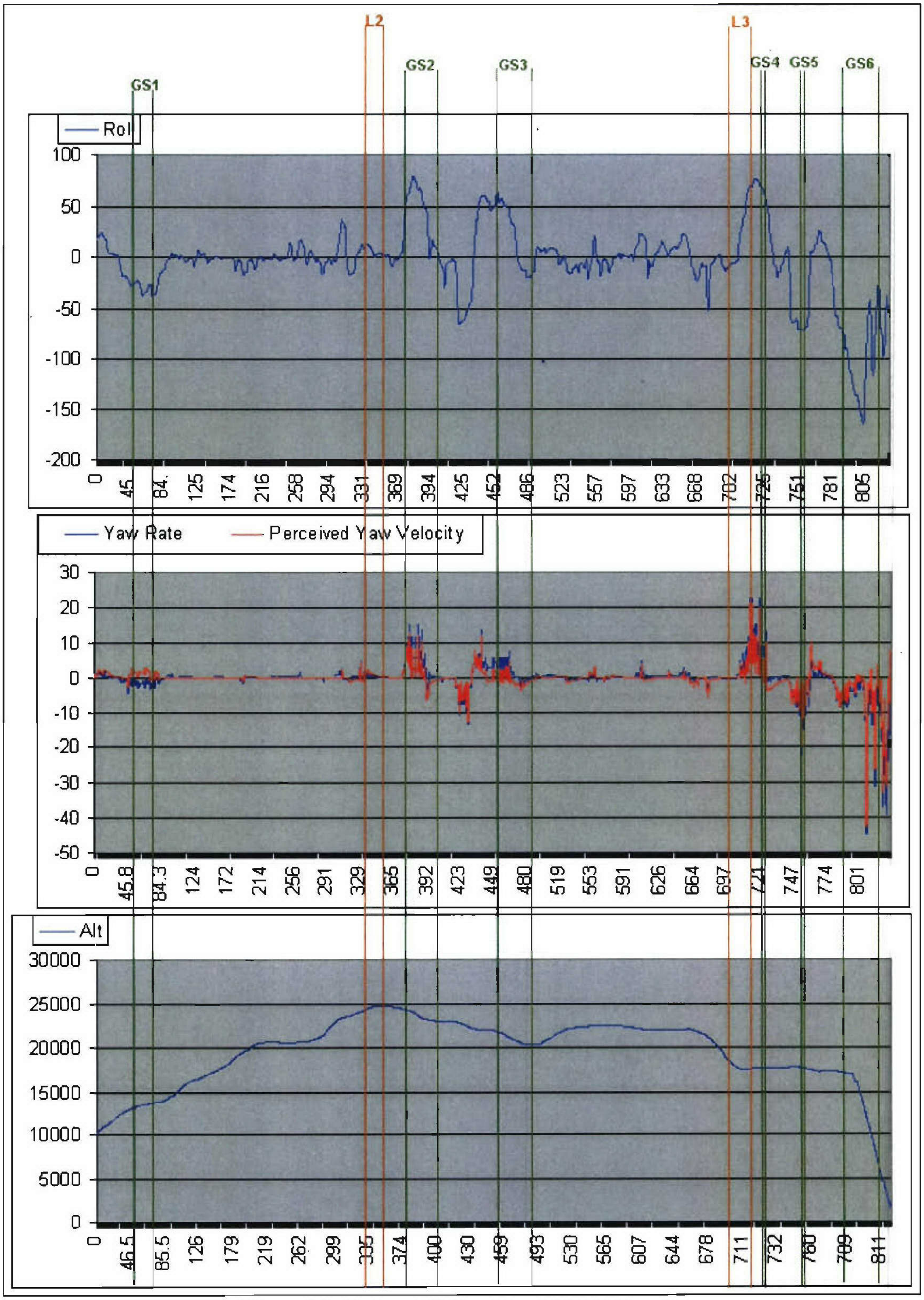

Figure 32. Data set C Combined SDAT Results

7.5 Data Set D

This data set lasts just over 10 minutes (609 seconds). We have nicknamed this data set *superjinker* because it looks like nearly constant air combat maneuvering throughout the whole data set. Such extreme maneuvering seems odd so close to the terrain. Perhaps this is a real combat mission. The vertical speed extreme values (Figure 36) are particularly noteworthy. Also, the turns are almost always to the left completing seven full 360 degree turns.

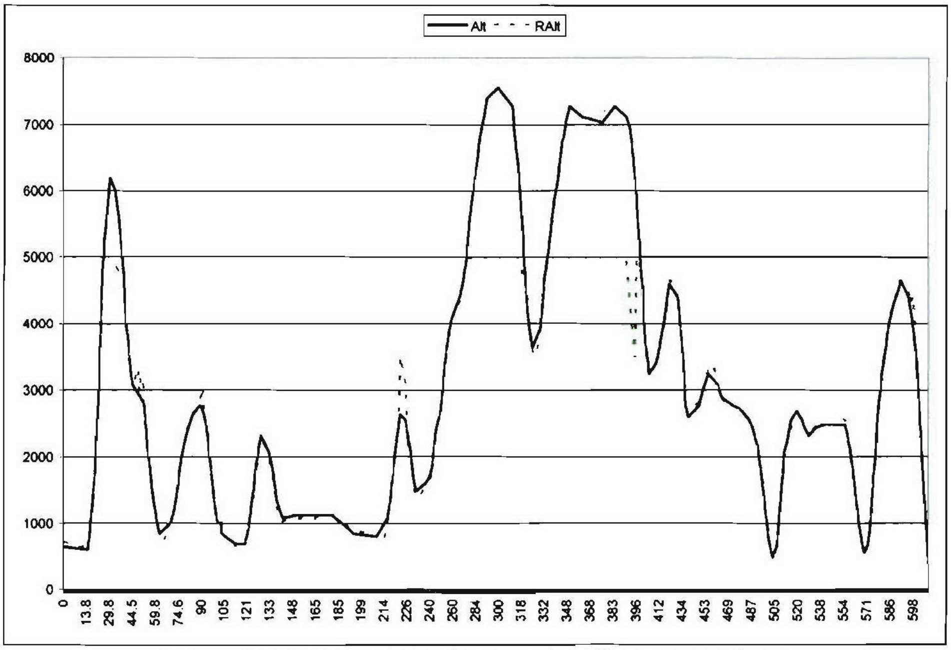

Figure 33. Data set D altitude and radio altitude (feet)

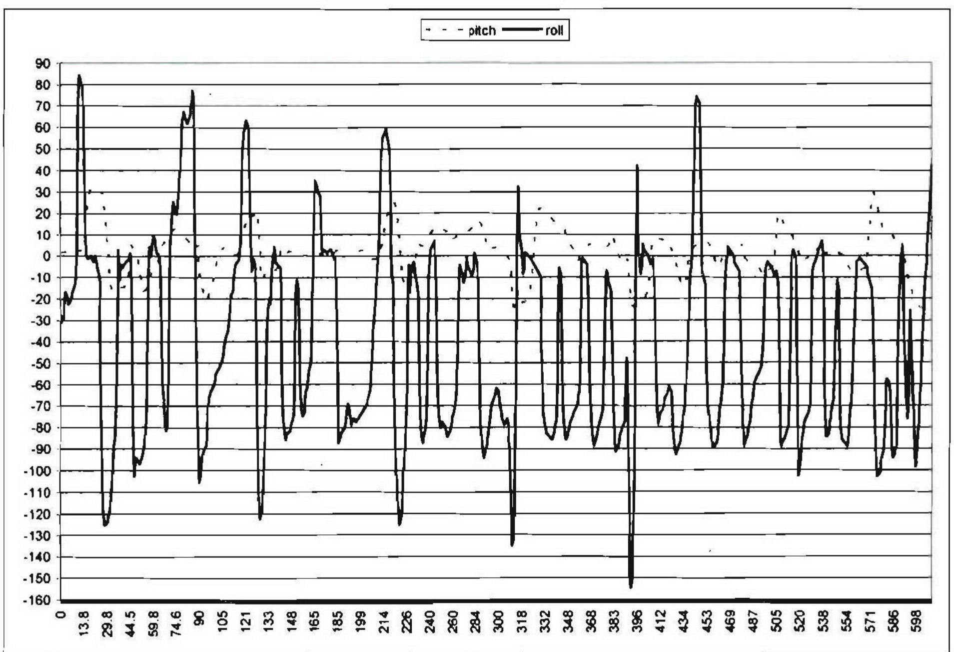

Figure 34. Data set D pitch and roll (degrees)

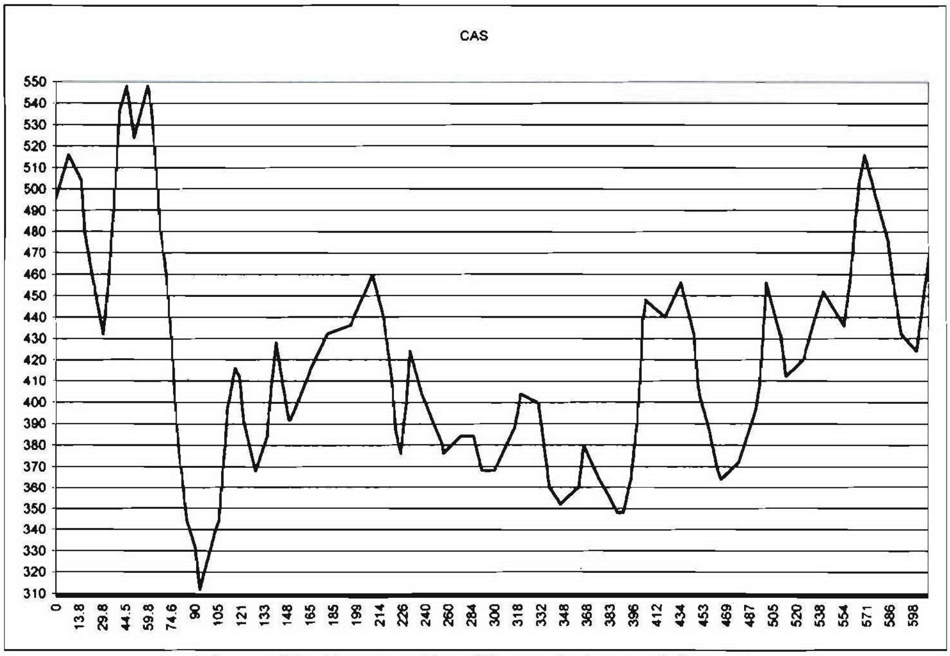

Figure 35. Data set D calibrated airspeed (knots)

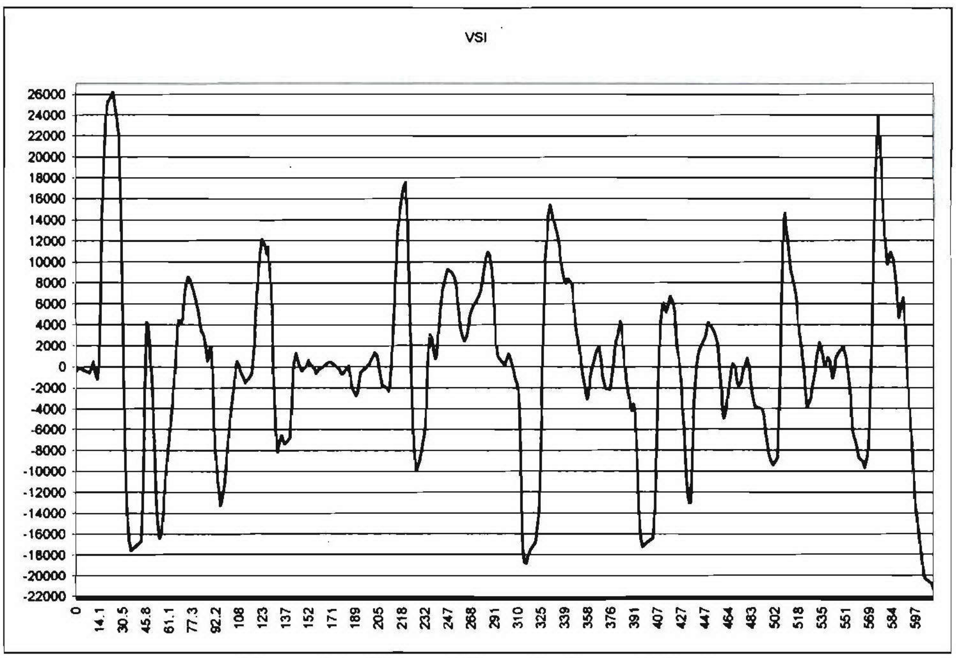

Figure 36. Data set D vertical speed (fpm)

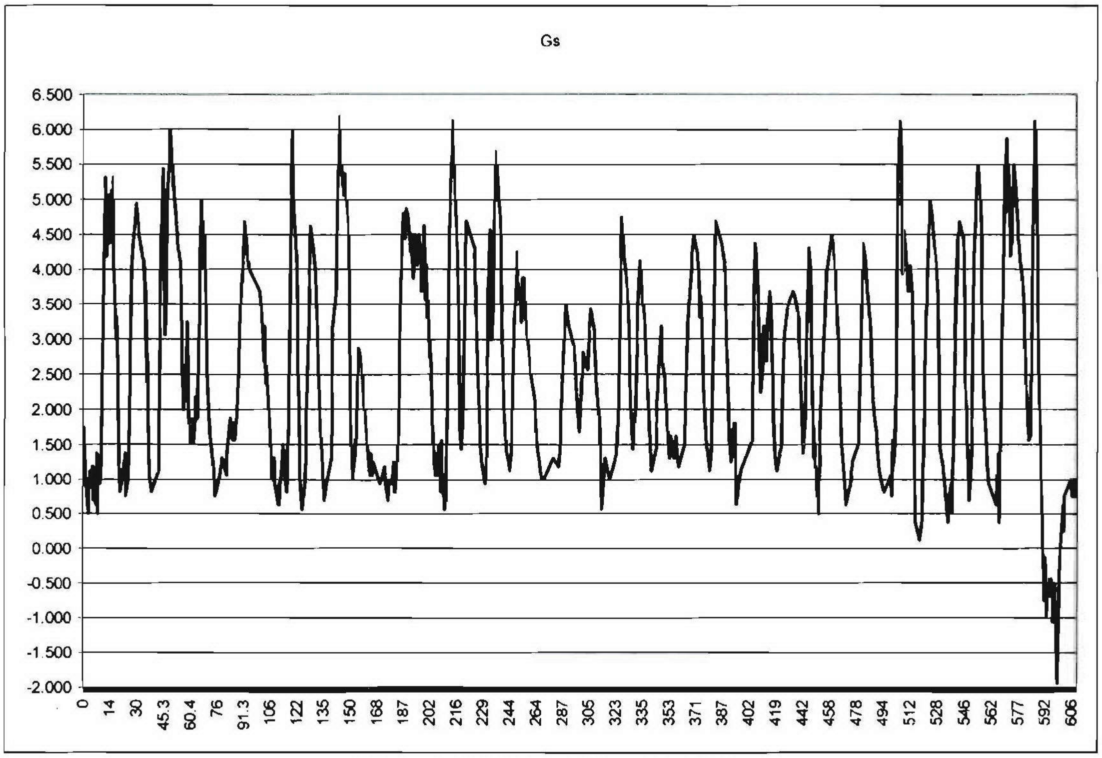

Figure 37. Data set D vertical G's

Pitch Analysis

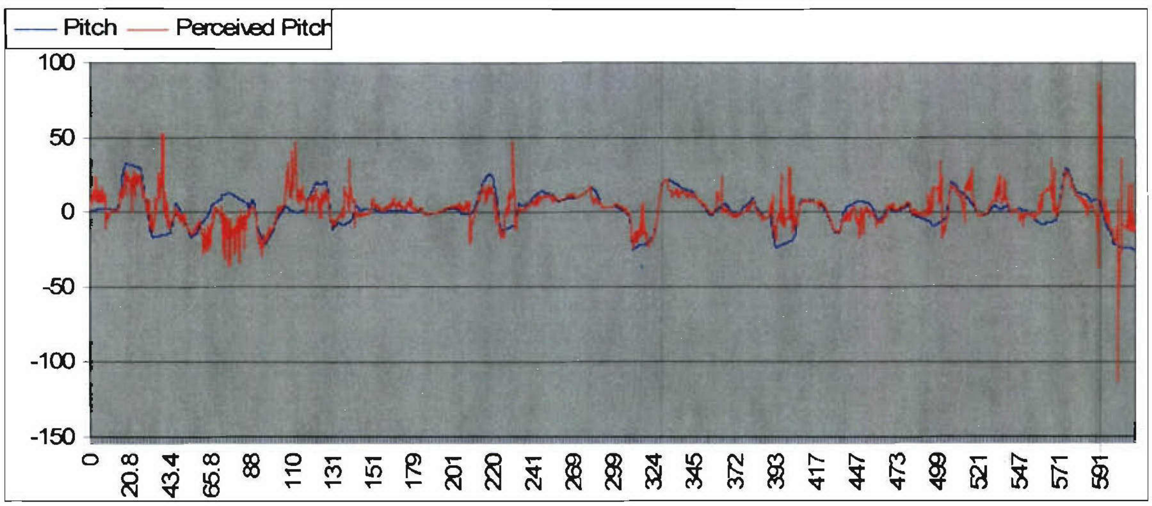

Figure 38. Actual and perceived pitch

This data set contains a number of instantaneous pitch perception deltas that are great than 40 degrees. Two are greater than 75 degrees. However, given the nearly constant roll changes, it is difficult to analyze which calculated perceived pitch values are realistic. Based on our current assumptions regarding the perceived pitch calculation, it is unreasonable to analyze pitch anomalies for this data set.

Leans Analysis

Table 14. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default	Event 1: very few Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1 (default) Event 2 • 3 deg roll delta • 3 seconds	Event 1: 321-361 Event 2: 329-361 Event 3: 353-361 Event 4: 357-361 (whole sequence only at 2 Hz sampling rate)
1.1, 1.5, 3.2	Event 1 • 60 deg roll • 2 deg/sec roll rate Event 2: • 3 deg roll delta • 3 second duration	Event 1: numerous Event 2: 493-514 (3.2, full data) , 537 (3.2, 2 Hz) Event 3: 493-504, 541-570 (int) Event 4: 494

Table 15. Leans illusion detection description

Leans Illusion #	Illusion Timing (seconds)	Description
1	321-361	This event sequence starts from straight and level flight. Sub-threshold roll changes lasting about 9 seconds result in a bank angle of -9 deg. The sequence continues with high negative vertical velocity followed by a high roll rate. The sequence persists across all of the roll threshold values but only shows up at the 2 Hz sampling rate. Given the persistence and bank angle delta of this sequence, it is possible that it represented a bank angle perception problem for the pilot. However, it began after the large descent was already occurring and seems to be associated with pulling the nose up out of a dive. Also, the event occurs only half way through the data set and is followed by continued high maneuvering activity.
2	493-504	This events sequence starts at a high bank angle and the sub-threshold roll changes results in a change of nearly 10 degrees over about 8 seconds. It is concurrent with a large negative vertical velocity and followed by a high bank angle change. It only occurs at the highest threshold value and only at the full data sampling rate.
3	537-550	This event sequence starts at a bank angle of about -3 and the sub-threshold roll changes result in a bank angle of about 6 degrees in about 7 seconds. It is concurrent with a small negative vertical velocity and is followed by a high bank angle change. It only occurs at the highest threshold value and at the 2 Hz sampling rate.

A sequence very similar to Leans Illusion 1 seems to occur about time 400 that includes a similar large loss in elevation. It also seems to begin during the descent and is associated with pulling the nose up. However, the tool didn't detect it as a sub-threshold roll sequence. Illusions number 2 and 3 only appear for a single threshold value and not at every data sampling rate. As such, there is only a small likelihood that they presented a bank angle perception problem for the pilot. However, there are numerous other roll changes that look like very similar sub-threshold drift from both level and banked flight but the tool doesn't detect them. There seem to be small super-threshold movements within these apparent drift sequences. As such, they may not result in large problems for the pilot but may be indicative of ongoing difficulties in maintaining bank awareness. Given the highly active roll maneuvers indicative of this data set, there are very few instances of sub-threshold roll rates lasting for any length of time starting from level flight. While there are a large number starting from higher bank angles, few of them result in sustained changes in bank angle. It seems unlikely that a sub-threshold roll rate perception problem contributed to this mishap.

Graveyard Spiral Analysis

Table 16. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1,	5 deg/sec deltas	Event 2: numerous Event 3: 159-160, 200-217, 297-326, 389-407, 547-548, 557-570, 582-584 Event 4: 205-217, 305-326, 389-407, 557-570
1.5	5 deg/sec deltas	Same as above without the first and last sequences but adding Event 3: 104-105, 486-504 Event 4: 486-504
2.5	5 deg/sec deltas	Event 3: 97-118, 200-217, 310-326, 486-504, 547-570 Event 4: 97-118, 205-217, 310-326, 486-504, 552-570
1.1	7 deg/sec deltas	Event 3: 200-205 (up to 8), 309-326 Event 4: 309-326
1.5	7 deg/sec deltas	Event 3: 200-205, 309-326 Event 4: 309-326
2.5	7 deg/sec deltas	Event 3: 97-118 (up to 9), 200-204, 310-326, 557-570 Event 4: 97-118, 310-326, 557-570

Table 17. Graveyard spiral detection description

Illusion #	Illusion Timing (seconds)	Description
1	97-118	This sequence includes washout, illusory rotation and rotation opposite the illusory direction at up to the 9 deg/sec perception delta. In includes high bank angles, high negative vertical velocity and a large loss of altitude. It

		occurs at the highest threshold value and the partial sequence occurs at the middle threshold value at a lower perception delta. It is likely that this sequence represented a yaw rate perception problem for the pilot.
2	159-160	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 5 deg/sec perception delta. It includes high bank angles but no negative vertical velocity. It occurs only at the lowest threshold value. It is unlikely that this represented much of a perception or control problem for the pilot.
3	200-217	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 8 deg/sec perception delta. It includes high bank angles and a small amount of negative vertical velocity (but reducing during the sequence). The illusion occurs at every threshold value. It is very likely that this sequence represented a yaw rate perception problem for the pilot.
4	279-326	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 7 deg/sec perception delta. The sequence includes high bank angles, high negative vertical velocity and a very large loss of altitude. The illusion occurs at every threshold value. It is very likely that this sequence represented a yaw rate perception problem for the pilot and may have resulted in a temporary loss of control.
5	389-407	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 5 deg/sec perception delta. The sequence includes high bank angles, negative vertical velocity and a very large loss of altitude. It occurs only at the lowest threshold value. It is possible that this sequence represented a rotation perception problem for the pilot and may have resulted in a temporary loss of control.
6	486-504	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 5 deg/sec perception delta. The sequence includes high bank angles, negative vertical velocity and a large loss of altitude. It occurs at the lowest and middle threshold values. It is possible that this sequence represented a rotation perception problem for the pilot.
7	547-570	This event includes washout, illusory rotation and rotation opposite the illusory direction at up to 7 deg/sec perception delta. The sequence includes high bank angles, high negative vertical velocity and a large loss of altitude. The illusion occurs in various forms at every threshold value. It is very likely that this sequence represented a yaw rate perception problem for the pilot and may have resulted in a temporary loss of control.
8	582-584	This event includes washout and illusory rotation at up to 5 deg/sec perception delta. It includes high bank angles but no negative vertical velocity. It occurs only at the lowest threshold value. It may have presented some level of rotation perception difficulty for the pilot.

At all threshold levels there are numerous triggers for washout and illusory rotation (illusion event 1 & 2). This is certainly due to the repetition of short fast turns during this flight sequence. It indicates a situation where perception of rotation may have been an ongoing issue for the pilot. The large number of detected illusion sequences and the large rotation perception deltas indicate a continuing, perhaps increasing, perception difficulty for the pilot. Events 4 and 5 are concurrent with negative vertical velocities of greater than -15,000 ft/min and losses of altitude of over 3000 ft. Events 6 and 7 are concurrent with negative vertical velocities of around -8,000 ft/min and losses of altitude of about 1500 ft. While it seems likely that rotation perception problems represented a difficulty for the pilot, there is no illusion detected within 40 seconds of the end of the data set.

Combined Analysis

Figure 39 shows three graphs and the combined illusions detected. It appears that the frequency of the illusions increases across the data set which may indicate an increasing perception difficulty for the pilot. This combined with the highly active maneuvers indicate the potential for vestibular fatigue. However, there are not illusions detected within 40 seconds of the end of the data set.

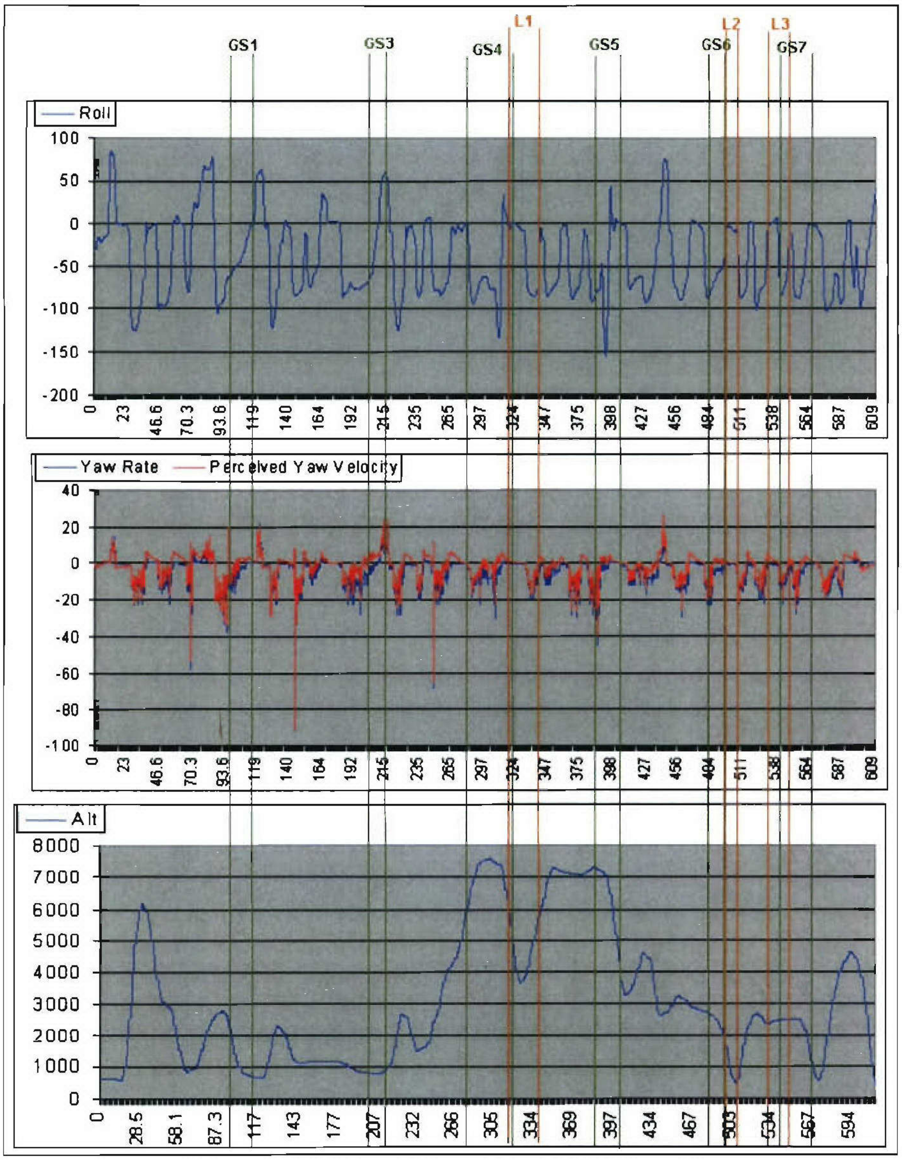

Figure 39. Data set D combined SDAT results

7.6 Data Set E

We received the E data set with a time anomaly: the time progresses normally for 495 seconds and then seems to go backward in time and then progress normally again. So, we decided to split the data set into 2 parts to correspond to the contiguous-looking portions of the data set.

7.6.1 Data Set E Part 1

Part 1 of the data set is 495 seconds (~8 minutes). It does not look too unusual except for the initial large pull-up from an initial dive. Because radio altitude stays at 5000 feet (upper limit of the sensor) and barometric altitude is above 24,000 feet, this data set does not end with ground impact.

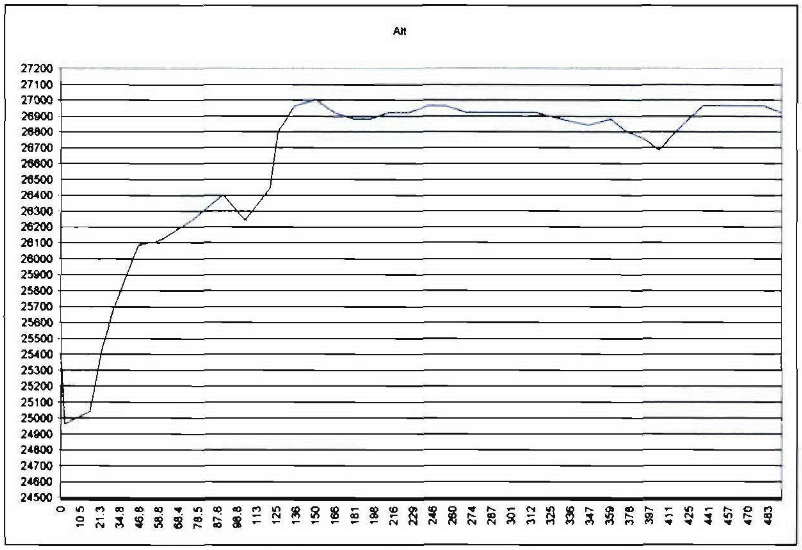

Figure 40. Data set E part 1 altitude (feet)

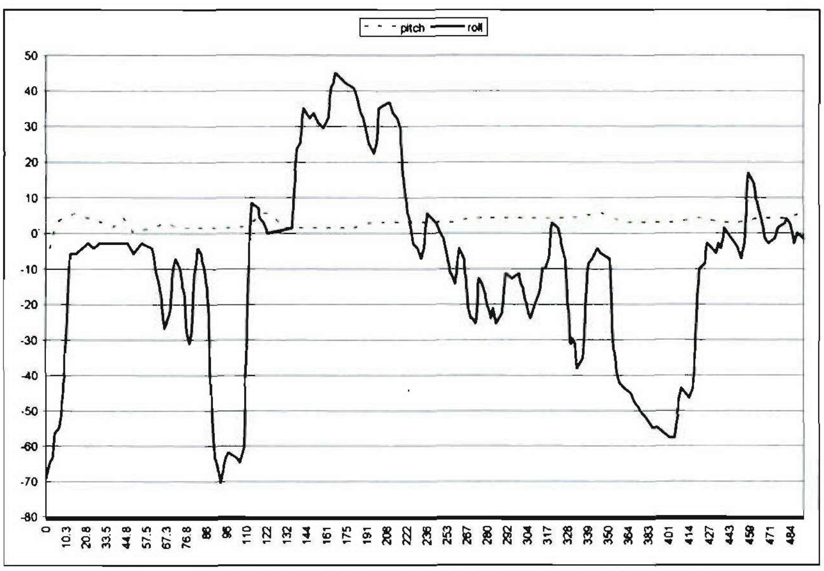

Figure 41. Data set E part 1 pitch and roll (degrees)

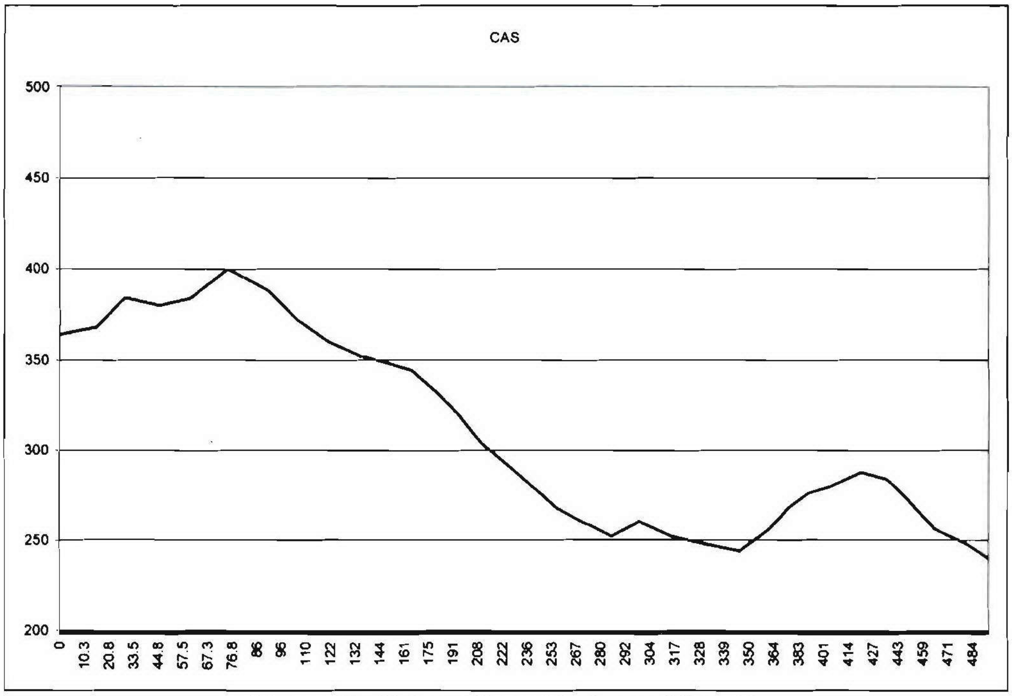

Figure 42. Data set E part 1 airspeed (knots)

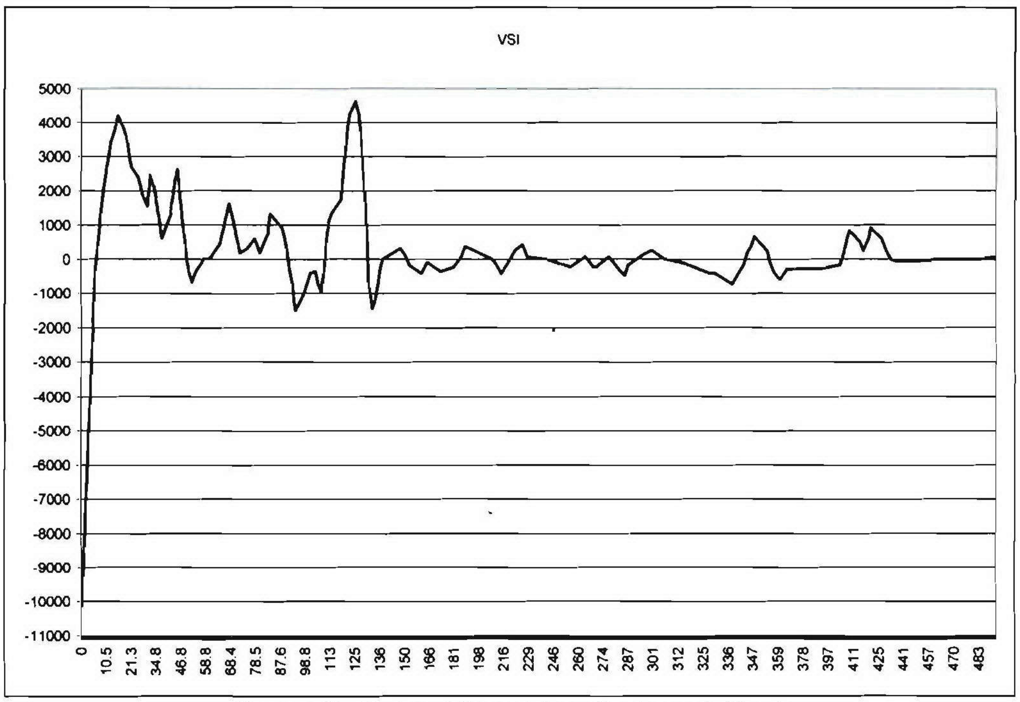

Figure 43. Data set E part 1 vertical speed (fpm)

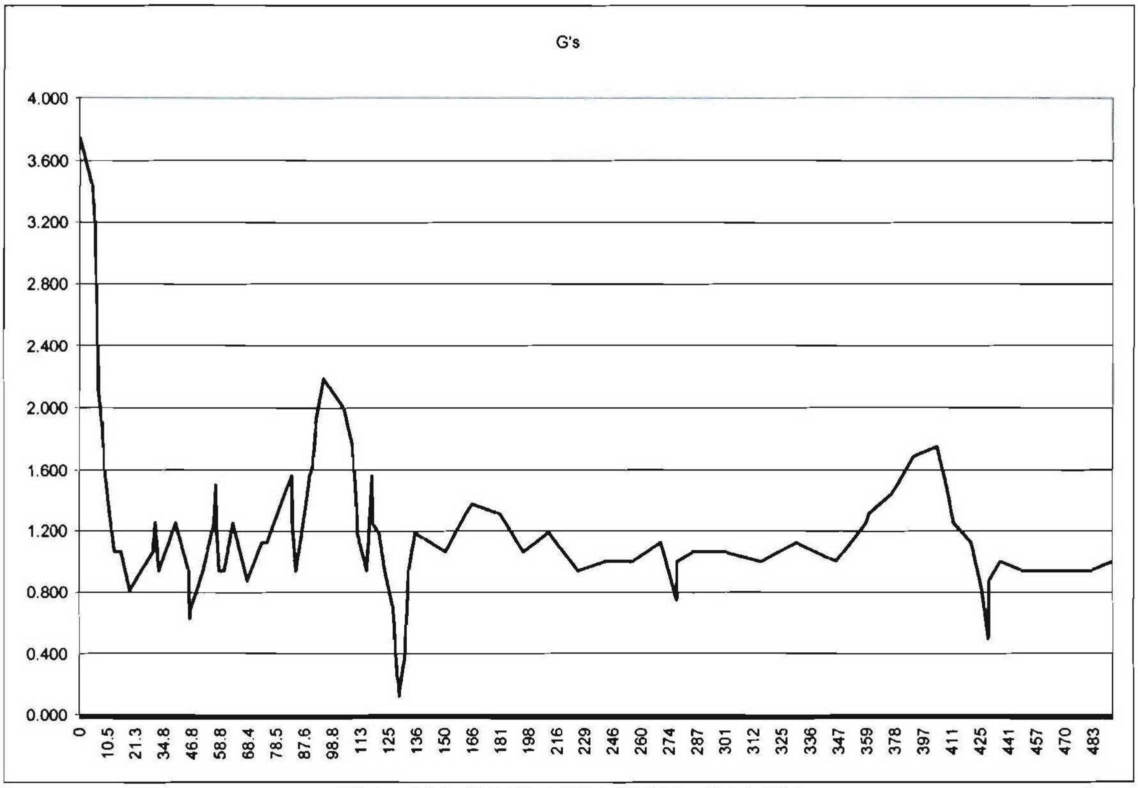

Figure 44. Data set E part 1 vertical G's

Pitch Analysis

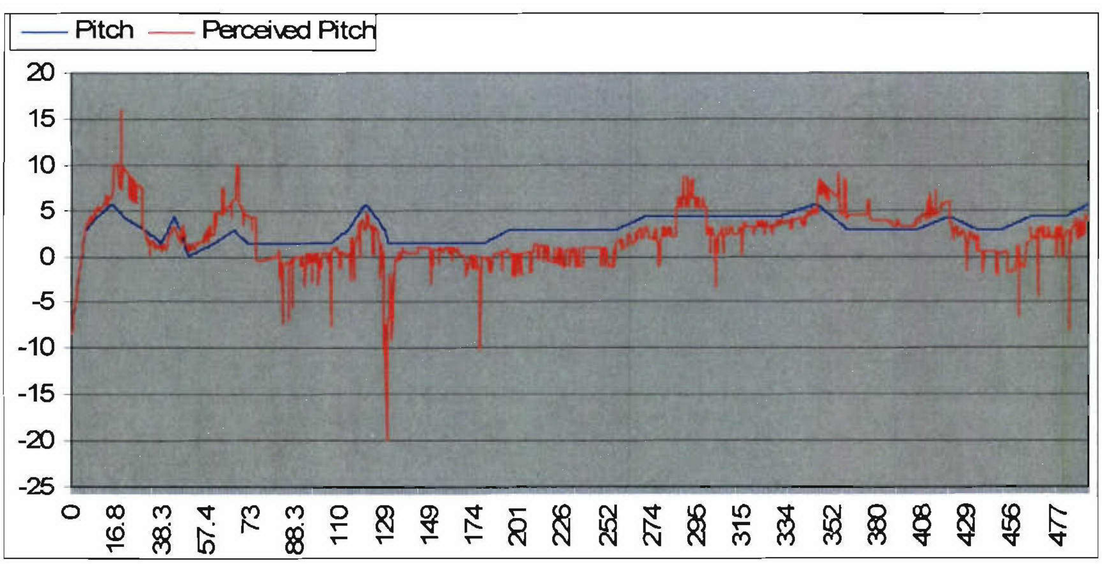

Figure 45. Actual and perceived pitch

Except for one instantaneous large perceived pitch calculation, there are no sustained pitch perception anomalies of more than 5 degrees.

Leans Analysis

Table 18. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default	Event 1: just a few instances Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: defaults Event 2 • 3 deg roll delta • 3 second duration	Event 1: same Event 2: 254-318 (2.5, 3.2), 450-455
1.5, 2.5, 3.2	Event 1 • 60 deg roll start • 2 deg/sec roll rate Event 2 • 5 deg roll delta • 5 second duration	Event 1: numerous Event 2: 189-207
1.1, 1.5	Event 1 • 60 deg roll start • 2 deg/sec roll rate Event 2 • 5 deg roll delta • 5 second duration	Event 1: numerous Event 2: 397-405

Table 19. Leans illusion detection descriptions

Illusion #	Illusion Timing (seconds)	Description
1	189-207	This is a non-standard leans sequence. The sub-threshold roll begins at a bank angle of about 34 degrees and reaches 24 degrees over about 15 seconds. The sequence appears at three of the four threshold values. There is no significant negative vertical velocity or obvious bank oscillations associated with the sequence. While there doesn't appear to be any loss of control, it is possible that this sequence represented a bank perception issue for the pilot.
2	247-280(?)	This illusion sequence starts at a bank angle of about 4 deg. The sub-threshold roll leads to a bank of about -4 during about 15 seconds. There is no significant negative vertical velocity concurrent with the event sequence. The sequence is persistent across the two higher threshold values. It is followed by roll oscillations that seem to trend toward the left. Although there is no serious loss of altitude, it is possible that this sub-threshold roll sequence presented a bank angle perception problem for the pilot.

3	397-405	This is a non-standard leans sequence that may be longer than the detection times represent. The sub-threshold roll movement started at a bank angle of about -50 and reach -58 over about 25 seconds. The sequence started earlier than this but had one or two very small super-threshold changes during the sequence. The sequence appears at the lower two threshold values and may partially appear at a third. Although there is no loss of control, it is possible that this represented a bank angle perception problem for the pilot.
4	439-450	This illusion sequence is a standard straight and level starting event. The sub-threshold roll leads to a bank angle of about -5 degrees across about 15 seconds. There is no significant negative vertical velocity concurrent with the event sequence. The sequence is persistent across all the threshold values. Although there does not appear to be any loss of control, it is likely that this sequence presented a bank angle perception problem for the pilot.

During this flight sequence, roll is almost never stable and there are a large number of small sub-threshold roll changes mixed in with the larger rolling actions. None of the detected leans sequences includes negative vertical velocity. Indeed, the data sequence starts out by gaining altitude then generally maintains altitude to the end of the data set. However, the number and persistence of sub-threshold roll sequences seems to indicate some level of difficulty maintaining bank awareness.

Graveyard Spiral Analysis

Table 20. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1, 1.5, 2.5	Default	None
1.1 2 Hz	3 deg/sec delta	Event 2: 9-10, 363-370 (2 Hz), 405-420, Event 3: 364-370 (2 Hz), 405-420,
1.5 2 Hz	3 deg/sec delta	Event 2: 9-10, 108-111, 357-358, 410-417 (int) Event 3: 108-111, 358, 410-413 (int) Event 4: 108-111, No additional at 2 Hz sampling rate
2.5 2 Hz	3 deg/sec delta	Event 2: 109-110, 173-183 (int), Event 3: 174-183 (int), No additional at 2 Hz sampling rate

Table 21. Graveyard spiral detection descriptions

Illusion #	Illusion Timing (seconds)	Description
1	9-10	This sequence includes washout and illusory rotation of up to 3 deg/sec perceptual rotation delta. There is no counter rotation opposite the

		illusory rotation and the sequence is very short. High bank angles and negative vertical velocity are concurrent with the sequence. It shows up at the lowest and middle threshold value. It is possible this represented some level of rotation perceptual difficulty but is unlikely to have represented a control problem.
2	108-111	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining a 3 deg/sec perceptual rotation delta. The sequence is concurrent with high bank angles and some level of negative vertical velocity. The sequence occurs at the middle threshold value and shows up partially at the higher threshold value. It is possible that this represented a perceptual problem for the pilot but is unlikely to have caused a control problem.
3	173-183	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec delta. The sequence is associated with high bank angles but very little or no negative vertical velocity. It only shows up at the highest threshold level. It is unlikely that this sequence represented a rotation perception problem for the pilot.
4	357-370	This event includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec delta. The sequence is associated with high bank angle but very little negative vertical velocity. It shows up at the lowest threshold value at the 2 Hz sampling rate and partially at the middle threshold value. It is unlikely that this sequence resulted in a rotation perceptual problem for the pilot.
5	405-420	This event includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec delta. The sequence is associated with high bank angle but no negative vertical velocity. The sequence shows up at the lowest and middle threshold values. It is possible that this sequence presented some level of rotational perception difficulty for the pilot.

None of the events includes negative vertical velocity and probably don't represent a control problem for the pilot. Events 1-4 are not very persistent across the threshold values and, as such, probably did not represent an attitude perception problem for the pilot. Although event 5 only represents a 3 deg/sec rotation perception delta, it may have represented some level of rotation perception problem for the pilot.

Combined Results

Figure 46 shows three graphs combined with the four leans detections and the last graveyard spiral detection. The most interesting part of the combined results is the long turn starting at about time345 with a left roll of -40 degrees and a rotation rate of about 3 degrees/second. Over about the next 60 seconds the bank angle seems to drift, around the perception threshold levels, to -60 degrees. The rotation rate also varies during this time. The tool detected a leans sequence associated with sub-threshold portions of this drift and a graveyard spiral type sequence near the end of the turn. While the AC seems to recover control following the turn, it seems likely that there was some loss of attitude awareness during this long turn.

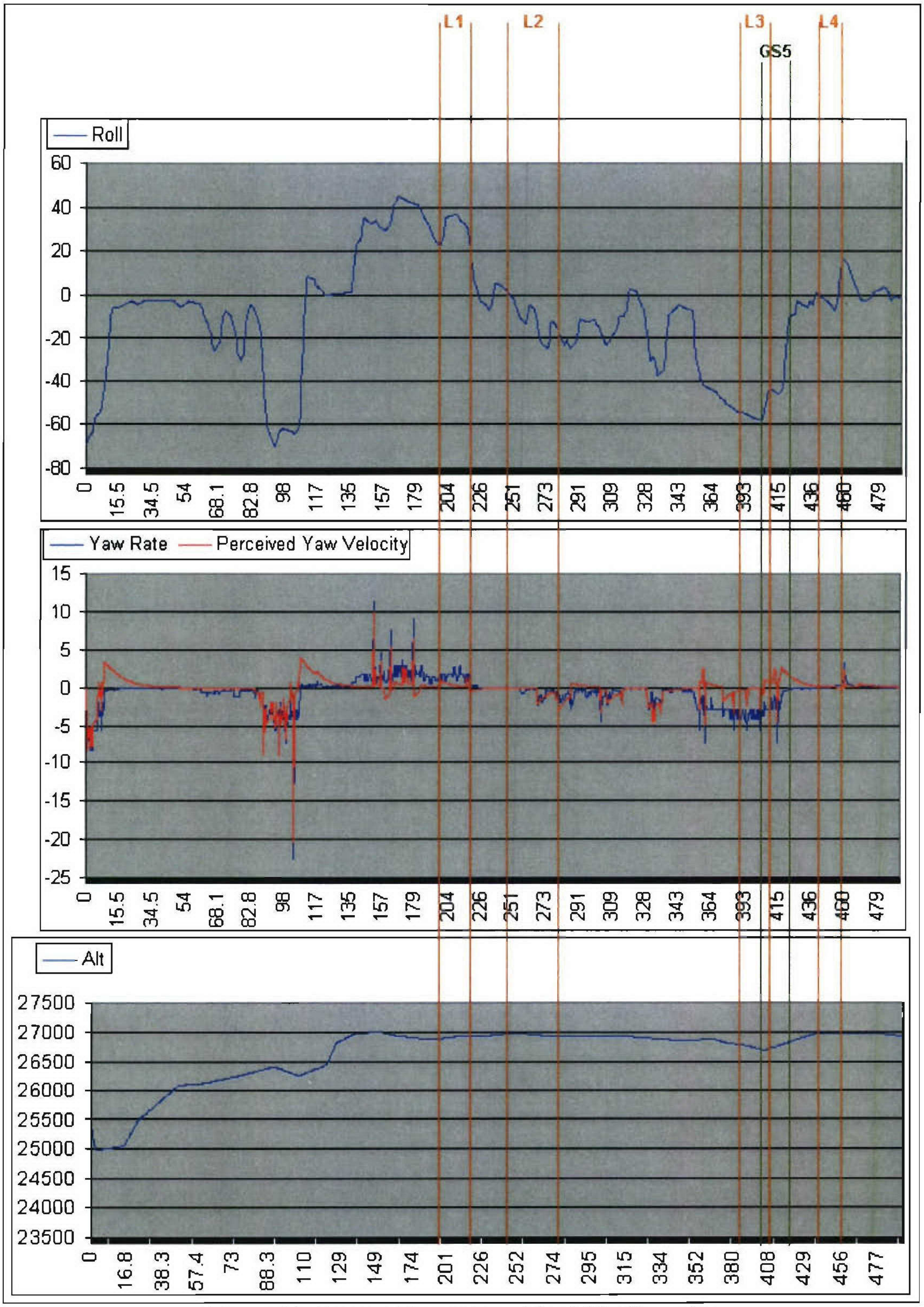

Figure 46. Data set E part 1 combined SDAT results

7.6.2 Data Set E Part 2

We received the E data set with a time anomaly: the time progresses normally for 495 seconds and then seems to go backward in time and then progress normally again. So, we decided to split the data set into 2 parts to correspond to the contiguous-looking portions of the data set.

Part 2 of the E data set lasts about 5 minutes (300 seconds). It contains a climb from about 21,500' to what appears to be a cruise altitude of 27,000'. The only unusual aspect of this portion of the data set is a left bank angle of nearly 60 degrees from about 70 seconds into the data set to about 100 seconds. During this high bank, though, no altitude is lost and vertical speed goes negative by only a small amount (not even 1000 fpm).

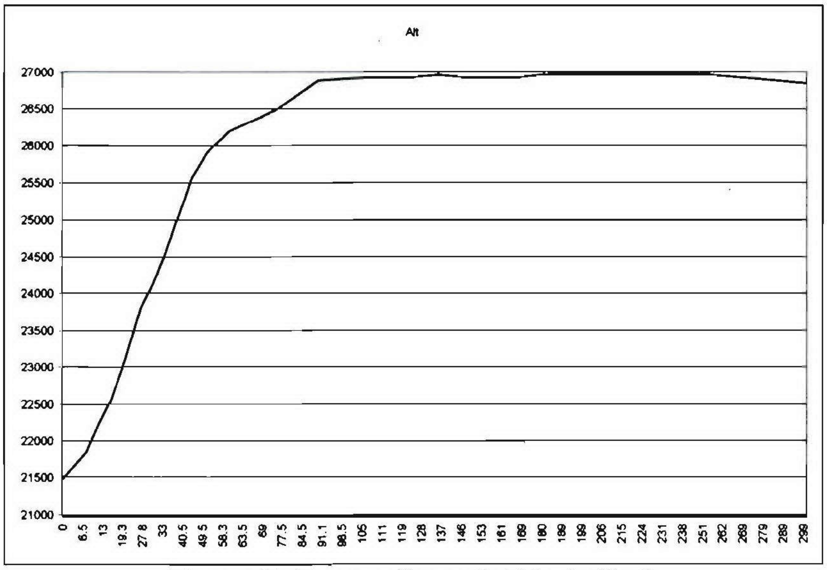

Figure 47. Data set E part 2 Altitude (feet)

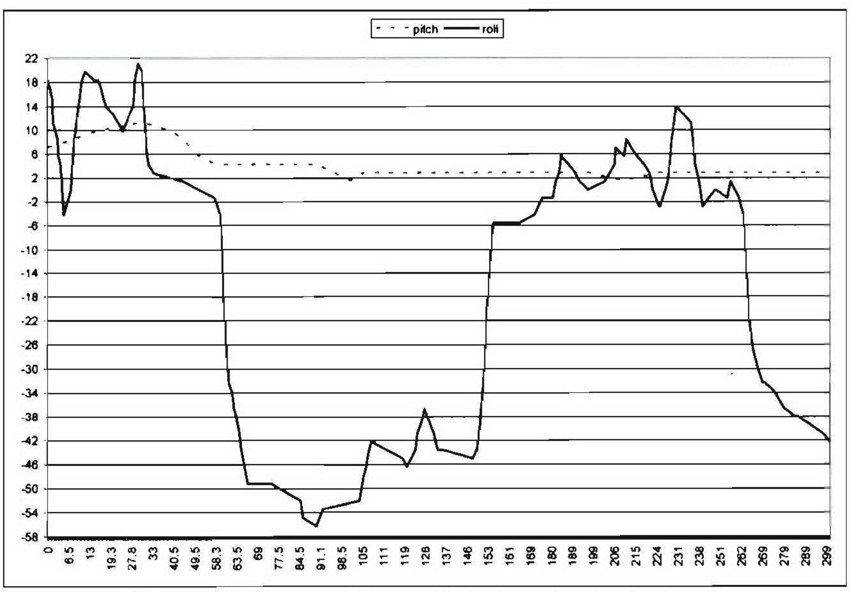

Figure 48. Data set E part 2 pitch and roll (degrees)

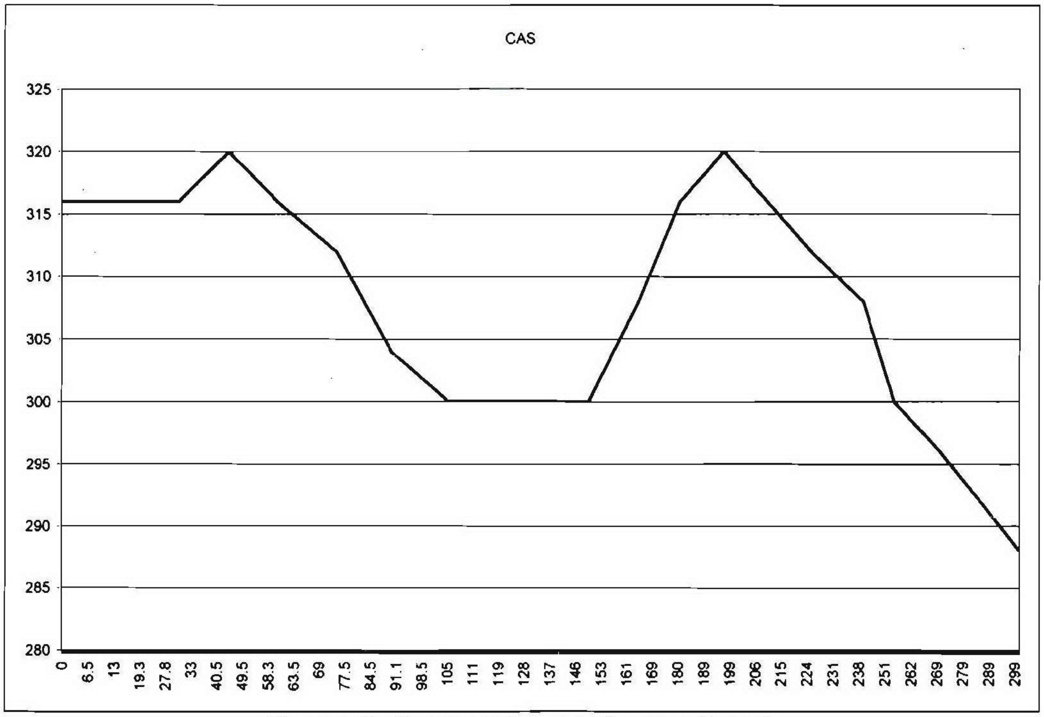

Figure 49. Data set E part 2 airspeed (knots)

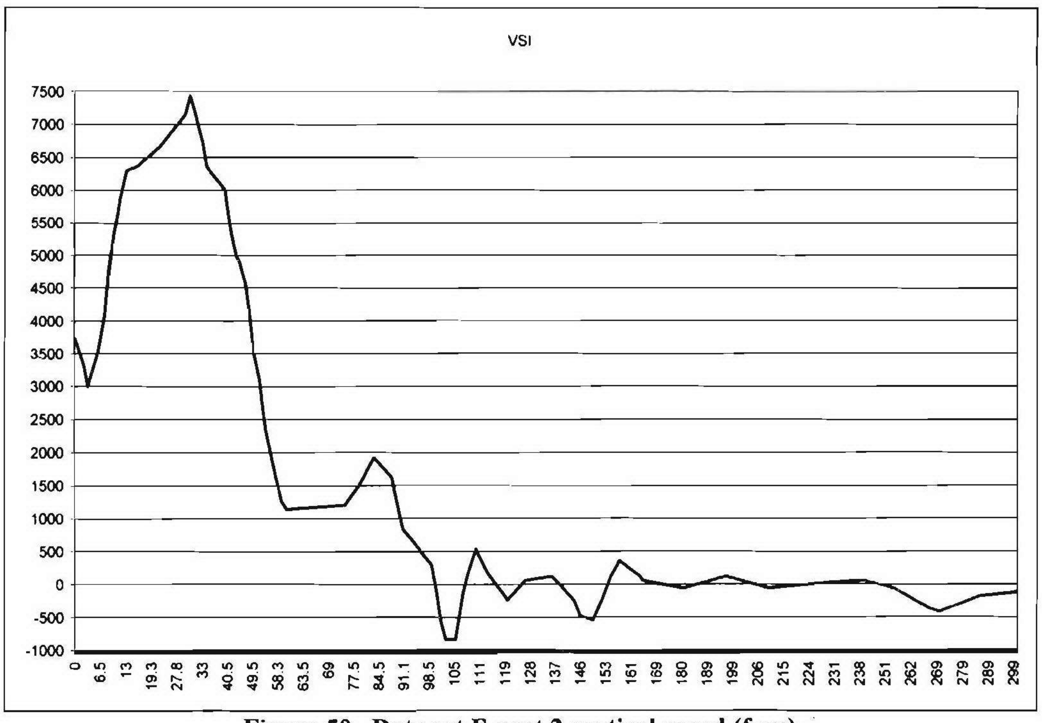

Figure 50. Data set E part 2 vertical speed (fpm)

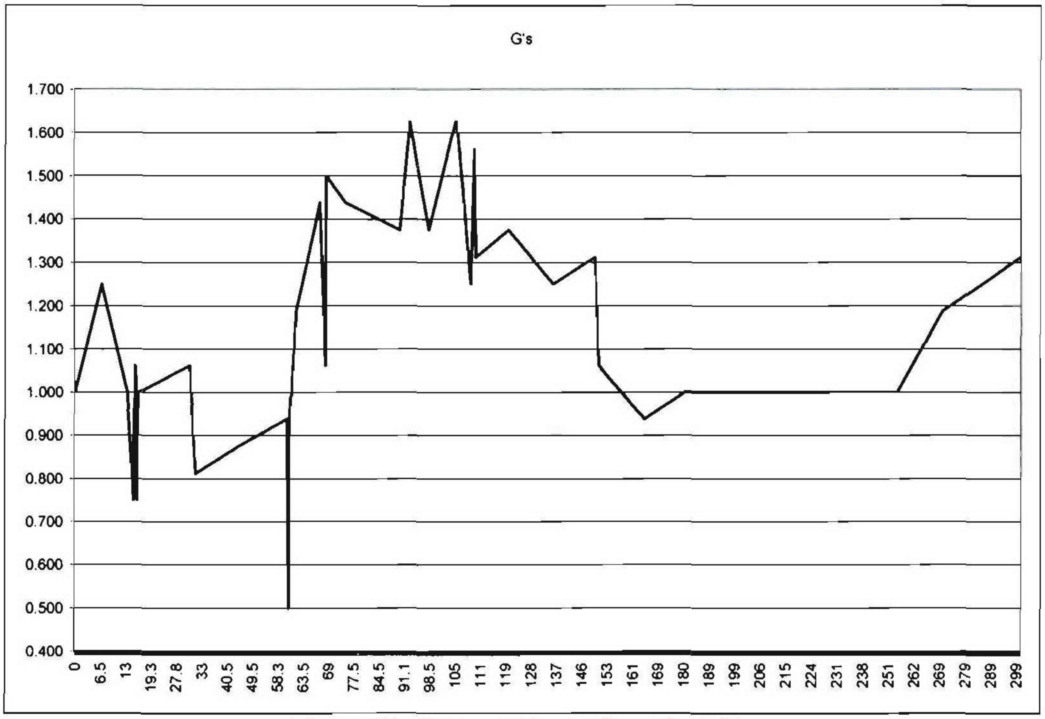

Figure 51. Data set E part 2 vertical G's

Pitch Analysis

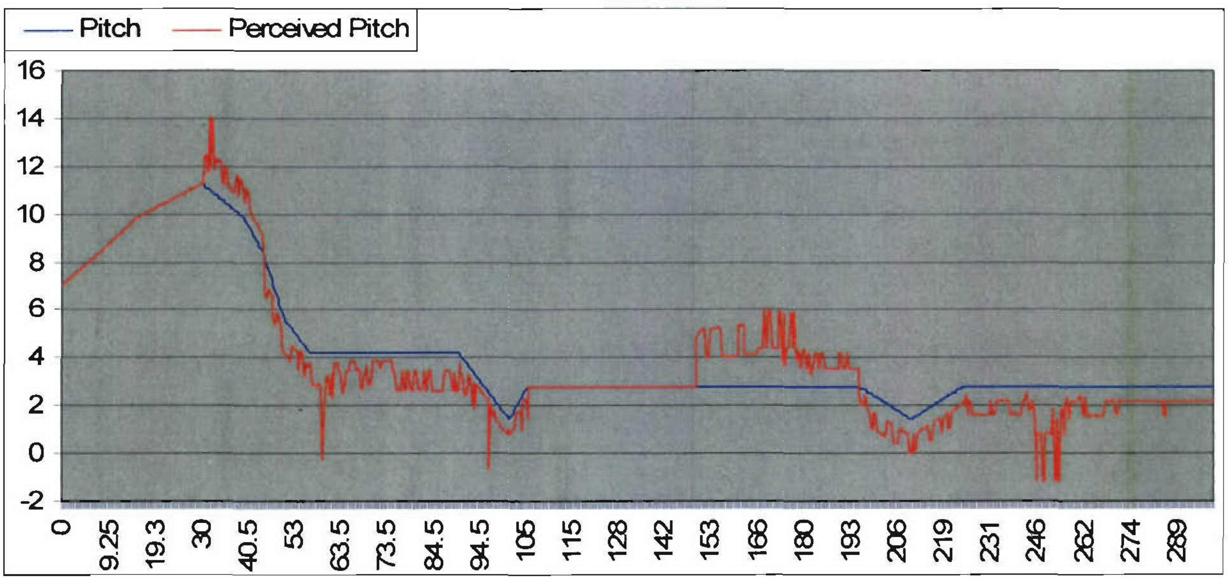

Figure 52. Actual and perceived pitch

There are no pitch perception anomalies of more than a couple degrees. The data set is rather blocky so there are exactly identical pitch values for considerable time. Note that the actual and perceived pitch values are exactly identical at the beginning of the data set and for a period in the middle. It is unlikely that a pitch perception problem occurring during this data set.

Leans Analysis

Table 22. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default	Event 1: a few Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: defaults Event 2 • 3 deg roll delta • 3 second duration	Event 1: a few Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1 • 10 deg roll start • 2 deg/sec roll rate Event 2 • 3 deg roll delta • 4 second duration	Event 1: numerous and extended Event 2: 58, 196-201 (2.5, 3.2)

Table 23. Leans illusions detection descriptions

Illusion #	Illusion Timing (seconds)	Description
1	35-60	This sequence begins at a bank angle of about 3 degrees and the sub-threshold roll actions reach a bank angle of about -4 degrees over 25 seconds. The sequence shows up at all the threshold levels but is not concurrent with any significant negative vertical velocity. Although there is no apparent loss of control, this sequence may have presented a bank angle perception problem for the pilot.
2	196-201	This sequence begins at a bank angle of about 4 degrees and the sub-threshold roll actions reach a bank angel of about zero (level) over about 10 seconds. The sequence shows up at the two higher threshold levels. There is no concurrent negative vertical velocity. Although there is no apparent loss of control and the aircraft ends in level flight, this sequence may have presented a bank angle perception problem for the pilot.

Illusion 1 is concurrent with the first part of a long turn at a bank angle of about-50 degrees. The AC seems to begin the turn with a rather wobbly roll. The second leans sequence is after this turn but seems to indicate that there was some sort of ongoing bank angle perception difficulty.

Graveyard Spiral Analysis

Table 24. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC	Illusion	

Yaw Threshold	Graveyard Spiral	
1.1, 1.5, 2.5	Default	None
1.1 2 Hz	3 deg/sec deltas	Event 2: 108-110, 120-127 (int) Event 3: 109-110, 121-127 (int) No new detections at 2 Hz sampling rate
1.5 2Hz	3 deg/sec deltas	Event 2: 77-83, 150-151 Event 3: 78-83, 150-151 Only at 2 Hz sampling rate
2.5 2Hz	3 deg/sec deltas	Event 2: 106-111 Event 3: 108-111 Only at 2 Hz sampling rate

Table 25. Graveyard spiral detection descriptions

Illusion #	Illusion Timing (seconds)	Description
1	77-83	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec perception delta. This sequence is concurrent with a high bank angle but there is no negative vertical velocity. It occurs only at the middle threshold value and the 2 Hz sampling rate. It is unlikely that this sequence represented a rotation perception problem for the pilot.
2	106-111	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec perception delta. This sequence is concurrent with a high bank angle but there is no negative vertical velocity. It occurs at the lowest threshold value and at the highest threshold value at the 2 Hz sampling rate. It is unlikely that this sequence represented a rotation perception problem for the pilot.
3	120-127	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec perception delta. This sequence is concurrent with a high bank angle but there is no negative vertical velocity. It occurs only at the lowest threshold value. It is unlikely that this sequence represented a rotation perception problem for the pilot.
4	150-151	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec perception delta. This sequence is concurrent with a high bank angle but there is no negative vertical velocity. It occurs only at the middle threshold value and the 2 Hz sampling rate. It is unlikely that this sequence represented a rotation perception problem for the pilot.

All four detected illusions are part of the same left turn at a bank angle of up to -50 degrees that lasts for over a minute and a half. The heading change (yaw) rotation rate is only about 3 deg/sec. Both the bank angle and rotation rate seem to wobble throughout the turn causing some acceleration to be above and some to be below the threshold values. While there may have been some level of rotation perception difficulty during the turn, it does not seem to represent a control problem.

Combined Results

The first leans sequence and all the graveyard sequences are all part of a the single long left turn. The sub-threshold roll drift brought the AC from a small positive bank to a small negative bank just prior to the initiation of the full turn. During the turn bank and rotation rate wobbles caused the graveyard spiral like sequences. While there is no apparent loss of control or negative vertical velocity, it is possible that there was some level of attitude perception problem during this turn.

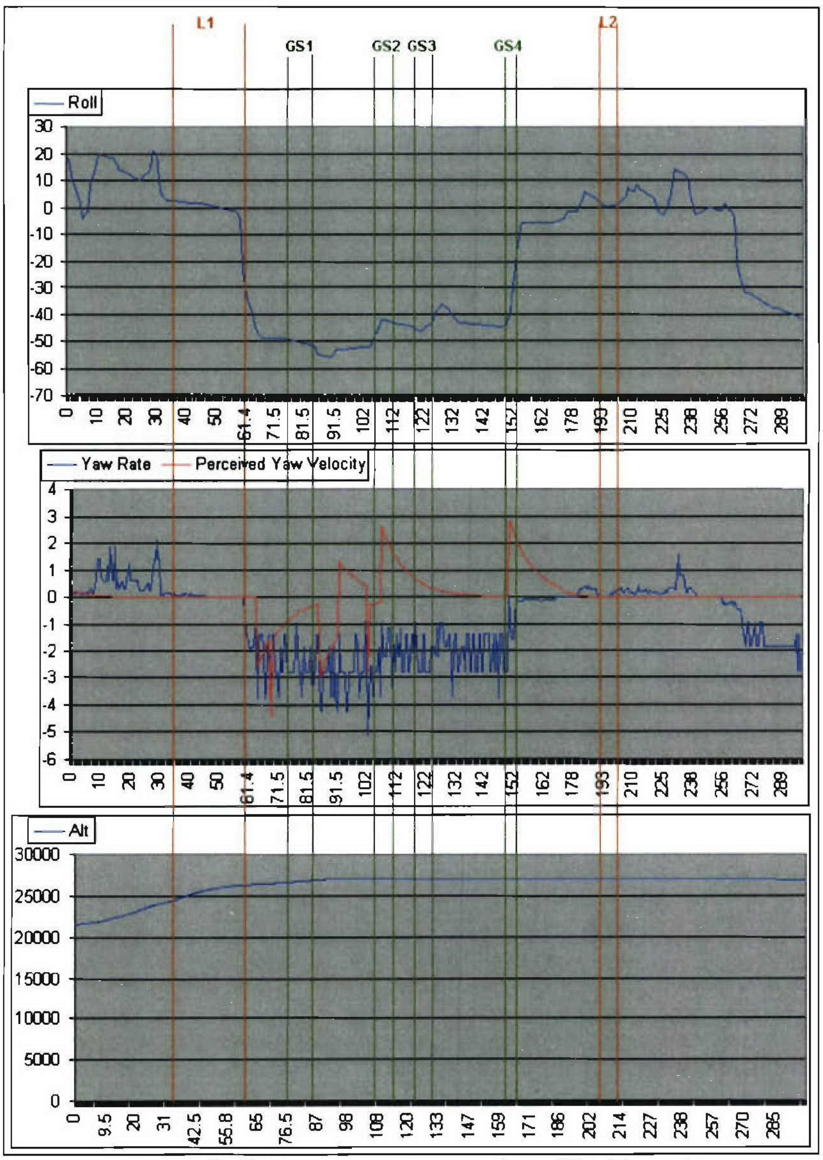

Figure 53. Data set E part 2 combined SDAT results

7.7 Data Set F

This data set lasts 19 minutes (1144 seconds). It appears to start with a take off. At time 600 seconds there is a series of turns that might be a clearing turn. The flight never seems very stable throughout. There is a large loss of elevation starting around time 900 getting down to under 1000 feet before climbing again. Near the end (the last ~15 seconds), the aircraft is almost inverted and in a large dive.

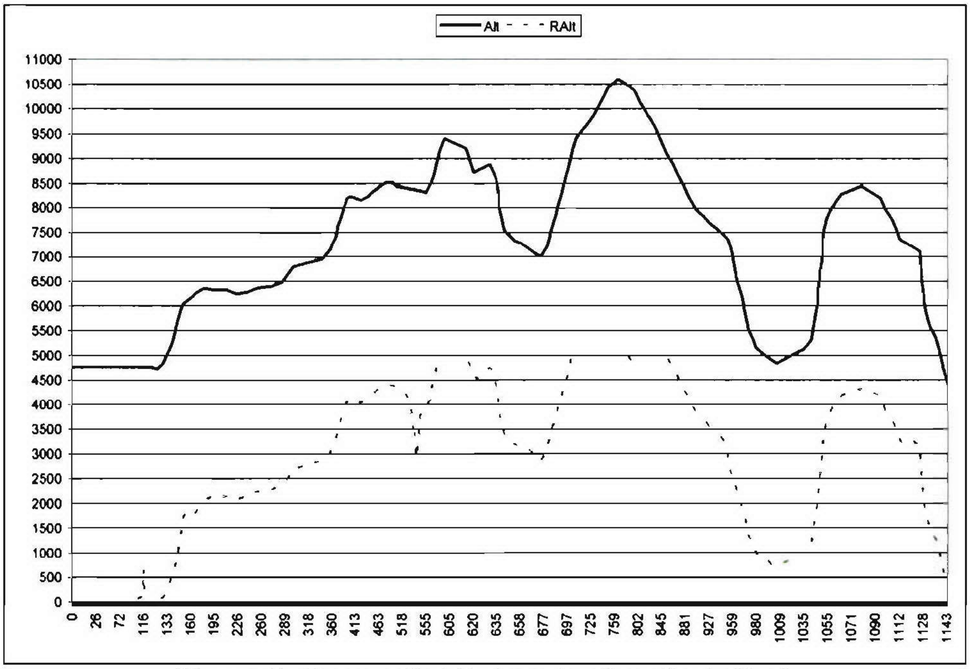

Figure 54. Data set F altitude and radio altitude (feet)

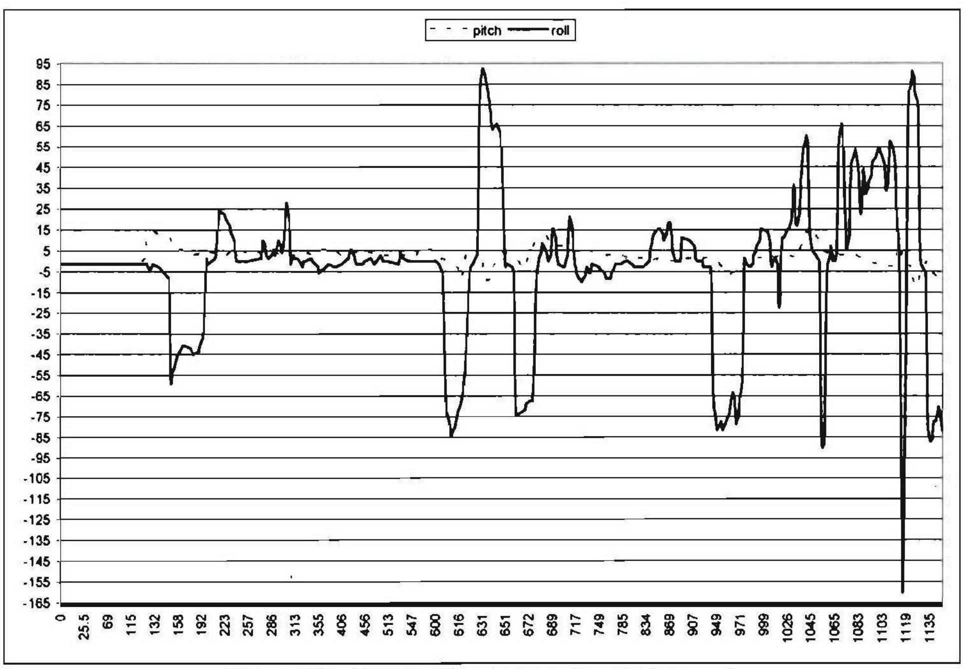

Figure 55. Data set F pitch and roll (degrees)

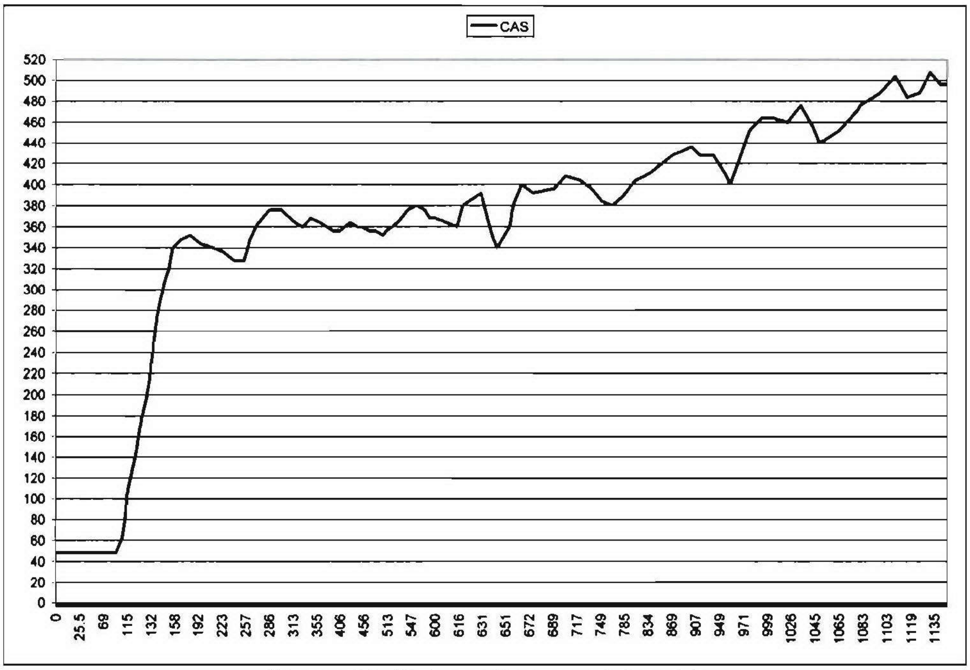

Figure 56. Data set F airspeed (knots)

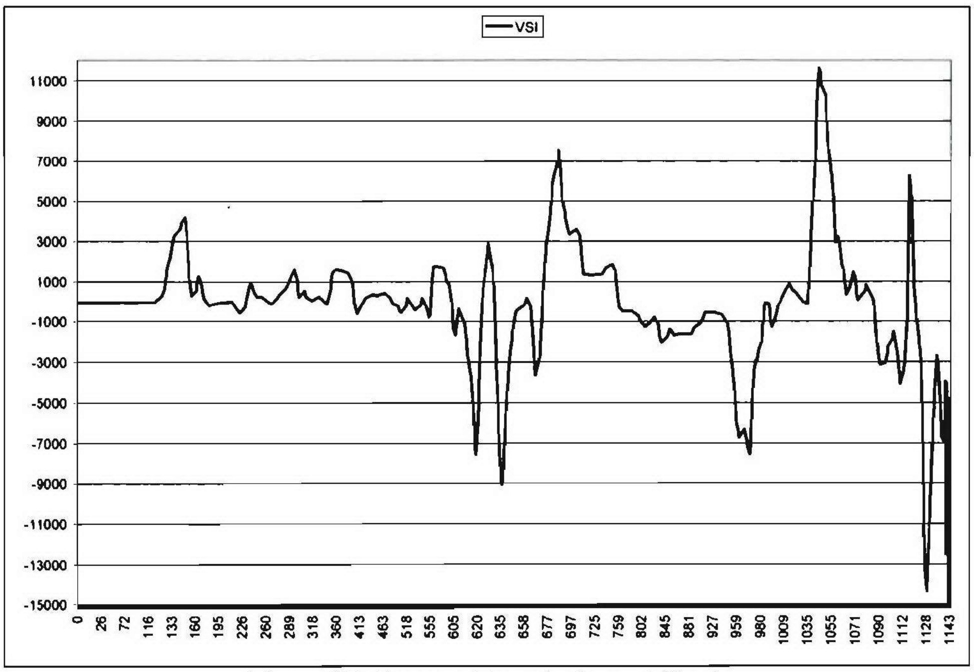

Figure 57. Data set F vertical speed (fpm)

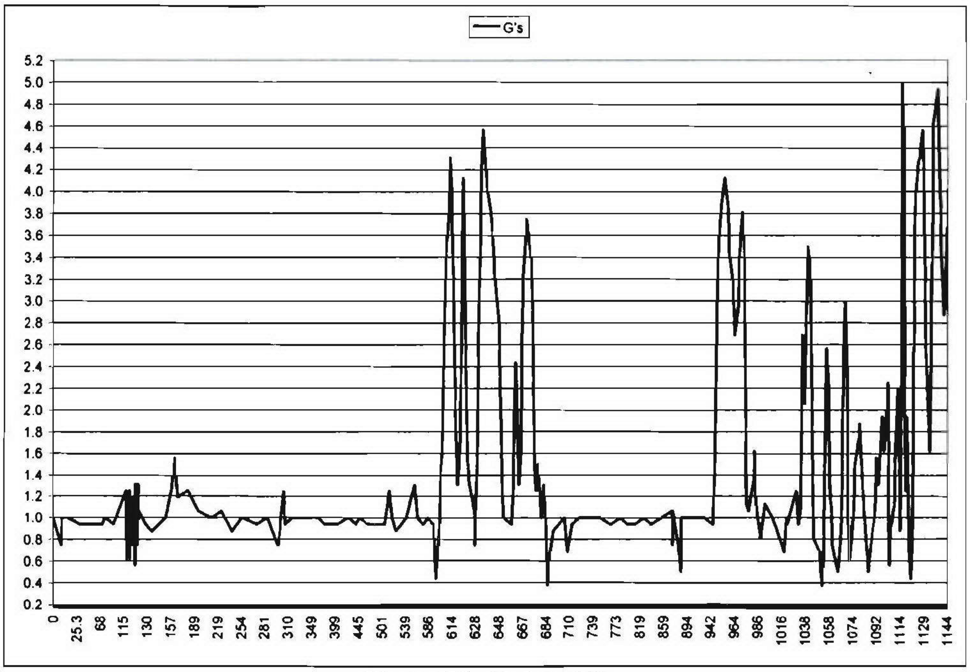

Figure 58. Data set F

Pitch Analysis

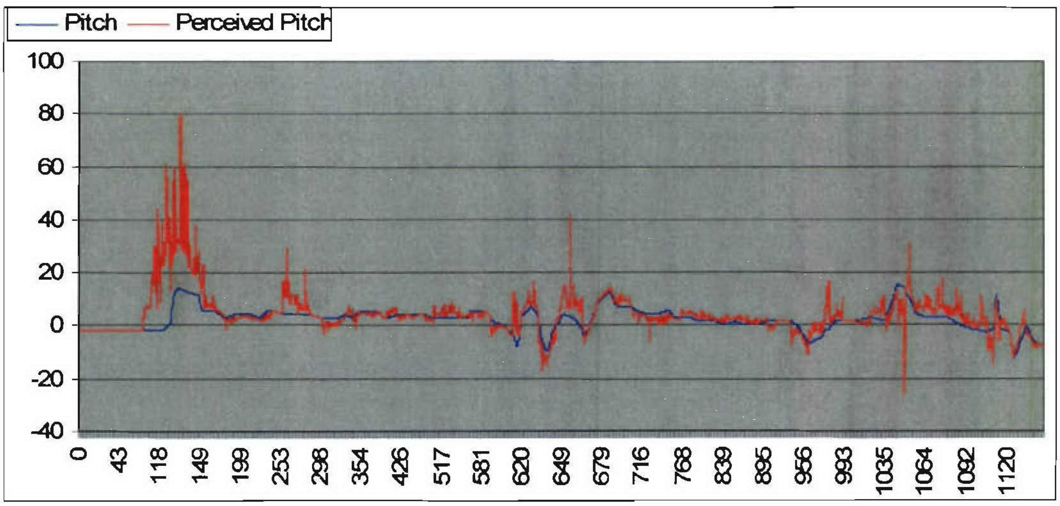

Figure 59. Data set F actual and perceived pitch

Table 26. Pitch perception anomalies

Time	Description
110-160	• 80 degree maximum perceived pitch • 13 degree maximum actual pitch • > 65 degree pitch perception delta • < 10 degree of bank till time 150
1036-1065	• -26 degree maximum perceived pitch (1049) • 15 degree maximum actual pitch (1048) • ~ 40 degree pitch perception delta

	• 50 to -80 bank angle range ○ 4 to -4 during period of (1046-1054)

There are a number of instantaneous pitch perception anomalies that reach perception deltas greater than 20 degrees. There are also a couple continuous pitch perception deltas but none that are continuously more than a 5-10 degree perception difference. The one large anomaly starting at time 110 is related to the take off of the aircraft. The dramatic linear acceleration causes a large increase in the perceived pitch. Once the airspeed starts to level off near time 160, the perceived and actual pitch begin to match up. The other pitch anomaly of interest occurs near the end of the data set starting at elapsed time 1036. The actual pitch is pulled up to 15 degrees rather dramatically while the perceived pitch drops suddenly to -26 degrees. The perception drop is probably due to the reduction in airspeed and probably isn't the cause of the nose up attitude. Much of this is during a period of relatively little bank angle and may be a response to a very low radio altitude (< 1000 ft). It is seems unlikely that a pitch perception problem contributed to this mishap.

Leans Analysis

Table 27. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default	Event 2: none
1.1, 1.5	Event 1: default settings Event 2 • 3 deg roll delta • 3 second duration	Event 2: none
2.5, 3.2	Event 1: default settings Event 2 • 3 deg roll delta • 3 second duration	Event 2: 356-423 (int @ 3.2 & 2 Hz sampling rate), 936-983 Event 3: 936-983 Event 4: 945- end
1.1, 1.5	Event 1 • 20 deg roll • 2 deg/sec roll rate Event 2 • 4 deg roll delta • 4 second duration	Event 2: none (1.1) Event 2: 762-765 (1.5)
2.5, 3.2	Event 1 • 5 deg roll • 2 deg/sec roll rate Event 2 • 4 deg roll delta • 4 second duration	Event 2: 146-196, 412-427, 456-473(3.2), 760-766, 788-844 Event 3: 788-844 (int) Event 4: 843-end

Table 28. Leans illusion detection description

Leans Illusion #	Illusion Timing (seconds)	Description
1	146-196	Standard leans sequence starting about -2 deg of roll and reaching about -8 across a 20 second time period. There is no concurrent negative vertical velocity. The event occurs at the two higher threshold values. This occurred shortly after take-off and is followed by a prolonged period of seemingly stable flight. While it is possible there was some issue with the accurate perception of bank angle, it is unlikely that this sequence represented a control problem to the pilot.
2	356-423	Standard leans sequence with a roll deg change of at least 3 degrees lasting for at least 3 seconds. It only shows up at the highest threshold value and at the 2 Hz sampling rate. Due to its lack of persistence, it is unlikely that this sequence represented bank angle perception problem for the pilot.
3	412-473	This leans sequence is somewhat non-standard starting at a roll of -5 deg and reaching 4 deg. It extends over a couple minutes of flight. It shows up intermittently at the two higher threshold values. There is no concurrent negative vertical velocity. It is possible that this event represented some difficulty maintaining awareness of bank angle. While there was no apparent loss of control, the length of this event could indicate some sort of ongoing distraction or disorientation issue.
4	760-766	Standard sequence starting about -2 deg of roll and reaches about -8 deg sec and lasting for at least 4 seconds. The sequence occurs at three of the four threshold values. There is no concurrent negative vertical velocity. Given the high level of persistence of this event across the threshold values, it is likely that there was some level of bank perception difficulty. While there is no apparent loss of control, it may reflect an ongoing difficulty maintaining roll awareness.
5	788-844	This is a nonstandard sequence staring from about -5 deg of roll and reaching a zero roll value but wavering for about 60 seconds. There is a concurrent negative vertical velocity of at least -500 fpm and increasing. This is followed by a larger roll that begins to extend into oscillations. This event occurs at both the higher two roll threshold values. As such, it is possible that this event represented a bank angle perception problem. The length of the event seems to indicate an ongoing issue. The concurrent loss of elevation and following bank oscillation seems to indicate the possibility that this sub-threshold roll perception issue contributed to the loss of control of the aircraft.
6	936-983	Standard leans sequence with a roll deg change of at least 3 degree lasting for at least 3 seconds. It is concurrent with a negative vertical velocity and is followed by large roll oscillations. Shows up at the two higher threshold values. It is possible that this indicates a roll perception issue.

The number and length of sub-threshold rolls that result in bank angle differences detected in this data set seem to indicate that the pilot was experiencing an ongoing problem with maintaining bank angle awareness. While none of the predicted bank perception differences reach 10 degrees, several of them coincide with losses in elevation. Events 5 and 6 (which are likely part of a single event) coincide with the large loss in elevation prior to the final climb and final descent. There is no separate detection of a sub-threshold roll illusion sequence associated with the final large bank oscillations and loss of altitude. It is possible that a bank angle perception problem contributed to this mishap.

Graveyard Spiral Analysis

Table 29. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
1.1, 1.5, 2.5	5 to 9 deg/sec deltas	Event 2: 614-626, 646-654, 963-983, 1113, 1129 Event 3: 615-626, 646-651, 964-983, Event 4: 615-622, 646-650, 964-983, Only minor changes across threshold values 615-626 up to 7 deg/sec delta 646-654 up to 10 deg/sec delta 963-983 up to 9 deg/sec delta
1.5	3 deg/sec deltas	Same as above, plus: Event 2: 1042-1047, 1071-1083 (int), 1129-1133 Event 3: 1083
1.1	3 deg/sec deltas	Same as above, plus: Event 2: 174-188 (int) Event 3: 175-188 (int)
2.5	3 deg/sec deltas	Event 2: 1112-1130 (int) Event 3: 1112-1115 Event 4: 1112-1115

Table 30. Graveyard spiral detection description

Illusion #	Illusion Timing (seconds)	Description
1	174-188	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec rotation perception delta. The sequence is concurrent with high bank angles but there is no negative vertical velocity. The sequence only occurs at the lowest threshold values. It is unlikely that this constituted a rotational perception problem for the pilot.
2	614-626	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 7 deg/sec rotation perception delta. The sequence is concurrent with high bank angles and

		negative vertical velocities up to -6000 ft/min. The sequence occurs at every threshold value. It is very likely that this sequence represented a rotation perception problem for the pilot.
3	646-654	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 10 deg/sec rotation perception delta. The sequence is concurrent with high bank angles and negative vertical velocities up to -7000 ft/min. The sequence occurs at every threshold value. It is very likely that this sequence represented a rotation perception problem for the pilot.
4	964-983	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 9 deg/sec rotation perception delta. The sequence is concurrent with high bank angles and negative vertical velocities up to -7000 ft/min. The sequence occurs at every threshold value. It is very likely that this sequence represented a rotation perception problem for the pilot.
5	1042-1047	This sequence includes washout and illusory rotation while maintaining 3 deg/sec rotation perception delta. It is concurrent with high bank angles but no negative vertical velocity. The sequence occurs only at the middle threshold value. It is unlikely that this represented a perception problem for the pilot.
6	1071-1083	This sequence includes washout and illusory rotation while maintaining 3 deg/sec rotation perception delta. It is concurrent with high bank angles but no negative vertical velocity. The sequence occurs only at the middle threshold value. It is unlikely that this represented a perception problem for the pilot.
7	1112-1133	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 3 deg/sec rotation perception delta. It includes high bank angles and large negative vertical velocities. The full sequence occurs at only the highest threshold value but the first couple events occur at the middle threshold value. It is possible that this represented a perception problem for the pilot and occurs with the apparent descent to ground impact.

Events 2 & 3 represent large perception deltas and occur as part of the same set of large left, right, left turns. While vertical speed is negative for some of the time, the sequences are followed by a long stretch of apparently controlled flight. Event 4 is part of one very large fast turn, includes large rotation perception deltas and is concurrent with a very low radio altitude. Events 5, 6, & 7 all occur near the end of the data set. They represent relatively small rotation perception deltas but may indicate an ongoing or increasing perception problem. It is possible that a rotation perception problem contributed this mishap.

Combined Analysis

Figure 60 shows three graphs combined with the timing of the detected leans and graveyard spiral events. The high number of illusions seems to indicate that there may have been an ongoing problem with attitude perception. The largest lost of elevation starting about time 775 is concurrent with four different illusion detections. The final graveyard spiral detection is closely timed with the end of the data set. It is possible that a rotation perception problem contributed to this mishap.

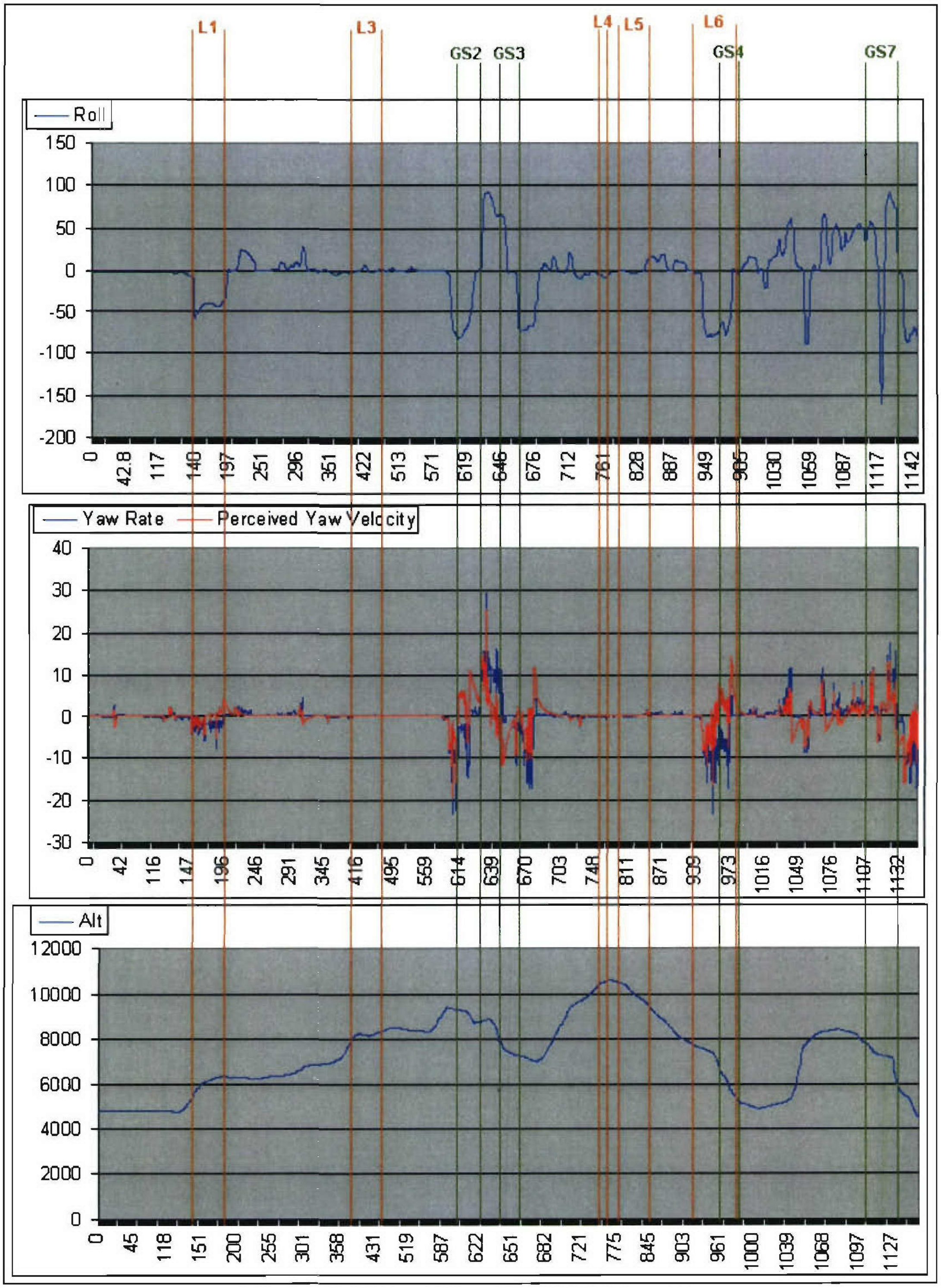

Figure 60. Data set F combined SDAT results

7.8 Data Set G

The elapsed time is about 5 minutes (312 seconds). It includes a couple long turns. It starts at about 12,000' and then mostly descends until ground impact. Within the last 10 seconds the aircraft is nearly inverted, at about 8 G's, and losing altitude at a rate in excess of 50,000 fpm.

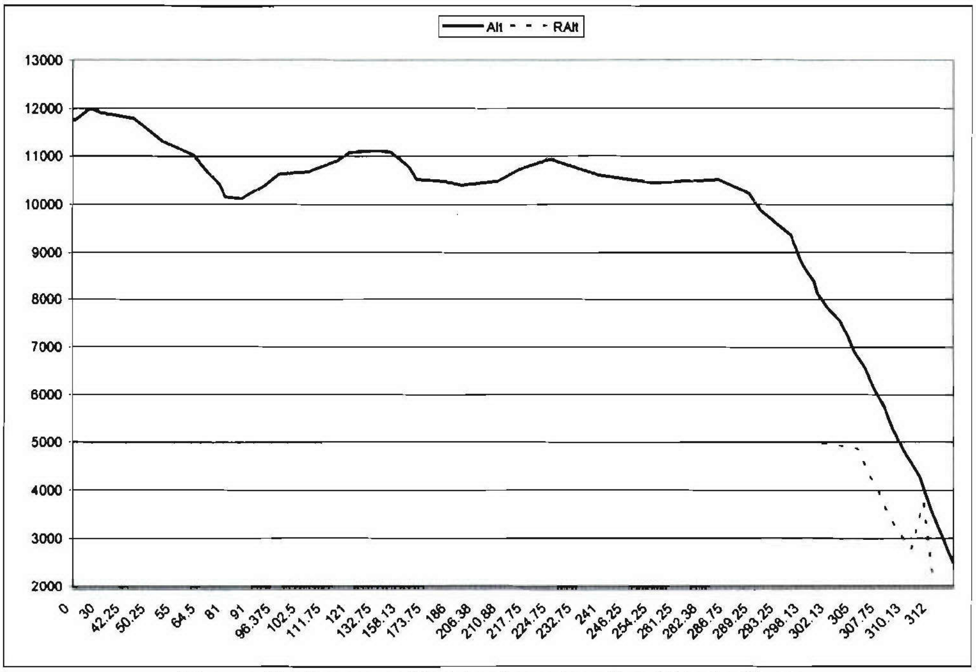

Figure 61. Data set G altitude and radio altitude (feet)

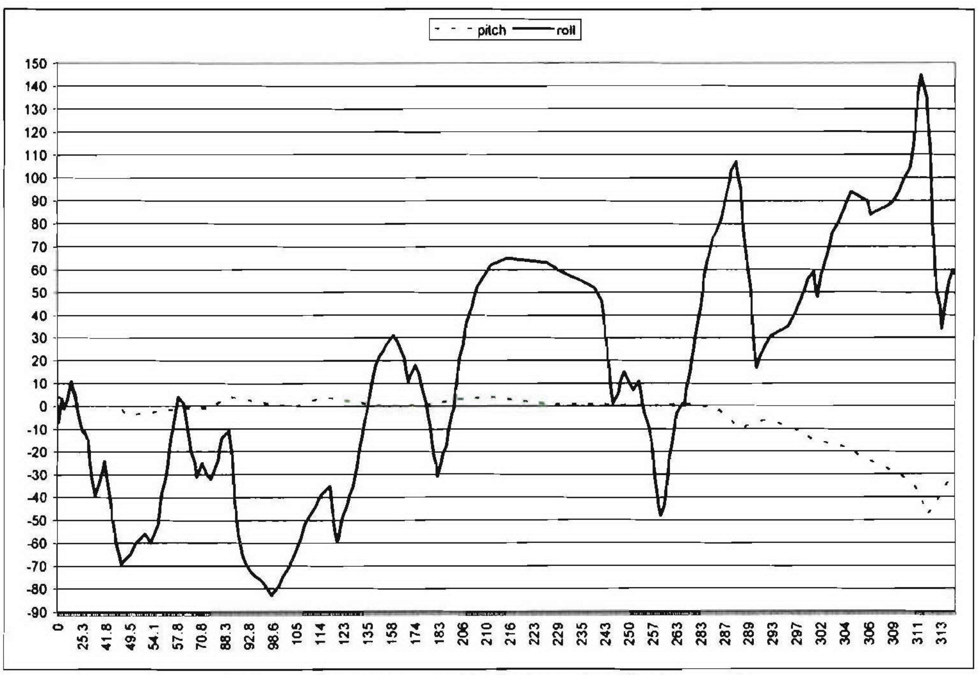

Figure 62. Data set G pitch and roll (degrees)

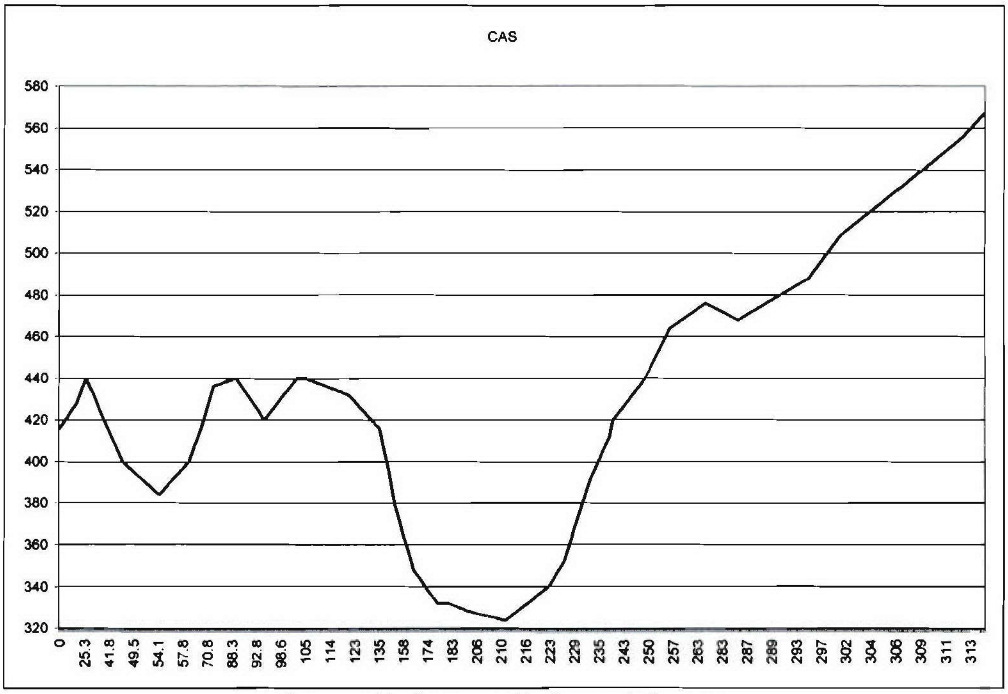

Figure 63. Data set G airspeed (knots)

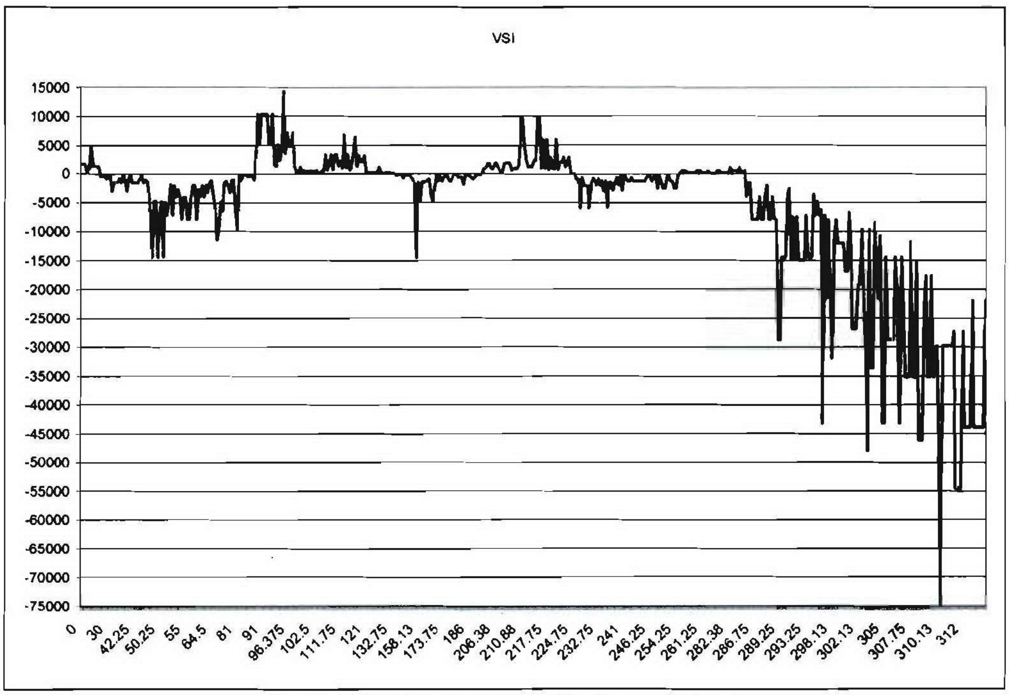

Figure 64. Data set G vertical speed (fpm)

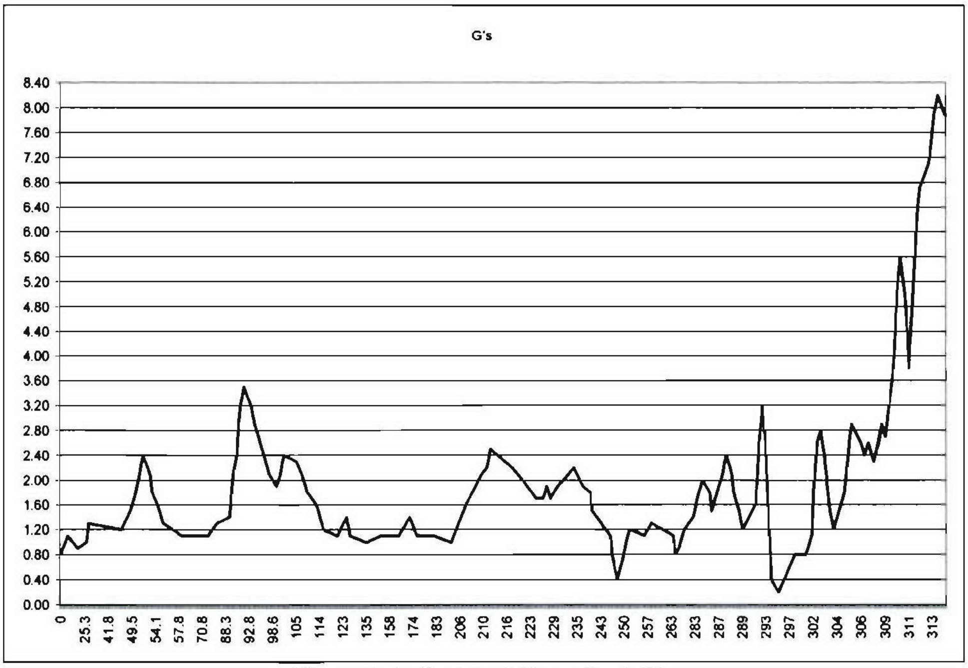

Figure 65. Data set G vertical G's

Pitch Analysis

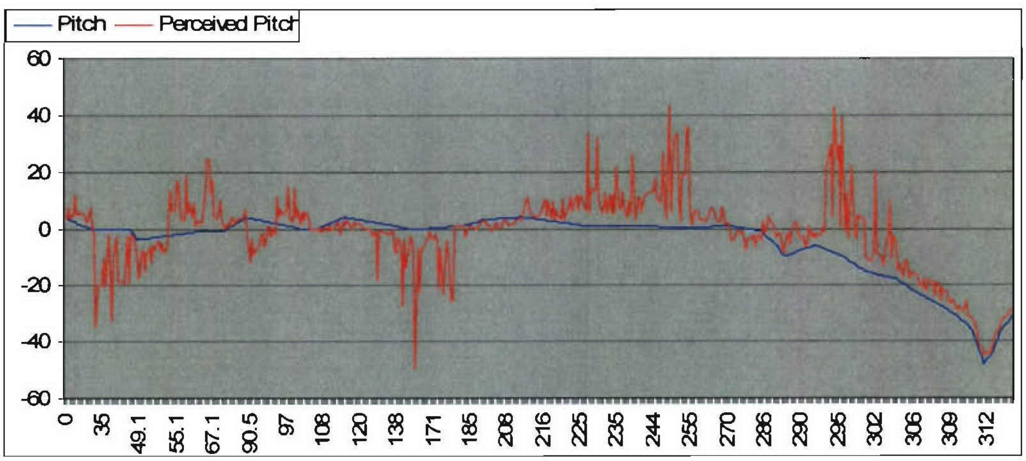

Figure 66. Data set G actual and perceived pitch

Table 31. Pitch perception anomalies

Time	Description
220-260	• 43 degree maximum perceived pitch • 0-1 actual pitch during time period • Continuous perception delta of about 10 degree • > 40 degree bank angle from 220-240 • < 30 degree bank angle from 245 to 255
285-305	• 42 degree max perceived pitch • -10 maximum actual pitch • > 30 degree bank for most of the time period

While there are instantaneous large pitch perception values, this data set is marked by sustained pitch perception deltas. The sustained difference reaches 10 degrees and last for up to a minute. The first notable anomaly starts at elapsed time 220. The actual pitch is just barely above level while the perceived pitch is constantly up near 10 degrees and reaches as much as 43. However, there is a high roll angle for much of this time period. At the end of this time period the actual pitch is gradually pushed over. The next anomaly begins very shortly there after as the actual pitch reaches about -10 but the perceived pitch climbs dramatically to greater than 30 degrees. Although the aircraft is in a high bank angle for much of this sequence, it is possible that the perception of positive or level pitch masked the actual and gradually increasing nose down attitude.

Leans Analysis

Table 32. Leans analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Roll Threshold	Illusion Leans	
1.1, 1.5, 2.5, 3.2	Default settings	Event 2: none
1.1, 1.5, 2.5, 3.2	Event 1: default settings Event 2 • 3 deg roll delta • 3 sec duration	Event 2: none
1.1, 1.5, 2.5,	Event 1 • 20 deg • 2 deg/sec Event 2 • 3 deg roll delta • 3 sec duration	Event 2: none
3.2	Event 1 • 20 deg • 2 deg/sec Event 2 • 3 deg roll delta • 3 sec duration	Event 2: 65-135 Event 3: 65-82 Event 4: 65

Table 33. Leans illusion detection descriptions

Leans Illusion #	Illusion Timing (seconds)	Description
1	65-135	This is a non-standard leans sequence. It begins at a bank angle of greater than negative 20 degrees and a roll rate around 2 deg/sec. Sub-threshold roll movements result in a change of greater than 3 deg and I concurrent with a large negative vertical velocity. However, this sequence shows up

		only at the highest roll threshold value and is not followed by any of the typical leans oscillations. As such, it is unlikely that this represented a control problem for the pilot. Also, it is very early in the data set and is followed by a prolonged period of roll stability.

There is a single leans sequence detected for this data set. It represents a non-standard leans sequence, is not persistent across the roll threshold values and occurs very early in the data set. It is unlikely that a sub-threshold roll perception problem contributed to this mishap.

Graveyard Spiral Analysis

Table 34. Graveyard spiral analysis settings and detections

SDAT Settings		Illusion Sequence Event timing
VAC Yaw Threshold	Illusion Graveyard Spiral	
2.5	Default	Event 2: 211-250 Event 3: 212-250 Event 4: 225-250
1.1 (2 Hz), 1.5	Default	Event 2: 110-118 Event 3: 110-118
1.1, 1.5,	3 deg/sec deltas	Event 2: 110-128, 237-250, Event 3: 110-128, 238-250, Event 4: 238-250,
2.5	3 deg/sec deltas	Same as 2.5 threshold above

Table 35. Graveyard spiral detection descriptions

Illusion #	Illusion Timing (seconds)	Description
1	110-128	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 5 deg/sec rotation perception deltas. It is concurrent with very high roll angles but no negative vertical velocity. It occurs at the lower and middle threshold values. It is possible that this sequence represented a rotation perception problem for the pilot
2	211-250	This sequence includes washout, illusory rotation and counter rotation opposite the illusory direction while maintaining up to 5 deg/sec rotation perception deltas. It is concurrent with high roll angles and some negative vertical velocity. It occurs at the highest threshold value and at the other two threshold values at the 3 deg/sec rotation perception delta. It is possible that this sequence represented a rotation perception problem for the pilot

Both sequences occur well before the apparent loss of control of the AC. While they might have presented a perception problem for the pilot and perhaps represent some level of ongoing perception difficulty, it is unlikely that they contributed to the mishap.

Combined Analysis

This data set contains very few sub-threshold roll movements and the two yaw rotation perception anomaly sequences occur one and two minutes prior to the end of the data set. While the pitch perception anomaly near the end of the set may have masked the progressive pitch down attitude, it is unlikely to have descent to apparent ground impact. It is unlikely that any vestibular based attitude detections contributed to this mishap.

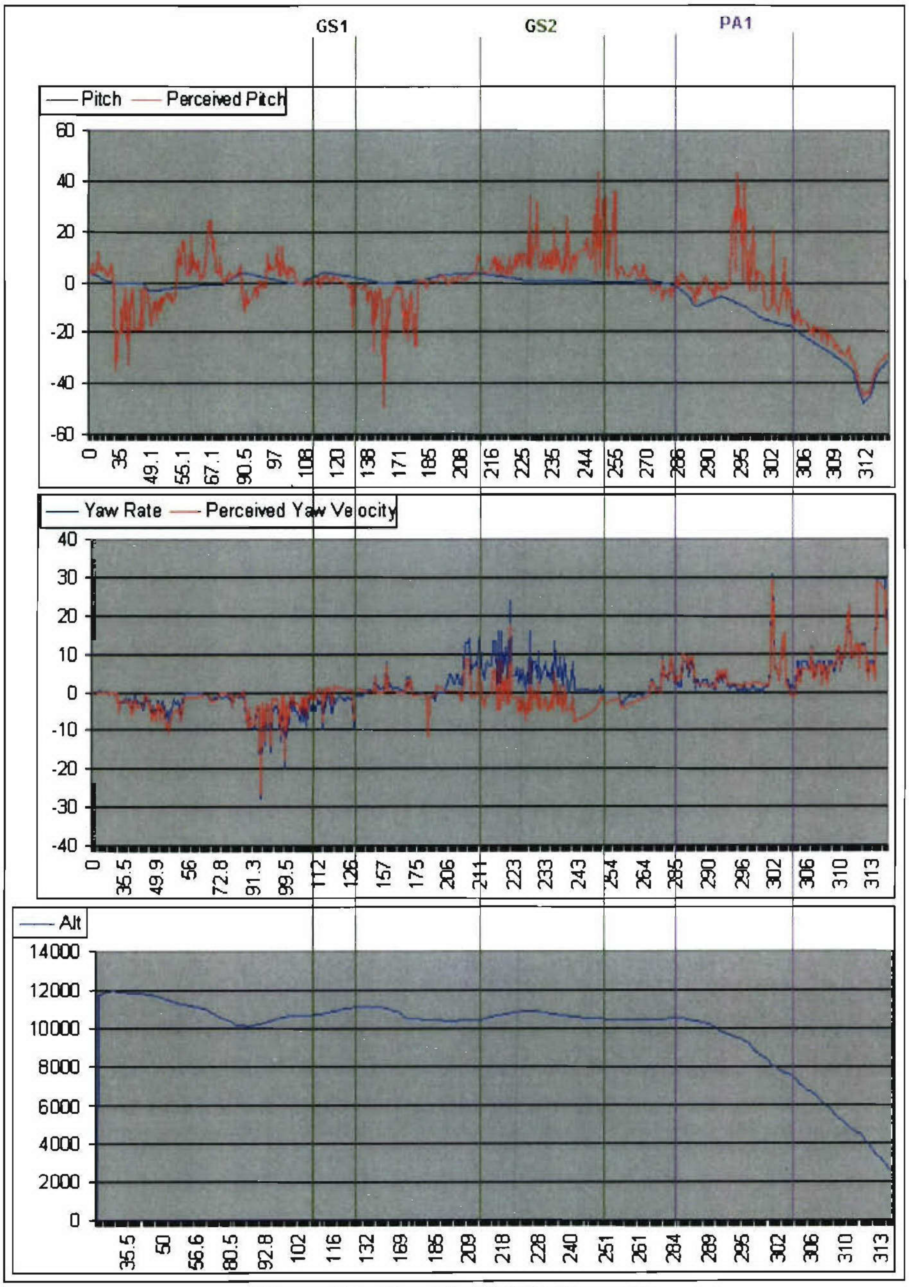

Figure 67. Combined SDAT results

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9 Appendix A. Flight Data File Format

The following are instructions for formatting flight data into the required file format. Table 36 shows the flight data parameters required and their associated columns. Figure 68 shows an example of the flight data file format.

SD Analysis Tool Excel Spreadsheet Format (version 3)

1. The sheet must be named FlightData
2. The maximum lines of flight data that the tool can currently handle is 5000.
3. Cell A1 must have the number of events in it (i.e. if there are 200 lines of data in the spreadsheet, then A1 = 200).
4. Row 2 has labels in it (such as Airplane State Parameters, Pilot State Parameters and SAVVOY Workload Scores.)
5. Row 3 has parameter names
6. Row 4 has units of measure
7. Row 5 is the first row of flight data
8. Columns A thru AA must have values in them. The following values can be set to nominal values (or zero) if you do not have the data for them: Latitude, Longitude, LongStickForce, LatStickForce, Head X, Head Y, Head Z, and all Pilot Workload values. Everything else must have a value for the system to work correctly.
9. There can be no functions in the spreadsheet, or anything else (such as charts) that would result in the Excel spreadsheet trying to save when a model run is complete.

Table 36. Flight data file parameters, units and columns

Parameter	Units	Column
Clock	sec	A
Baro_Alt	feet	B
Hdg_mag	degrees	C
Pitch	degrees	D
Roll	degrees	E
Yaw (heading)	degrees	F
IAS	knots	G
VSI	fpm	H
AOA	degrees	I
Radio_Alt	feet	J
cmd_pitch		K
cmd_roll		L
latitude	degrees	M
longitude	degrees	N
LongStickForce	lbs (+ AFT)	O
LatStickForce	lbs (+Right)	P
Vertical G's	G's	Q
Head_X		R
Head_Y		S
Head_Z		T
S (workload)		U
A (workload)		V

V (workload)		W
V (workload)		X
O (workload)		Y
Y (workload)		Z
Y (workload)		AA
Cognitive Workload		AB
Elapsed time	Sec	AC

	A	B	C	D	E	F	G	H	I	J	K	L	
1	3444												
2	Aircraft State Parameters												
3	Time	Corrected_Altitude	True_Heading	Pitch	Roll	True_Heading	Calibrated_Airspeed	VSI	AOA	Radar_Altitude	cmd_pitch	cmd_roll	La
4	sec	ft	deg	deg	deg	deg	kts	ft/min	deg	ft	(deg)	(deg)	(d
5	4125	14920	359	7	-3	359	236	-254.8672566	8	5000	0	0	
6	4125.25	14918.93805	359	7	-3	359	236	-1027.690551	8	5000	0	0	
7	4125.312	14917.87611	359	7	-3	359	236	-509.7345133	8	5000	0	0	
8	4125.437	14916.81416	359	7	-3	359	236	-203.5680964	8	5000	0	0	
9	4125.75	14915.75221	359	7	-3	359	236	-254.8672566	8	5000	0	0	
10	4126	14914.69027	359	7	-3	359	236	-509.7345133	8	5000	0	0	
11	4126.125	14913.62832	359	7	-3	359	236	-340.7316265	8	5000	0	0	
12	4126.312	14912.56637	359	7	-3	359	236	-203.5680964	8	5000	0	0	
13	4126.625	14911.50442	359	7	-3	359	236	-509.7345133	8	5000	0	0	
14	4126.75	14910.44248	359	7	-3	359	236	-340.7316265	8	5000	0	0	
15	4126.937	14909.38053	359	7	-3	359	236	-203.5680964	8	5000	0	0	
16	4127.25	14908.31858	359	7	-3	359	236	-254.8672566	8	5000	0	0	
17	4127.5	14907.25664	359	7	-3	359	236	-127.4336283	8	5000	0	0	
18	4128	14906.19469	359	7	-3	359	236	-145.8050667	8	5000	0	0	
19	4128.437	14905.13274	359	7	-3	359	236	-203.5680964	8	5000	0	0	
20	4128.75	14904.0708	359	7	-3	359	236	-254.8672566	8	5000	0	0	
21	4129	14903.00885	359	7	-3	359	236	-1027.690551	8	5000	0	0	
22	4129.062	14901.9469	359	7	-3	359	236	-92.61164849	8	5000	0	0	
23	4129.75	14900.88496	359	7	-3	359	236	-84.95575221	8	5000	0	0	

FlightData / Sheet2 / Sheet3

Figure 68. Excel flight data file example

10 Appendix B. Implementation of Mulder's Law

Mulder's Law combines the magnitude of an angular acceleration and the time of application to determine if a change in velocity is sufficiently high to be perceived by the vestibular system. In essence, larger accelerations over short periods of time and smaller accelerations over long periods of time can both be perceived. Various studies have produced different perception threshold values. Some of these differ across the angular dimensions (pitch, roll & yaw) that coincide roughly with the semi-circular canals. Others have presented different thresholds depending on how long the acceleration is sustained. As yet, we know of no definitive studies one way or the other. A recent conversation with Chuck Oman (friend of Chris' from MIT) has encouraged us to simplify things and stick with a single threshold value for all three axes and for any time period. While the tool will still allow users to change the threshold values, the default will now be 1.5 deg/s (as suggested by Dr. Oman).

Applying Mulder's Law to any single time slice in the data set is simple. The result of multiplying the acceleration by the time interval is compared to the threshold value. If it's above, the change in velocity is perceived by the vestibular system. We're calling this line by line calculation "instantaneous Mulder's". Table 37 shows 1 Hz sampled data and resulting instantaneous Mulder's calculation.

Table 37. Sample flight data at 1 Hz sampling rate

Line #	Time	Heading	Yaw Rate	Yaw Accel	Inst Mulder's
1	30.25	200.4	-0.01	0	0
2	31.34	200.4	0	0.01	0.01
3	32.42	200.33	-0.06	-0.06	-0.06
4	33.52	199.05	-1.16	-1	-1.1
5	34.6	196.8	-2.08	-0.85	-0.92
6	35.66	193.96	-2.68	-0.57	-0.6
7	36.75	191.22	-2.51	0.16	0.17
8	37.85	188.26	-2.69	-0.16	-0.18
9	38.95	185.52	-2.49	0.18	0.2
10	40.03	182.68	-2.63	-0.13	-0.14
11	41.12	178.72	-3.63	-0.92	-1
12	42.2	173.92	-4.44	-0.75	-0.81
13	43.3	168.88	-4.58	-0.13	-0.14
14	44.4	165.01	-3.52	0.96	1.06
15	45.5	161.83	-2.89	0.57	0.63
16	46.59	158.04	-3.48	-0.54	-0.59
17	47.68	154.27	-3.46	0.02	0.02
18	48.78	150.45	-3.47	-0.01	-0.01
19	49.89	146.61	-3.46	0.01	0.01
20	50.97	142.88	-3.45	0.01	0.01
21	52.08	139.03	-3.47	-0.02	-0.02

Notice that there is a change in rotation (a left turn) staring at around 33 seconds and that the turn rate settles down into a roughly constant rate by about 46 seconds (this is an X-plane flight using the mouse and I tend to wobble into my turns and I don't pull enough so the turn rate is pretty slow). Also notice that none of the instantaneous Mulder's calculations reach the 1.5 threshold level. Using the instantaneous calculation, we would predict that a pilot deprived of visual input would likely not feel the acceleration into this turn. The result is an approximately 3.5 deg/s discrepancy (delta) between actual and perceived yaw rotation.

A more complex calculation is required to model Mulder's Law calculations for values of 'time' larger than the sampled data interval. Again, the idea is that small but 'sustained' accelerations can be noticed if they occur long enough. The current methodology for combining accelerations is to average them then multiply by the time duration. For example:

> Lines 4 & 5 have accelerations of -1.0 and -.85
> The average is -0.93
> The time interval of application is 34.6 – 32.42 = 2.18
> The Mulder's Law calculation is then 0.93 * 2.18 = 2.03

This combined acceleration is greater than the 1.5 threshold so the corresponding change in velocity would be perceived. The amount of change is calculated by the difference in velocity across the associated lines of data (2.08 - .06 = 2.02 deg/s).

One problem is the need to limit the number of accelerations to combine across a large data set. According to Cheung's chapter in Bill's SD in Aviation book, Mulder's Law holds true for accelerations less than 10 seconds in duration. As such, we limit the number of combined accelerations to 10 seconds of data. However, we couldn't simply combine each 10 seconds and get a result. Combining many really low accelerations (lines 1-3, for example) with larger ones (lines 4 & 5) could result in masking some perceived changes. The methodology is to check the combination of each successive acceleration in turn to determine if they reach the threshold value.

Given any data sequence:

- If Instantaneous Mulder's (IM) of line 1 is above threshold then apply change to perceived and go to next line of data
- If IM1 is below threshold then don't apply change to perceived and go to next line of data
- If IM2 is above then apply change from 2, ignore 1 and move on
- If IM2 is below then check combination of 1&2
- If combined 1&2 is above then apply change and move on
- If combined 1&2 is below then don't apply change and check next line

Extending this sequence to a long series of sub-threshold individual and combined accelerations, the checking sequence would look like this:

> check line 1
> check line 2
> check 2 & 1
> check 3
> check 3 & 2
> check 3 & 2 & 1

check 4
4, 3
4, 3, 2
4, 3, 2, 1
5
5, 4
5, 4, 3
5, 4, 3, 2
5, 4, 3, 2, 1
6
etc

If, for example, the combination of 5, 4 & 3 were above threshold then the accelerations from 1 and 2 would be ignored as too low and 6 would then be checked by itself without referring back to combinations with 5, 4 or 3. This allows us to check each subsequent acceleration without unnecessarily combining it with lots of very low accelerations that might mask a perceived amount while still checking long sequences of low accelerations. One limit to the checking sequence is the 10-second time period. Once we've checked the combinations of 10 seconds without getting above threshold, we drop off the first value in the sequence and include the next one. This way it acts as a 10-second sliding window of perception.

Another problem here is obviously one of too many combinations. If the sampling rate is at 1 Hz then we could end up checking the sequence for ten lines of data. The number of calculations is ((n x (n-1))/2) so ten lines of data is 45 calculations. If the sampling rate is 2 Hz then we end up with 190. Those aren't too bad but if any higher sampling rates are used, we end up with way too many calculations and we certainly can't take up that kind of processing time in an aircraft.

Ways to shorten the sequence:

- Above Threshold - Certainly the sequence is broken every time we get an above threshold calculation (instantaneous or combined). The resulting change to velocity is applied to the perceived amount; previous lines not included are discarded and the sequence starts over.
- Minimum Acceleration Limit – Some really low accelerations are so far below threshold that even when combined for 10 seconds they won't be noticed. Our thought is that such accelerations can be ignored and any checked sequence prior to it that is sub-threshold can be dropped and the sequence started over. At the 1 Hz sampling rate, we might choose a conservative lower limit of 0.1. At 2 Hz it could be 0.05.
- Positive versus Negative Accelerations – A sequence of positive and negative accelerations of similar magnitudes essentially cancel each other out in terms of the resulting change in velocity. Combining sub-threshold accelerations using an average can reasonably be applied to accelerations with different signs as the result will be correspondingly small.

11 Appendix C. Acronyms & Terms

3D	three-dimensional
AFB	air force base
AFRL	Air Force Research Laboratory
AFSA	Air Force Safety Agency
AFSC	Air Force Safety Center
AGL	(altitude) above ground level
AI	attitude indicator
Alt	altitude
AOA	angle of attack
deg	degree(s)
FAA	Federal Aviation Administration
FOV	field of view
G	acceleration due to gravity
G-LOC	G-induced loss of consciousness
HDD	head-down display
hdg	heading
HUD	head-up display
Hz	Hertz (cycles per second; so, 2 Hz is 2 cycles per second)
IAS	indicated airspeed
IFR	instrument flight rules
IMC	instrument meteorological conditions (poor visibility)
MA&D	Micro Analysis & Design
MAAD	Micro Analysis & Design
mag	magnetic
msl	(altitude above) mean sea level
NTSB	National Transportation Safety Board
NVG	night vision goggles
OKCR	opto-kinetic cervical reflex
RAlt	radio or radar altitude (height above the ground)
SA	situation awareness
SBIR	Small Business Innovation Research
SD, SDO	spatial disorientation
sec	second(s)
SGI	somatogravic illusion
SIB	safety investigation board
SO	spatial orientation
US, U.S.	United States
USAF	United States Air Force
VFR	visual flight rules
VMC	visual meteorological conditions (good visibility)
VOR	vestibulo-ocular reflex
VSI	vertical speed indicated