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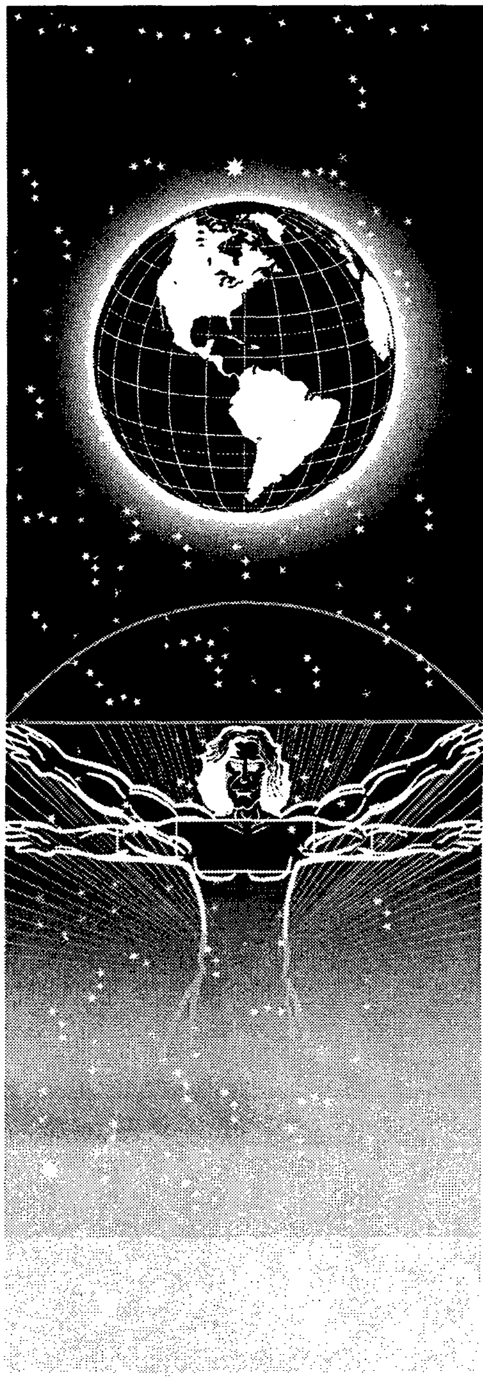

UNITED STATES AIR FORCE ARMSTRONG LABORATORY

THE OPTOKINETIC CERVICAL REFLEX (OKCR) IN PILOTS OF HIGH-PERFORMANCE AIRCRAFT

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)*

For over sixty years, researchers and engineers have based investigations and the design of cockpit displays and structures upon the presupposition that, during flight, the pilot maintains a head alignment coincident with the aircraft's vertical axis (Z-axis). Recent flight simulator studies have verified the existence of a pilot neck reflex which refutes this long-standing assumption. This reflex, named the optokinetic cervical reflex (OKCR), occurs during visual flight and is theorized to be an attempt by the pilot to stabilize a retinal image of the horizon to maintain spatial orientation. As a result, pilots view a fixer-horizon image and not a moving-horizon. The objectives of the research were to determine if the optokinetic cervical reflex occurs during actual flight of high performance jet aircraft and to model the response. This was an observational study in which the head positions of nine pilots were recorded during actual F-15 aircraft flight and analyzed. Results indicate that the OKCR caused pilots to tilt their heads during aircraft bank. Also, the reflex was found to be independent of the bank phase: entering versus exiting the turn. The OKCR was shown to be a strong, natural response and the flight results correlated extremely well with the simulator results. The impact of these results on pilot training, spatial disorientation, physiological injury and safety, and the re-design of displays for aircraft attitude and virtual reality are discussed.

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1.0 INTRODUCTION

1.1 Problem

Presuppositions and assumptions without scientific verification can be as innocuous as the pre-Copernicus “fixed earth theory” or as dangerous as an unfounded premise that put a human in a life threatening situation. This is especially valid when assumptions are made regarding the human-in-flight environment. Recent studies into pilot head orientation during flight have refuted a previous, long-standing assumption that pilots always align their head and body vertically with the aircraft (in the Z-axis) throughout all flight maneuvers. This original premise was stated in 1936 (Poppen) following the successful implementation and employment of the first attitude indicator display. The statement was merely an educated (albeit incorrect) observation and was never supported through scientific evidence or testing.

The persistence of the assumption for the past six decades has been due to a number of issues. Primarily, the assumption had never been challenged by actual scientific studies involving pilot head alignment. Secondly, the assumption had been propagated via pilot training and education which discourage motion of the head during flight. This training leads pilots to "believe" they do not tilt their heads during flight. Finally, no direct link had been established between aircraft mishaps, aircraft displays and the possibility that Poppen’s 1936 statement was incorrect. The closest attribution is that of spatial disorientation (SD). SD is typically attributed as a *cause*, in and of itself, of human error (and mishaps) but not as a *result* from a conflict between aircraft displays and the reality of pilot head alignment during flight.

Two recent investigations (Patterson, 1995 and Smith, 1994) have documented the existence of a pilot reflex currently named the optokinetic cervical reflex (previously: opto-kinetic collic reflex), or OKCR (Patterson, 1995). Both studies have found that pilots naturally tilt their heads during aircraft bank in an apparent attempt to align their eyes with the visible horizon. This reflex occurs during visual flight but not during instrument (no external visual stimuli) flight. The discovery of the OKCR is important since pilots, up until now, have been trained to minimize their head motion during flight. Both studies were completed in non-motion aircraft simulators. Until this time, no studies have objectively investigated the existence of the OKCR during actual flight.

1.2 Research Objective

The purpose of this research is to determine if the optokinetic cervical reflex occurs during actual flight of high performance jet aircraft. The focus is on the lateral flexion reflex (angle of head tilt [left and right]) in response to aircraft bank (or roll) angle. The connection between these variables will provide information as to which environmental sensory cues are important to the pilot in order to maintain the aircraft's attitude. Increased understanding of this subject can be used in the accurate design of aircraft attitude displays--specifically, the design and choice of symbology used in helmet-mounted displays (HMD), head-up displays (HUD), and virtual reality displays. Furthermore, flight-related topics such as training and physiological effects should be re-evaluated in light of the results.

2.0 BACKGROUND AND REVIEW OF LITERATURE

Common sense indicates that during human development the human body attempts to maintain vestibular order by keeping the head vertical with respect to the earth's gravitational acceleration. We have even developed language expressions to reflect this behavior: "she's got her head on straight" or "he's level headed." Animals such as birds, fish, reptiles and most mammals all attempt to keep their heads level and perpendicular to the earth's surface.

As a self-mobile being on the Earth's surface, the human is equipped with visual, vestibular and other sensory organs which provide the necessary feedback to deal with normal physical events. But, these events are usually limited to activities such as crawling, standing, walking, running , climbing, etc. The sensory information input to the visual, vestibular and other sensory channels for these activities is relatively low in frequency and magnitude when compared with more complex activities. Therefore, it should not be surprising that during highly dynamic motion, the visual and vestibular systems have difficulty bringing order to an overwhelming, chaotic influx of sensory information. This is especially true when this activity involves the unnatural occurrence of motion in the coronal plane (roll plane) such as what occurs during flight.

Today's high performance jet fighter aircraft can approach speeds in excess of 2 Mach, perform rolls at rates greater than 360° per second, and subject it's occupant(s) to acceleration forces over eight times the force of earth's gravity. These extremely foreign conditions force the human system to compensate using reflexes and abilities developed on the Earth's surface. These reflexes are typically inadequate for the extreme conditions, resulting in injury, fatality, or the necessary re-design of the vehicle (an aircraft in this case). Often, new reflexes are found as a result of placing a human in a foreign environment. This is believed to be the case in the discovery of the OKCR.

The following sections will convey design and human factors issues pertaining to flying aircraft and using displays. A brief description of the physiological components relevant to these issues will be addressed first. This will be followed by a literature review of past and current research into motion and head alignment; in particular, pilot head alignment. A working knowledge of displays in the cockpit will be necessary to fully understand the human factors interface between the pilot and the flight environment.

The final section is a case study of head- and helmet-mounted displays (HMD) and the impact the OKCR will have on future HMD design. The first part of this section will focus on the inherent differences between HMDs and conventional displays. The second part is a discussion of the concept of “frame of reference” as it applies to flight, HMDs and the OKCR. An example will follow documenting the "model-environment reversal effect" resulting from current HMD attitude symbology and the predicted orientation of the pilot's head during flight based on the OKCR. Finally, the last part will conclude with a review of current HMD attitude displays and the theoretical bases from which these displays are designed.

2.1 Reflexes to the Visual and Vestibular Systems

The functions of self-motion and visualization require inputs from the human sensory system. In particular, signals from the visual, vestibular and kinesthetic sensory receptors interact and are assimilated to provide stability for motion and sight. The vestibular system is composed of two major organ pairs: the semicircular canals and the otolith organs, both located in each inner ear. The semicircular canals are generally stimulated by angular acceleration and deceleration of the body. The otoliths are composed of the utricle and saccule, with the utricles located in the horizontal plane and saccules in the vertical plane. They are stimulated by linear motion, acceleration, as well as the rate of change of acceleration. Otoliths can also be stimulated by a simple tilt of the head with respect to the earth's gravitational acceleration.

The interrelationship between motion, visual reference and response to vestibular inputs has lead to the evolution of many complex and unique reflexes (Table 2.1). These reflexes can be categorized into two basic types: those which compensate for the movement of the head, and others which compensate for the movement of the visual "target." The goal of many of the reflexes is to maintain a stable retinal image.

The vestibulo-ocular reflex responds to vestibular inputs and has two phases: slow and quick. When the head is rotated, the eyes rotate slowly (slow phase) in the opposite direction, which is then followed by a quick return of the eye (quick phase, or saccade). During the quick phase, the retinal image is not fixed and is consequently smeared, therefore, this phase must be accomplished rapidly.

The cervico-ocular reflex occurs when the head is stationary (fixed) and the torso moves independently. This reflex responds to kinesthetic receptors in the neck and is evoked by horizontal and vertical torso rotation. Interestingly, eye torsion is not induced by stimulation of neck receptors via rotation of the body in the frontal plane (or about the x-axis). This is what occurs during aircraft bank (roll) if the pilot maintains the head essentially fixed in space--the body and aircraft will rotate about the pilot's neck. The vestibulocollic reflex occurs during dark conditions with no visual stimulus. The reflex is a nystagmic movement of the head when the whole body is rotated and is common in animals such as birds to maintain stabilized head orientation as the body moves about.

Vestibular nystagmus is the involuntary, rhythmic motion of the eyes induced by vestibular inputs. Nystagmus occurs in all three planes of motion: horizontal, vertical and torsional. They are all characterized by both saccades and slow phase rotation of the eyes. Constant torsional deviation (countertorsion) of about 8° of eye rotation can be produced from a sideways tilt of the head when the body is erect (Howard, 1982). Countertorsion, however, does not occur when the body is supine. Howard stated that eye torsion is incorrectly registered by the orientation system and that the somaesthetic-otolith complex is a better judge of the head-body posture than reference to neck-joint kinesthetic receptors alone. The somatosensory system responds to the pressures and stretching in muscles, skin and joints. The optokinetic nystagmus (OKN) is stimulated by motion of the visual scene (target) with respect to the observer. In an attempt to maintain a stable image, the eyes will alternate slow pursuits with rapid saccades. These are compensatory reflexes and are thus very primitive (Howard, 1982).

The foveal eye pursuit movements are voluntary and are meant to stabilize a retinal (foveal) image as opposed to the whole visual scene. Reading text requires this ability as only the fovea of the eye has the resolution to detect the high-frequency visual features of text. The control of these movements involves a higher order of decision making and processing than the involuntary reflexes previously discussed.

The pseudovestibulo-collic reflex (Young, 1986) is more correctly an illusion of the human system. When a stationary person views a rotating visual scene, that person will have the sensation of falling in the opposite direction and will tilt their body opposite to the rotational scene. This reflex is driven by the visual input which conflicts with the absence of the "correct" vestibular stimulation.

Due to the complexity of the vestibular system, the dynamics of a particular situation make illusory perceptions common. Three otolithic illusions are the illusory tilt, oculogravic illusion and the unperceived tilt. The illusory tilt is common for anyone who drives a car (but not a motorcycle). The centrifugal forces in a curve cause a shear force on the otolith maculae which is interpreted as a sideways tilt of the head. The oculogravic illusion is a subset of the illusory tilt which applies to a sudden linear acceleration in the forward direction giving the illusion of pitch. The unperceived tilt (commonly called the "leans") occurs when the otolith maculae are normal to the gravitoinertial force caused by a banking plane, and in the absence of visual cues to disambiguate, this is interpreted as the normal upright. A subject with body aligned with gravitoinertial forces fails to perceive vehicle tilt (Howard, 1986b). Howard (1986b) does not specify whether the subject's head is also aligned with the gravitoinertial force vector. This is an important issue--it is obvious the author assumes the pilot's head and body are both maintained in the vertical during the banking maneuver.

The Coriolis illusion or cross-coupling can be induced when one tilts their head, while their body is being rotated, with respect to the axis of rotation. This illusion gives the sensation of falling perpendicular to the head tilt axis. For example, if a person is vertical and spinning on their vertical axis, then a forward tilt of the head will yield a sensation of falling to the right. Similarly, a tilt of the head toward the right shoulder would give the sensation of falling backwards. Cross-coupling can cause nausea and extreme discomfort as well as disrupting the visual system's ability to maintain a stable retinal image, therefore pilots are taught not to move their heads during maneuvers to prevent the Coriolis illusion. Howard (1982) has suggested the nausea may be caused by a conflict between the canal inputs giving a false head tilt sensation and the otolith, visual and kinesthetic inputs which give the true signal of head orientation. Consequently, if movements of the head are confined to the plane of rotation of the body, these effects (nausea, disorientation) are avoided (Howard, 1982). If this is true, *the OKCR should not induce cross-coupling effects since the head tilts (sideways) during an aircraft roll, and pitches (up/down) during aircraft pitch; both head movements are* within *their respective plane of body rotation. Therefore, the optokinetic cervical reflex should not be considered deleterious behavior in the cockpit.*

Table 2.1. *Human Vestibular and Visual Reflexes (various sources)*

Reflex:	Stimulus:	Results in:	System:	Purpose:
Nystagmus	Vestibular stimulus or movement of external visual environment	Rhythmic motion of the eyes	Visual	Stabilize overall visual image
Vestibular nystagmus	Vestibular stimulation. To compensate for head motion.	Movement of eyes in same plane as the head/body rotation	Visual	Stabilize overall visual image
Vestibulo-ocular reflexes	Head movement	Compensatory eye movement	Semicir. Canals Otolith (Utricles)	Stabilize the retinal image
Optokinetic nystagmus	To compensate for movement of external visual environment or target	Movement of eyes to follow the stimulus	Visual (Peripheral)	Stabilize overall visual image
Foveal pursuit eye movements	To compensate for movement of external visual environment or target	Movement of eyes to follow the stimulus	Visual (Foveal)	Stabilize retinal image rather than overall
Positional Nystagmus	Body is held in a tilted position	Nystagmic deflection of eyes	SC Canals and Otoliths	Interaction of Vestibular Sys.
Cervico-ocular reflex (also: spino-ocular)	Motion of torso (horizontal or vertical only) relative to a stationary head	Nystagmic movement of eyes opposite to torso movement	Proprioceptors in neck	Possible stabilization of retinal image
Constant torsional deviation (countertorsion)	Head is tilted to one side (But not when body/head in supine position)	Eyes rotate in opposite direction about the visual axis	Steady excitation of Otolithic organs (Utricles)	Stabilize retinal image
Pseudo-vestibulo collic reflex	Rolling visual field	Head tilts opposite to the motion of external visual stimulus	Visual (absence of vestibular input)	Illusion causes sensation of self-inclination
Optokinetic cervical reflex	Rolling visual scene during flying conditions	Head tilts toward (with) the rotating visual image	Visual	Theorized stabilization of retinal image
Vestibulocollic reflex	Sinusoidal rotation of body in the dark	Nystagmic movement of the head	Otoliths	Stabilization of the head

2.2 System Engineering: Human versus Aircraft
Orientation Planes and Axes of Motion

When a person attempts to align themselves with an external object (e.g. the horizon) this is considered egocentric orientation. When a person attempts to align two external objects, one of which they are anchored to at some point, it is called semi-egocentric orientation. An example of this is a pilot aligning the aircraft's wings with the horizon (the pilot is "attached" to the aircraft). Howard (1982) stated there are no natural standards of orientation other than vertical and horizontal. For instance, there is no standard or norm for the angle of 30° in nature. Pine trees and standing persons are vertical; the horizon is horizontal. If a subject was asked to verbally estimate the tilt angle of a given object, it would be closer to a recognition task than one of discrimination. The subject would need to examine the object, then mathematically estimate how far *from vertical* (or *horizontal*) the object is rotated. Human visual performance (detection, identification and description) tends to be superior when the stimuli are horizontal or vertical rather than oblique (Howard, 1982).

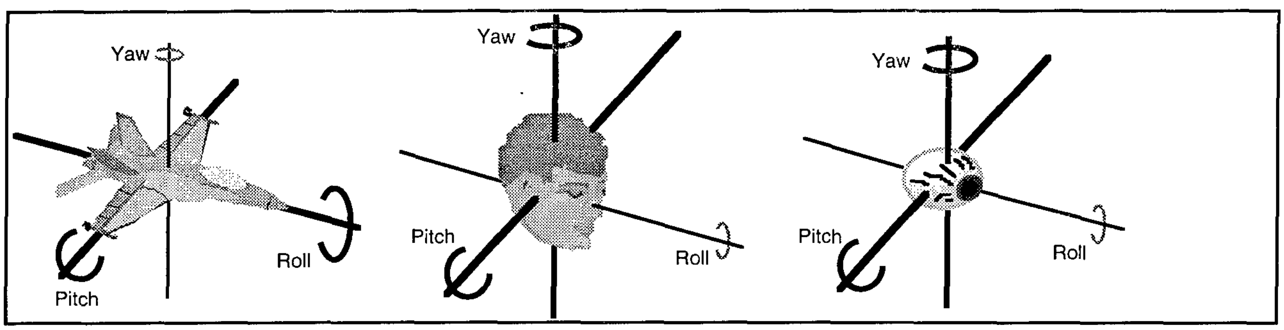


Figure 2.1. *Major Axes of Motion for Aircraft, Human Head and Human Eye. Primary Axes are annotated by heavier lines.*

If one compares the human's *terra firma*-based visual system orientation with motion while in an aircraft, there are obvious differences in the orientation planes (Figure 2.1). Voluntary muscular control of the eyes has certain limitations. First, the eyes cannot be translated in any Cartesian direction (X, Y or Z). Of the remaining three degree's of freedom, only two are voluntary: pitch and yaw. While the eyes do rotate in the roll axis, it is a reflexive response to a tilt of the head (rotational nystagmus), and not under normal voluntary control. Balliet and Nakayama (1973) have shown, however, that subjects can be trained with visual feedback to develop voluntary conjugate torsion. Table 2.2 gives the average range of eye motion for a young person (sex unspecified). The primary position of the eye has been defined by Howard (1982) as "the direction of gaze with head in an erect posture and visual axis horizontal and perpendicular to the inter-ocular axis." It is clear the eyes have a substantially greater range of motion in both the pitch and yaw planes than in the roll plane.

Table 2.2. *Range of Voluntary Movement of the Eye. (Sources: *Howard, 1982; ** Crone, 1975 ; ***Howard and Templeton, 1964)*

EYE MOVEMENT	ROTATIONAL EQUIVALENT	RANGE FROM PRIMARY POSITION DEGREES (°)
Depression	Pitch (Downward)	45-50 *
Elevation	Pitch (Upward)	40-45 *
Adduction/Abduction	Yaw	45-50 *
Torsion	Roll	8 * 6 ** 1-3 ***

Similar to eye motion, supplemental control of the visual system via movement of the head is also much greater in the pitch and yaw planes of rotation than the roll axis. Table 2.3 lists the

Table 2.3 *Range of Voluntary Motion at the Joint of Neck for Male Civilians (Source: Woodson, Tillman and Tillman, Human Factors Design Handbook, 2nd Ed., 1992)*

HEAD MOVEMENT	ROTATIONAL EQUIVALENT	RANGE OF MOTION (DEGREES)	
		AVERAGE	STANDARD DEV
Ventral Flexion	Pitch (Downward)	60	12
Dorsal flexion	Pitch (Upward)	61	27
Latero-flexion (Right or left flexion)	Roll	41	7
Right or left rotation	Yaw	79	14

average ranges of motion for the male human head. These values suggest the human visual system is intended to function primarily in the pitch and yaw planes. This allows human's to look up or down and scan across a horizon.

In direct contrast to head and eye motion are the planes of motion for an aircraft. The aircraft is controlled by affecting its pitch, yaw and roll axes. But, unlike a car or boat, pitch and *roll* are the primary axes of *aircraft* motion. Recall that pitch and *yaw* are primary for the human head. To make a heading change, a pilot will bank (roll) the aircraft for a period of time and then level the wings. During the turning procedure, the pilot's body is placed in an orientation and under forces it is not uniquely adapted to handle--that of a tilt or roll at forces which are greater than 1g. It should be clear now, that the human visual and vestibular systems are relatively incompatible with flight.

While moving on the ground, persons will also avoid rotating the visual scene. Humans will voluntarily rotate their heads in the pitch and yaw axes during motion (walking, driving, etc.), but will not typically rotate the head in the roll axis. For example, walking with a tilted head is typically felt as foreign or uncomfortable. Since the human visual system is dependent upon sensing the visual vertical, the visual horizontal, and resolving gravitational forces, voluntary rotation of the head in the roll axis is not a desirable behavior since it disrupts *all* three inputs to the internal equation for stability.

2.3 Research into Head Alignment and Motion of Environment

2.3.1 Non-Flight Related Research

Past research has been accomplished in the area of studying head tilt as the result of modifying the external environment, but little has been mentioned about these effects as applied directly to the flying environment. Held, Dichgans and Bauer (1975) found that subjects who observed a large disk of random dots rotating at a constant rate around their line of sight had the sensation of moving in the opposite direction often tilting in the opposite direction. Young, Oman, and Dichgans (1975) replicated the above study using a full-field simulator dome with random rectangles projected on a white background. Again, the subjects sensed an illusory self-tilt resulting in a tilt of their body opposite to the rotation direction of the visual display. This reflex was labeled the *pseudovestibulo collic reflex*. Both experiments above involved subjects passively observing a continuously rotating field of randomly placed objects. This visual scene did not provide a unique visual stimulus (i.e., a horizon) for the subjects to maintain or fixate in their field of view. Since the scene lacked a unique stimulus, the subject did not have an external frame of reference - a concept which will be discussed later in this section.

Merker and Held (1981) studied the effect of head tilt angle and a rotating visual field on the amplitude of optical torsion (rotation of the eye about the visual axis). The study concluded that the torsion varied directly as a function of head tilt, but was not affected by the visual field rotation. The subjects' various head tilts were fixed via a bite bar. Day and Wade (1966) found during head tilt, the apparent vertical (the subject's estimate of what they feel is vertical) deviates in the direction opposite the head tilt. Wade and Day (1968) also found the after-effect of head tilt (2-3 minutes) resulted in judgment of the visual vertical to be displaced in the direction of the previous head tilt. Yang and Pei (1991) concluded, from *space* motion sickness studies, that head motion coincident in direction with a rotating visual field reduces motion sickness symptoms.

2.3.2 Flight Related Research: The Optokinetic Cervical Reflex (OKCR)

Studies using head and aircraft position data from simulator flights have been recently completed. Results from Patterson (1995) have shown a significant correlation between head tilt angle and aircraft bank or roll angle during simulated flights in a dome simulator. The study has shown pilots tend to tilt their head from the aircraft's longitudinal (z) axis during flight under Visual Meteorological Conditions (VMC) - when the pilot uses external environment cues (horizon, land features, sun) - to maintain stable flight. However, during Instrument Meteorological Conditions (IMC), when the pilot is restricted to using only the aircraft instruments (i.e. attitude and heading indicators), the reflexive head tilt response is not evident. Patterson has suggested the name: Optokinetic Cervical Reflex (OKCR) to describe the physiological response. From Patterson's data, Figure 2.2 shows head tilt as a response to angle of aircraft bank during VFR conditions. The reflex appears to have a linear component which asymptotically levels off at approximately 15 to 20° of head tilt at aircraft bank angles greater than 40°.

Further work by Smith (1994) in an aircraft simulator supports the proposed correlation of head tilt with aircraft roll. In addition, Smith found that pilots who participated as passive observers during low-level flights flown by auto-pilot (a task such as a navigator) also exhibited the head tilt during aircraft banks. During the passive task, pilots were tasked with verifying navigational waypoints and watching for birds and other aircraft. The OKCR induced during passive observation appeared to have a quicker onset rate than the OKCR seen during active flight control. In both the Patterson and Smith studies, the simulators were fixed-based and provided no simulated motion to the operator.

Subjective analysis of videos or photographs of operators in high-speed vehicles (aircraft, racing motorcycle, bobsled) support the proposition that the human controller of the vehicle will attempt to maintain an "eyes-level" retinal image of the visible horizon during vehicular roll or pitch. What is interesting to note is the effect manifests itself upon the human operator or controller but not necessarily upon passengers who are not concerned with the continuous task of controlling the vehicle's position and maintaining spatial orientation. For example, the Olympic bobsled team is composed of two or four persons seated in a single column (front to back) in a narrow sled. Only the forward team members, the drivers, are observed tilting their heads in the opposite direction of the sled's roll angle during the turns. Figure 2.3 shows a two-person team in a banked turn. The driver's head is tilted to the right during what is equivalent to a counter-clockwise roll of the sled. In contrast, the other bobsledder's head appears to be looking down the axis of the sled. Similar effects can be seen in two-seat fighter aircraft as well as in multi-person crews in larger jets (Patterson, 1989). For example, in a multi-seat aircraft the forward

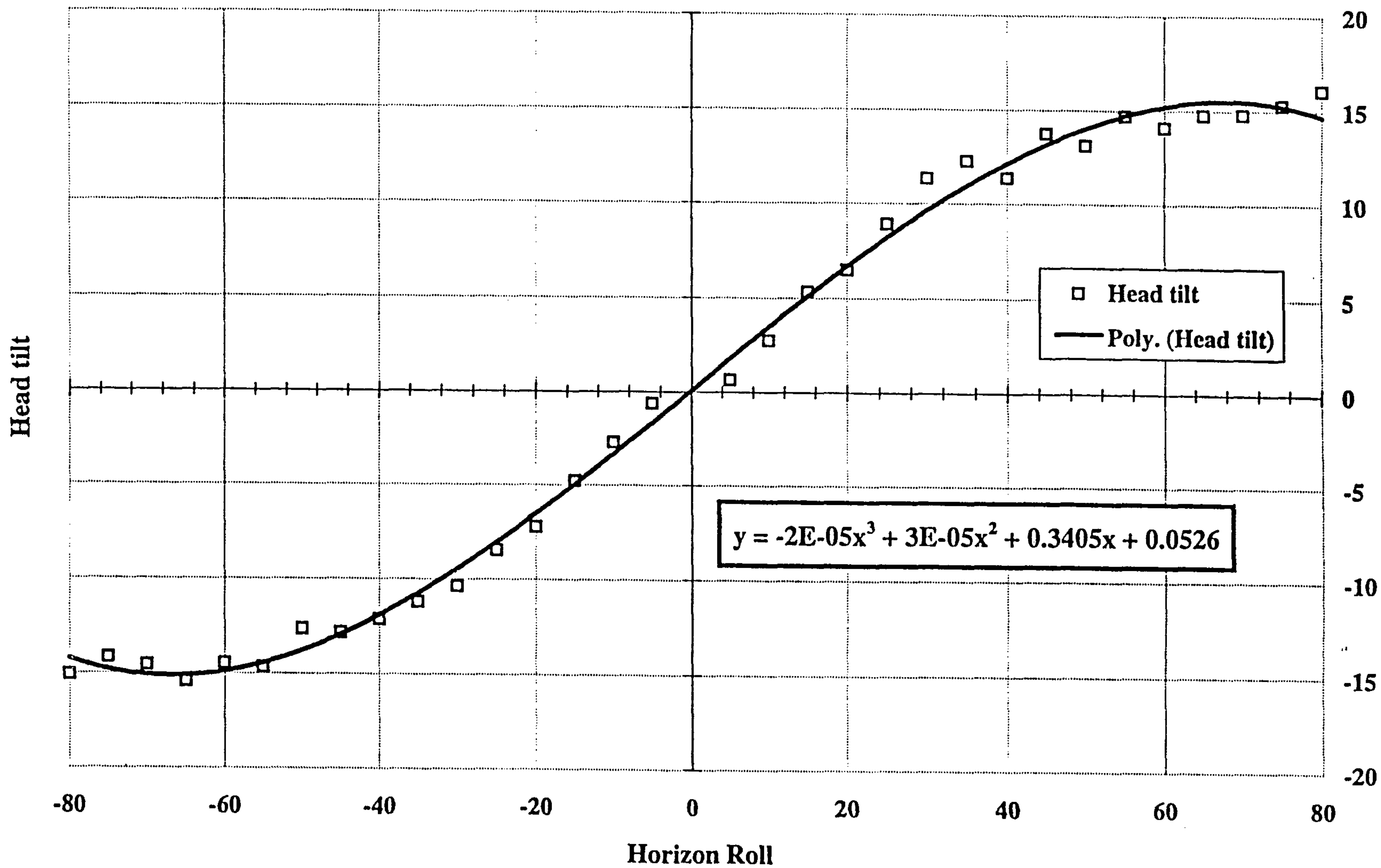


Figure 2.2. Flight Simulator data results: *Pilot Head Tilt as a function of Aircraft Bank Angle* (Patterson, 1995).

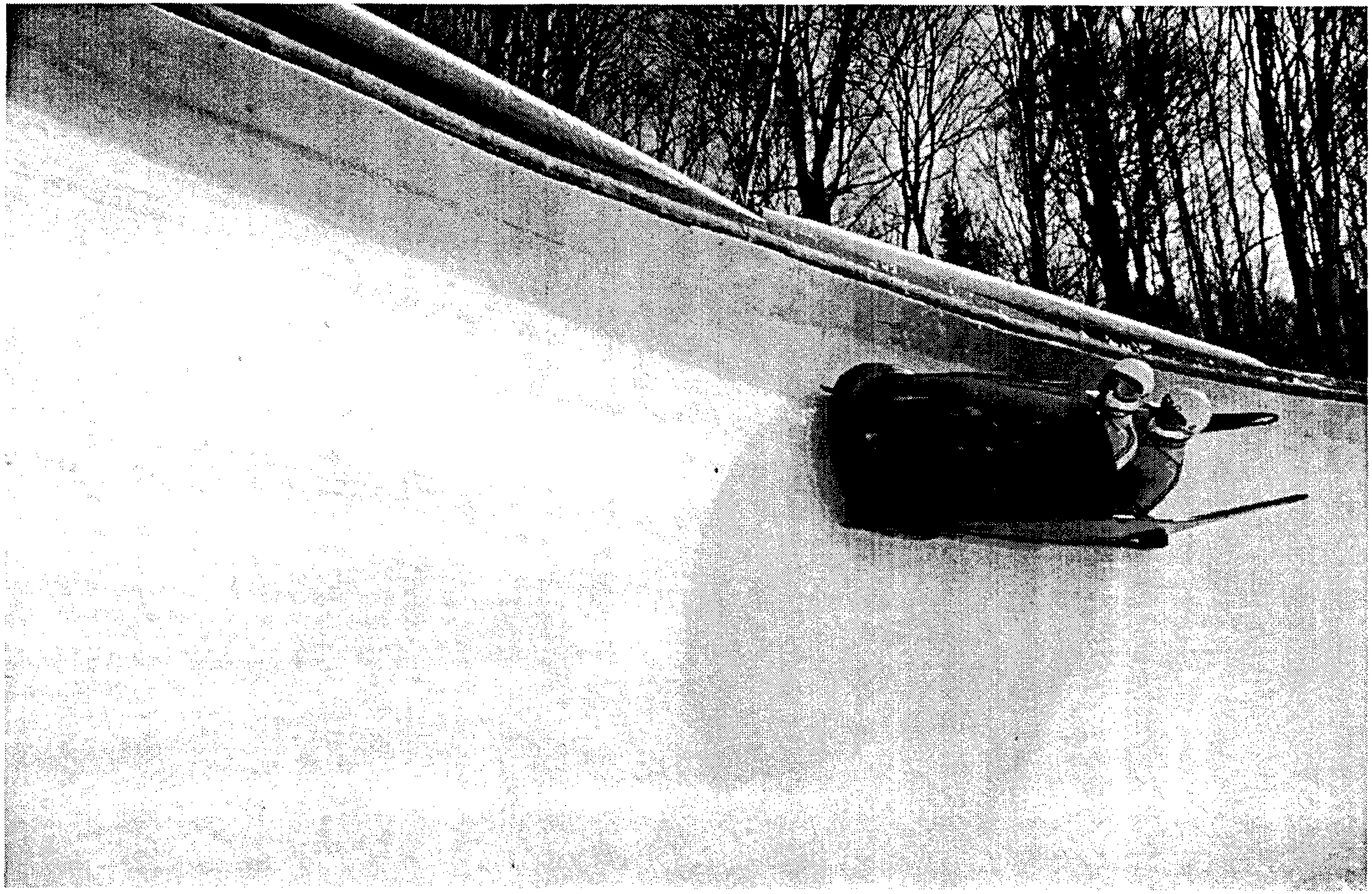


Figure 2.3. *Opto-kinetic cervico reflex (OKCR) exhibited by driver of a two-person bobseld team* (bobsled image: Viesti Associates, Inc.)

person is usually the pilot, the "backseater" may be a navigator or an electronic warfare officer (EWO). It is hypothesized that the OKCR would be more evident in the pilot and navigator than the EWO since both the pilot and navigator would be tasked with maintaining spatial awareness while the EWO would be more concerned with operating the various cockpit displays and less cognizant of the specific, second-to-second details of maintaining spatial awareness. This occurrence seems to suggest the OKCR is a specialized response; a result of a combination of visual, kinetic and cognitive task attention inputs to the human system.

2.3.3 Comparison of the Optokinetic Cervical Reflex to the Pseudovestibular Collic Reflex

Initially the results (the pseudovestibulo collic reflex, PVCR) from Held, Dichgans and Bauer (1975) and also Young, Oman, and Dichgans (1975) seem to conflict with those of Patterson (1995) and Smith (1994) who determined that the subjects will tilt their heads, as a result of the OKCR, *with* the rotating environment (the rotating horizon image viewed through the cockpit) and not opposite it (Table 2.4). This may first be explained by the fact that both Patterson and Smith used a simulated visual flight environment whereas the earlier studies used a visual display composed of random objects (no unique visual components) which rotated at constant and continuous rates. Secondly, Held, *et al.* (1975) found the tilt effect to depend on size of visual image and *peripheral* stimuli more than central stimuli. In comparison, the OKCR appears to result from foveal pursuit eye movements which are an attempt to maintain a stable retinal image of the horizon (Patterson, 1995). Finally, during simulated flight the subjects consciously perceive themselves as actually moving (flying) through a virtual environment. However, in the studies of Held, *et al.* (1975) and Young, *et al.* (1975) the subjects were not instructed to "fly" an aircraft, only to observe the visual scene.

In the literature Young, *et al.* (1975) assumed that pilots keep their heads vertically aligned in the aircraft during roll maneuvers, and therefore would see a rotating external visual environment. Having made that incorrect assumption, Young, *et al.* applied their laboratory findings to the flight environment by suggesting that having pilots maintain an erect head position and slow visual velocities during constant velocity flight would minimize the illusory self-inclination. In light of the optokinetic cervical reflex, the suggested recommendation for maintaining erect head position may be counter-productive to the apparently natural response of the human visual and vestibular system manifested in the OKCR. The pseudovestibulo collic reflex seems to occur only under the conditions that Young, *et al.* established in laboratory, but is not transferable to the cockpit. Since the pseudovestibulo collic reflex is does not involve true motion, the reflex should be considered an illusion since it is actually an illusory sensation of self-motion.

2.4 Simulated Flight Versus Actual Flight

The OKCR is a reflex which appears to have a strong visual component and is evoked primarily by visual stimuli more than vestibular or kinesthetic stimuli. Work by Patterson (1994) and Smith (1994) has shown that the OKCR can be produced in subjects flying "aircraft" in realistic dome simulators with the only sensory cues being a full 180° virtual visual environment which obviously lacks the robustness of vestibular, kinesthetic and auditory sensory inputs found during actual flight. Jacobs and Roscoe (1980) mention, however, that during flight there are few side forces since resultant gravitational and centripetal force during properly coordinated turns result in forces perpendicular to the pilot's seat and cabin floor (i.e., Gz forces). Therefore, the use of non-motion simulators is predicted to be adequate for flight simulation. Currently, no investigations have focused on which reflexes, if any, occur during actual flight. No objective data is available which documents the effect of both *true visual and physical* forces on the optokinetic cervical reflex.

Table 2.4 *Comparison of the Optokinetic Cervical Reflex to the Pseudovestibulo Collic Reflex*

Comparison of OKCR to the Pseudovestibulo Collic Reflex	
Optokinetic Cervical Reflex Patterson (1995), Smith (1994)	**Pseudovestibulo Collic Reflex** Held, *et al* (1975), Young, *et al* (1975)
Head tilts **with** the visual scene	Head tilts **opposite** the visual scene
Rich Visual Flight Environment with **unique visual features**	Large visual display composed of **randomly** placed imagery, rotating at a constant rate
Stimulated by **foveal** pursuit to maintain a stable retinal image of a fixed visual stimulus	**Peripherally** stimulated
Subject is in "**motion**" (in a virtual environment)	Subject is **stationary**
Subject is **cognizant of "flying"**	Subject does **not** perceive that they are in self-motion
Occurs during flight	Does **not** occur during flight

2.5 Displays

2.5.1 Displays and Spatial Disorientation

Displays exist to provide information to the user or operator. The information must be presented in a format which allows the human to model the system they are in. Poorly designed displays will, at a minimum, usually result in limited or reduced benefit; worst case, a poor design could elicit degraded and even hazardous performance depending on the type of activity. The aircraft attitude indicator is meant to provide the pilot representational information about the aircraft's orientation in two of the three most *critical* parameters to describe the aircraft position in three-dimensional space: roll and pitch (the third being altitude).

During flight, the pilot must be aware, at least subconsciously, where the aircraft is in relation to the terrain. This is referred to as maintaining spatial orientation. If a pilot fails to comprehend the aircraft's current position (or attitude) relative to the ground, that pilot has become spatially disoriented. When disorientation occurs, the first crucial step is recognition of the situation from which a precise, and usually rapid, control response is required for recovery to a stable attitude. Much of the time, the pilot must reconcile potentially conflicting information from their visual and vestibular sensory input and the cockpit attitude-related displays. If the pilot does not recognize the spatial disorientation (SD) or misinterprets the necessary control response, the results could be collision with other aircraft (while in close formation), collision with the ground, or stalling the plane. There are two main categories of SD: Type I: the pilot does not recognize the spatial disorientation; Type II: the pilot recognizes he or she is spatially disoriented. It has been estimated that SD has contributed to approximately 15 percent of recent annual military aviation mishaps (Kitfield, 1989). Gillingham (1992) has even suggested SD is the cause of two or three times as many USAF aircraft mishaps than are actually statistically recorded as SD influenced.

Patterson (1995) and Smith (1994) have both compiled a recent review of spatial disorientation issues as applied to aircraft and pilots (US military and civilian). Their research into the recently documented optokinetic cervical reflex (Patterson, 1994) raises serious questions about current design assumptions for aircraft attitude displays. In particular, the presupposition that a pilot maintains a vertical posture (head and body) in the cockpit throughout all flight maneuvers has been proven to be incorrect based upon simulated flight analysis.

2.5.2 Standard Attitude Display Formats

Although the virtues and drawbacks of the two common conventions for flight attitude displays have been discussed at length in previous investigations and research of the last fifty years, it is necessary to revisit the basic premises of display design, especially with regards to recent knowledge about the OKCR.

As previously mentioned, the attitude indicator is meant to provide the pilot representational information about the aircraft's orientation. A representational display consists of elements whose change in characteristics (position, size, etc.) against a background reflect changes in conditions of the modeled system (Sanders and McCormick, 1993). Traditionally, there have been two schools of thought with regards to attitude information displays. Both groups felt a pilot would be best served by showing a representation of the horizon behind that of an aircraft. Where there was controversy was deciding whether the aircraft should move against a fixed horizon, or the horizon should move behind a fixed aircraft.

The industrialized nations of the Western hemisphere have used what is termed the "moving horizon, fixed aircraft" symbology; whereas in the Eastern hemisphere (primarily the former USSR) the preferred design was a "moving aircraft, fixed horizon." Figure 2.4 shows an example of each type of attitude display and a list of additional nomenclature for each type of display (Johnson and Roscoe, 1972). Roscoe, Johnson, and Williges (1980) have suggested the pilot's "frame of reference" is a determining factor for which display format is preferable. If the pilot comprehends the display representing the aircraft moving against the external world then a moving aircraft display would be appropriate. But, if the pilot uses the display to represent the external world moving relative to the flying aircraft, then a moving-horizon attitude display is called for.

2.5.3 Compatibility of Control

It is desirable to have compatibility between the system's control motion and the display which would represent the effect of such a control action. For example, if a person pushed the "up" arrow on a keyboard, they would expect the cursor to move "up" on the screen--motion compatibility. In this simple example, the user's frame of reference is relatively obvious, but the frame of reference for a pilot is more complex. Depending on which convention is used, the moving element on an attitude display may be the horizon or the aircraft symbol. For a given control action (i.e. bank to the left), a moving-horizon would rotate clockwise while a moving-aircraft would rotate counter-clockwise. Table 2.5 compares the two attitude display types for an aircraft banking to the left. The moving-aircraft display clearly demonstrates compatibility of control. The aircraft is banked left; the aircraft attitude element is shown with left wing dipped below the horizon (it rotates left). To correct the attitude, the pilot would move the flight stick right and the display would respond with the aircraft element rotating right bringing the wings parallel to the horizon element.

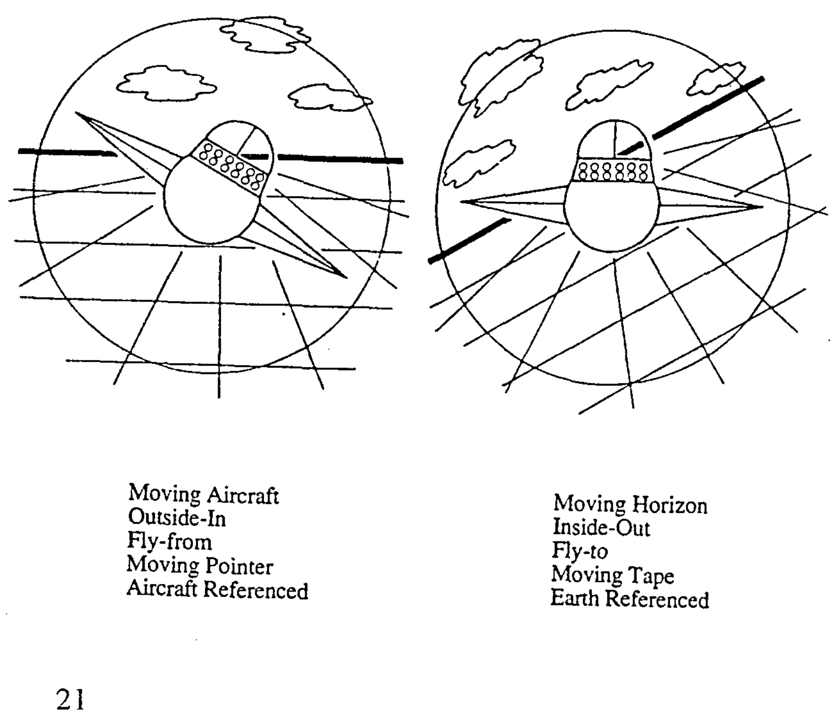
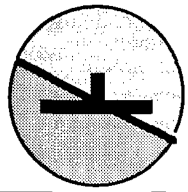
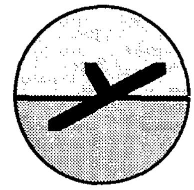


Figure 2.4. *Moving-Horizon and Moving-Aircraft Attitude Display References*

Table 2.5 *Comparison of Moving-Horizon and Moving-Aircraft Attitude Displays*

(Aircraft is banked to left)	***Moving-Horizon Display***	***Moving-Aircraft Display***
Graphical Representation		
Horizon Element Motion	Horizon Symbol rolls **clockwise**	**Fixed** with respect to cockpit
Aircraft Element Motion	**Fixed** with respect to cockpit	Aircraft symbol rolls **counterclockwise**
Stick motion to correct attitude (i.e. level the wings with horizon)	Move stick to **right** - in **same** direction as moving element (horizon)	Move stick to **right** - in **opposite** direction as moving element (aircraft)
Required motion of moving element to indicate "wings level"	Horizon symbol must rotate back to the **left** (counterclockwise)	Aircraft symbol must rotate back to the **right** (clockwise)
Control Compatibility?	NO	YES
Does display match the forward view with head vertical in cockpit?	YES	NO

Motion compatibility in an aircraft attitude display is especially important during critical phases of flight when immediate control decisions are required. One such instance occurs when the pilot suddenly loses the external frame of reference or visual environment. Three examples when this can present itself as a problem are: (1) flying into cloud cover or haze, (2) breaking away from a lead aircraft during close formation flight, and (3) recovering from gradual entry into an unusual or unexpected attitude. When the external stimuli, which had been providing spatial orientation information, instantly disappear, the pilot must enter instrument flight rules (IFR) flight and use the cockpit displays (primarily the attitude indicator) to determine the aircraft's orientation. If the pilot incorrectly attributes the motion of the horizon element (in the moving-horizon format) to the motion of the real aircraft's wings, then the pilot-reflexive stick control input to "level the wings" will result in the opposite effect: the aircraft will bank (or pitch) further from "wings level." This has been termed "reversal error" and has been documented by Fitts and Jones (1947) and further by Johnson and Roscoe (1972). Roscoe, *et al* (1980) has stated that "in *routine* maneuvers pilots have little trouble with the moving horizon," but that when quick, accurate responses are demanded, the elements which respond directly to the pilot's control should move in the expected direction. This is *not* an attribute of the moving horizon type display, it is however an attribute of the *moving aircraft* format.

2.5.4 Alternative Attitude Displays

In an effort to compensate for the apparent inadequacies of both the moving-horizon and moving-aircraft displays, Fogel (1959) devised a frequency-separated display called the "kinalog" display. Since the vestibular and proprioceptor system respond to accelerations only, Fogel determined during that phase of flight (when a maneuver is initiated and the body receives the effect of acceleration) the display should be different from one during a steady turn. During a bank to the left, the attitude display would initially be a moving-aircraft type (the aircraft element rotates left, counterclockwise). Once the aircraft assumes a steady angle of bank, both the horizon and aircraft elements would rotate right (clockwise) until the aircraft element was parallel to the real aircraft's wings; a moving-horizon type display. Roscoe and Williges (1975) found subjects were less susceptible to reversal errors while using the frequency-separated display than the moving-horizon display. The moving-aircraft display produced fewer reversal errors, but Rosoe and Williges showed during simulated disturbed-attitude tracking, the moving-aircraft display was inferior to the frequency separated type.

2.6 Case Study: Helmet Mounted Displays (HMD)

2.6.1 Helmet Mounted Display Systems

The concept of placing dynamic information which remains within the pilot's visual field-of-view (FOV) regardless of head orientation is not a novel one. In fact, simple helmet-mounted sights have been flown by the Air Force and Navy as early as 1969 on F-4B, F-101 and F-106B aircraft. A helmet-mounted tracker and helmet mounted display used in combination are classified as visually coupled systems (VCS). Visually coupled systems entail two major functions: a *display function* whereby information is displayed to the operator, and a *control function* derived from the operator's head motion and line-of-sight direction. For a fully interactive visually coupled system, both control input and display feedback are necessary. Helmet-mounted displays (HMDs) may be monocular, biocular or binocular; color or monochrome.

There are two general types of HMDs: see-through environment and opaque environment. Most HMDs project a display against the existing environment, similar to the head-up display (HUD). A helmet-mounted cueing system (HMCS) is an example of this "see through" HMD, where symbology is overlayed on the environment scene. The other type of HMD displays are projected upon an opaque background which blocks the true external environment from the user's eye(s). This type of opaque HMD is the type which is now commercially touted as "virtual reality." The total environment is created within the goggles, visor, etc. The user cannot physically see the real world outside, only the virtually created image.

The employment of helmet mounted displays in high-speed vehicles is more complex than placing a "miniature HUD in front of the eye" and letting the pilot fly. As helmet-mounted display (HMD) technology is poised to move from laboratories and test facilities into the cockpits of today's military aircraft and vehicles as well as "virtual reality" simulators, trainers and commercial market products, it is critical to focus investigations on the human-display interface unique to these systems. In particular, the question to be addressed is: which images and characters (the symbology) should be employed on the HMD during specific phases of activity and most importantly with regards to the operator's head orientation in the environment, be it real or "virtual." The possibility of complete elimination of the head-up display (HUD) with full replacement by HMD may be a trend in future military aircraft, thus placing further urgency on the design of a functional symbology approach.

2.6.2 The Spatial Frame of Reference

Frame of reference has been defined as "an attribute of a certain object which does not normally vary, and in terms of which variations of the same attribute in other objects perceived as more or less the same time may be judged." Howard (1982). For example, the floor and walls of a room are normally in the horizontal and vertical; the orientation of other objects (i.e., a bookshelf or a person) in the room are judged from the walls and floor. During self-motion, we take our environment as fixed and therefore attribute any image motion to our own eye, head and body motion. We do not assume that the room itself is moving. In an aircraft, a pilot has two frames of reference: (1) the outside environment including the Earth's horizon, the sun and cloud formations; and (2) the aircraft body, wings and cockpit. The environment gives the pilot a fixed stimulus from which to determine the aircraft's orientation. The aircraft structures give the pilot a fixed stimulus from which to determine his or her own orientation within the cockpit. The aircraft itself also acts as a reference for the various displays in the cockpit.

A crucial difference between HMDs and standard displays (including HUDs) is the concept of the reference frame. Traditional displays are usually secured to a fixed reference frame. In high-performance fighter aircraft, the head-down displays (HDD) and the HUD are fixed rigidly to the frame of the aircraft. For example: status lights, multi-purpose color display monitors, HUDs and standard attitude indicators--these displays are all fixed in the cockpit. Since they are fixed, this requires the human user to orient eyes, head and/or body to a correct position to effectively view the information presented. These displays were designed under the *assumption* that the operator will be in a particular orientation when viewing the display. Some displays have a narrow field-of-view (FOV). For example, the collimated image of the HUD on an F-18 has a four to five degree FOV in which the pilot must have their head if the complete symbology is to be visible (Smith, 1994).

If displayed information is presented to assist the human involved in a non-passive activity requiring visual attention (e.g., flying an aircraft, driving a car, or operating machinery) the action of viewing the display usually diverts the person's eyes from the primary environmental visual stimulus (in the examples above: air/ground or target, the road, the machine). These displays may also require repositioning of the head and body as well as adjustments in eye position and accommodation. It is during these instances of changing the body, head and eye positions between "outside" and "inside" scenes that opportunity for misinterpretation occurs, especially if many display checks are required in a small segment of time and the operator is under vestibular and physical stress. Furthermore, since the displays only model the actual environment, there are likely to be many mental calculations occurring in the operator's mind to correlate what they view in the real environment to what the display is communicating about the "system" and environment.

HMDs eliminate almost all of the problems of repositioning arising from displays located in fixed reference frames. Since HMDs are always presented to the eyes in an "upright" position or body-axis referenced, they can be seen at any time, against most any background, independent of head and body position. As will be shown, however, the fact that HMDs are not fixed to the aircraft frame results in unique issues specific to spatial disorientation.

If a pilot becomes disoriented during flight, it is standard procedure to perform what is known as a "cross-check." This cross-check involves scanning the cockpit displays from which the pilot can develop a spatial model of the aircraft's true situation (attitude + altitude + airspeed) based upon the instruments. This is predicated upon the fact that modern aircraft instruments are more reliable than the human visual and vestibular system. Finally, the pilot accomplishes a mental compare-and-contrast of the models to determine which orientation model seems most credible and takes a control action to correct the aircraft and bring it to a stable attitude.

Attitude information can be ordered based on its priority of importance during spatial disorientation (see Table 2.6). The least important is the aircraft heading; unless the pilot is concerned about flying over particular airspace, the aircraft's heading is not required to maintain stable flight. The pitch of the aircraft is critical information. A pitch of at least zero is required to prevent controlled flight-into-terrain (CFIT). Finally, aircraft bank (or roll) is the primary critical piece of information--necessary to level the wings. While pitch is critical, a correction in pitch cannot be made in the absence of knowing the aircraft's roll position. For example, pulling-back on the stick (increasing pitch angle) while the aircraft is fully inverted will result in an inverted dive towards the ground. Weintraub, Haines, and Randle (1984) have suggested a reasonable recovery technique: first, roll the aircraft into a non-inverted wings-parallel-to-the-horizon position, and then raise or lower nose as necessary.

Table 2.6 *Importance of attitude information for recovering from spatial disorientation*

Attitude Information	Order of Importance
Roll Angle	Highly Critical
Pitch Angle	Critical
Heading	Not Critical

The two primary visual stimuli in determining aircraft orientation are:

(1) the aircraft frame-fixed displays (ADI, HUD, Altimeter)

(2) outside visual environment (horizon, peripheral cues from wing tips)

The addition of a helmet-mounted attitude display adds another (and third) stimuli to the "cross-check" pattern. What differs in each display is the reference frame against which the information is read. The HMD "floats" and is referred only to the pilot's head. The coordination and correlation of this attitude information may be a source of confusion and possible spatial disorientation, especially during emergency or critical situations. Johnson and Roscoe (1972) recognized a shift in the figure-ground relationship occurs when the pilot's frame of reference is moved from an external, real-world stimulus to a small, abstract instrument representing that real world.

Particularly, the instrument panel or the actual dial face becomes the reference background for any moving display elements. This is important to HMD symbology design since the figure-ground relationship may be ambiguous when the "moving" and "fixed" symbology elements *both* move against the pilot's view of the external world.

2.6.3 Example of Model-Environment Reversal

Of all symbology presented on future helmet-mounted displays, the attitude indicator may be one of the most important. The example in Figure 2.5 shows a particular scenario viewed at two different pilot head angle of tilt. (Note that the monocular HMD [right eye] shows the same symbology in both diagrams). Symbology in scenario #1 above is correct in representing the actual environment when the pilot maintains head and body with aircraft axis and is looking forward through the windscreen. This is in agreement with Table 2.5. In contrast, if the pilot tilts his or her head in the opposite direction of the aircraft bank (i.e. a result of the optokinetic cervical reflex, OKCR), the pilot would see what is shown in scenario #2. This scenario exhibits major departures from the actual environment. First, the HMD aircraft symbol is shown to be parallel to the real horizon; second, the HMD horizon symbol is shown to be different from the actual horizon as well as a "mirror-image" of the actual aircraft wings in the peripheral view. The difference between the aircraft attitude indicator (and HUD) and that in the HMD is a matter of frame of reference. In the former, the display is fixed to the aircraft and is designed to be viewed with the head at 0°, whereas in the HMD the image is fixed to the pilot's head and is always projected at an assumed 0° head angle regardless of where the pilot's head is angled with respect to the aircraft.

2.6.4 Current Design Rationale for HMDs

A number of formats have been proposed for presenting attitude information specifically for helmet mounted display systems. In general, though, the basic premise for the attitude indicator display has not changed in over sixty years since Lt James H. Doolittle flew an airplane

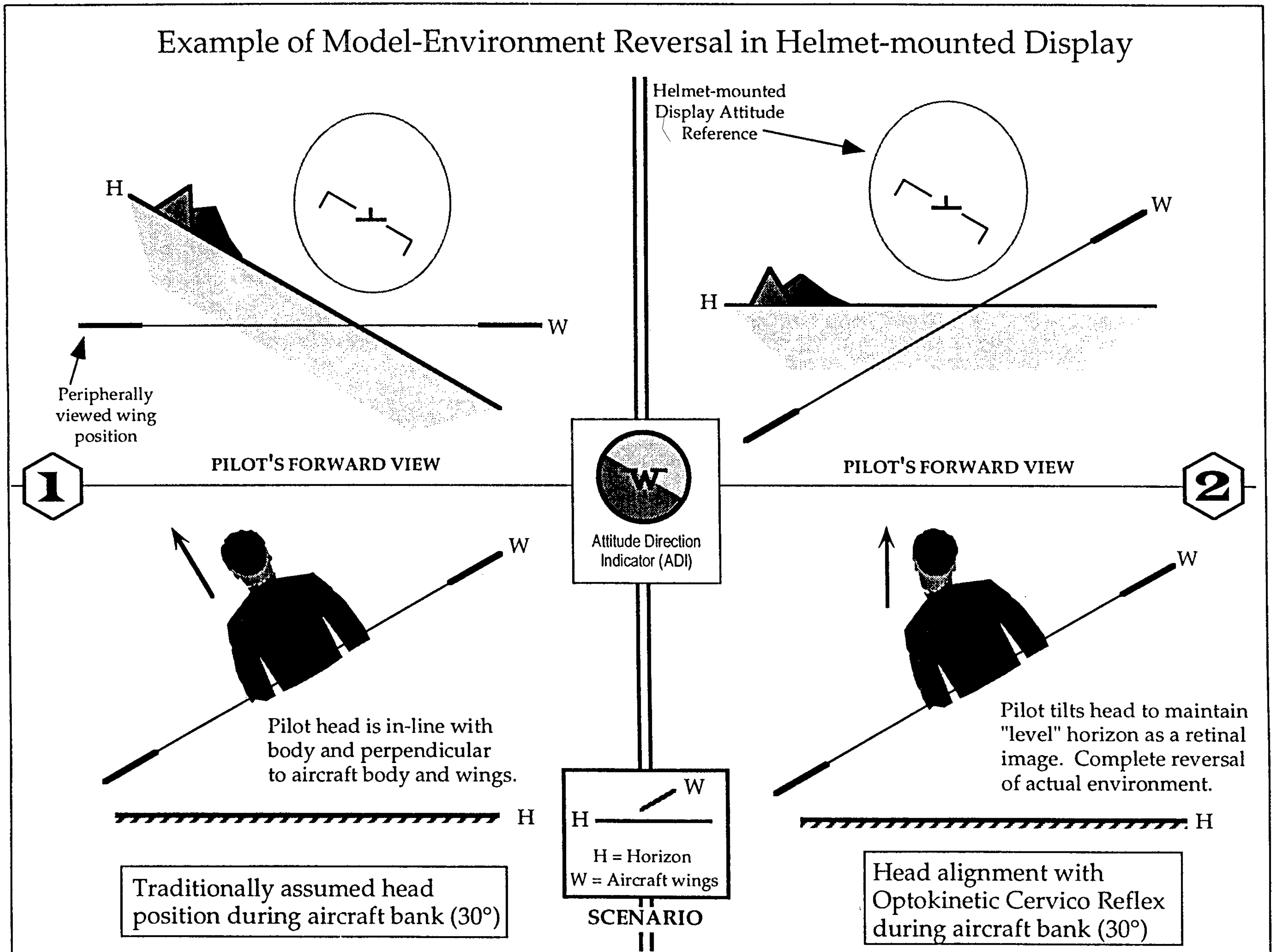
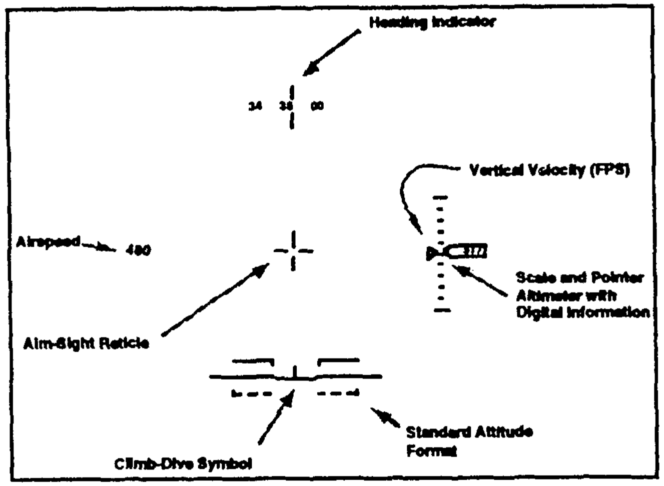


Figure 2.5. *Example of Model-Environment Reversal occuring when Helmet-mounted Displsy (HMDs) are combined with the Opto-kinetic Cervico Reflex (OKCR).*

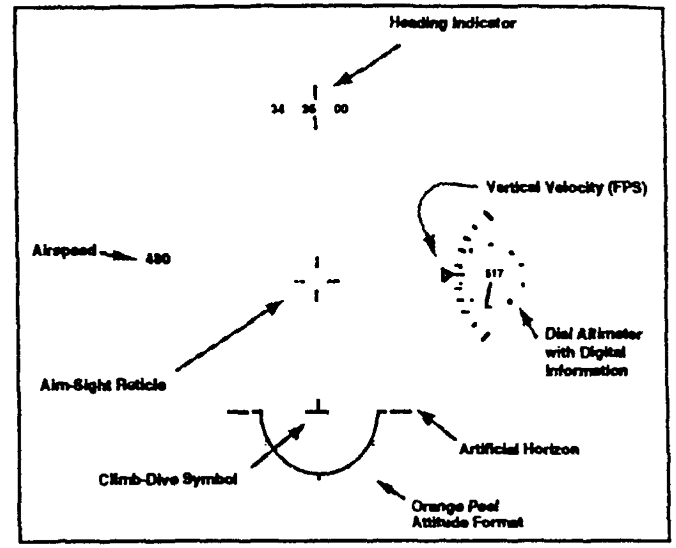
20 miles round-trip to the same landing spot using only instruments and no visual information from outside the cockpit. The attitude indicator used by Doolittle was the Sperry Horizon--he predecessor to the modern day artificial horizon display. The success of this "moving horizon, fixed aircraft" display was attributed to Poppen (1936) through his assumption that the display correctly models what the pilot sees when he or she looks forward, out of the cockpit. For this reason, the display type is also called an inside-out model. This rationale for the design of attitude displays has persisted since the early part of this century and that same "moving horizon" display concept was transferred from the instrument panel onto the HUD and is now being implemented on HMD symbology sets as well.

Geiselman and Osgood (1992, 1993) designed and evaluated candidate HMD symbol sets based on empirically derived principles of human information processing. The goal of which was determining the symbology forms and features conveying the intended information most efficiently. The study involved a standard format, the "orange peel" format, and the "theta ADI" format (see Figure 2.6). The simulator results of the research found significantly fewer ground strikes (aircraft impact into terrain) with the orange peel and theta ADI formats than the standard attitude representation. In the flight-path maintenance with computer generated disturbances portion of the study, the theta format was found to be significantly superior to the standard format. Graphical analysis of the results also indicate the possibility that subjects experienced more difficulty in stabilizing disturbances in the *roll* plane than in the pitch and heading planes. This effect was not expanded upon in the report. Each of the HMD attitude formats above presented the aircraft marker (climb/dive symbol) as fixed and level (with the pilot's head) at all times. All formats were therefore of the inside-out, or "moving-horizon" display type. In addition, current HMD systems (see Figure 2.7) use one of the three moving-horizon type formats for attitude information and reference.

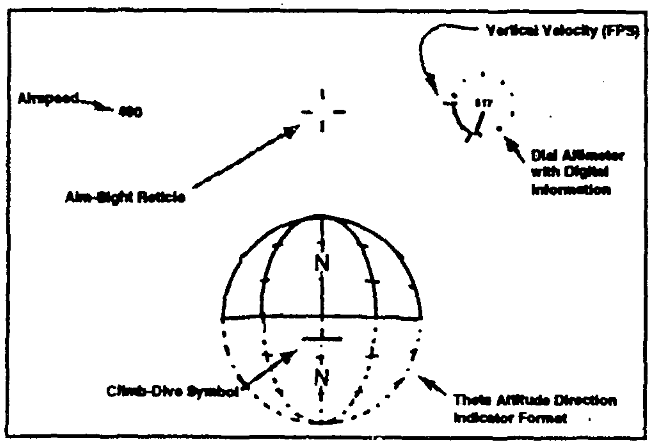
Jones, Abbott and Burley (1992) compared two HMD attitude displays: the traditional aircraft body-axis design and a conformal display, in full 360° flight simulators. The two symbology formats tested are shown in Figure 2.8. Both formats represent a pilot's “9 o'clock”



STANDARD FORMAT

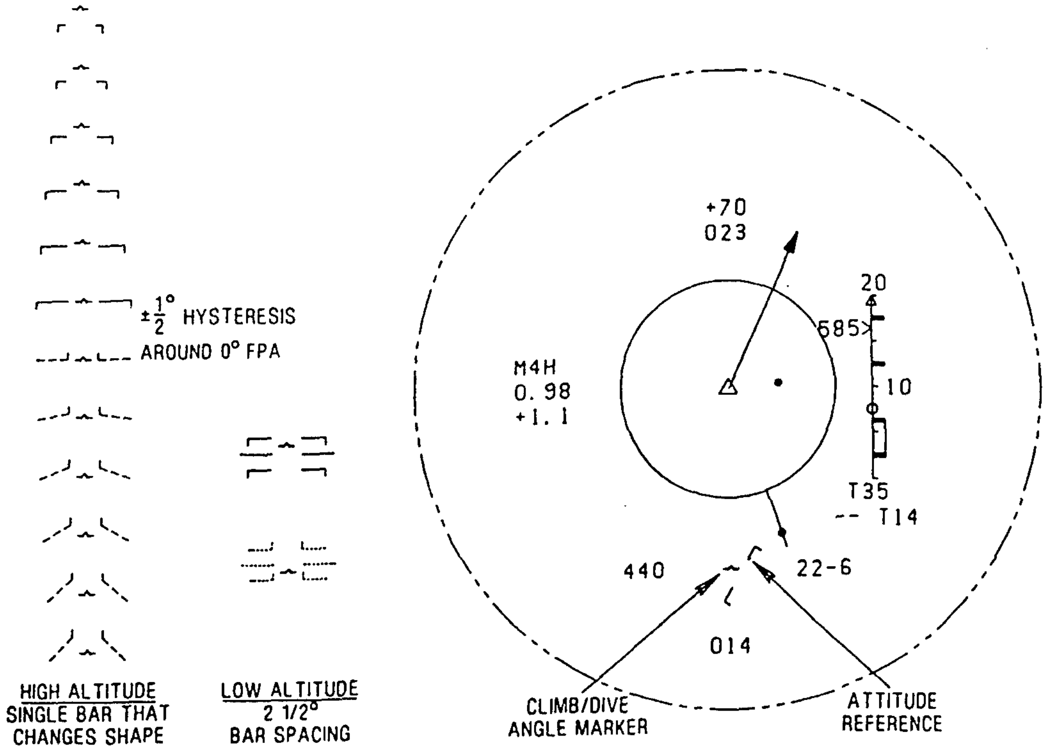


"ORANGE PEEL" FORMAT

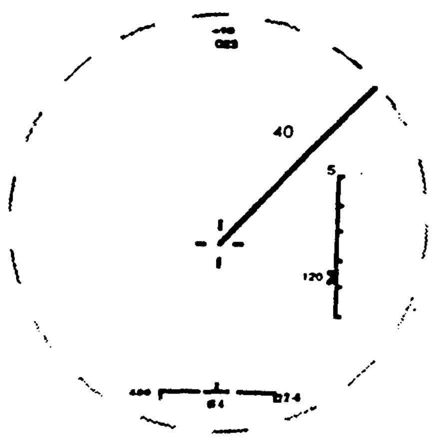


"THETA ADI" FORMAT

Figure 2.6. *Three Helmet-mounted Display attitude formats* (Geiselman and Osgood, 1992, 1993).

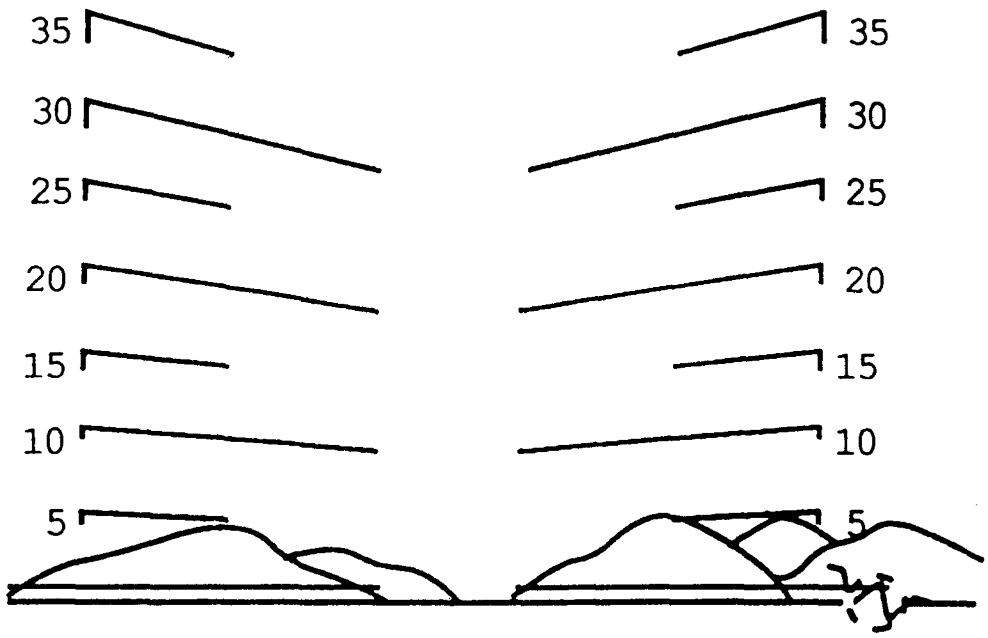


Vista Sabre II HMD Symbology (Source: US Air Force)

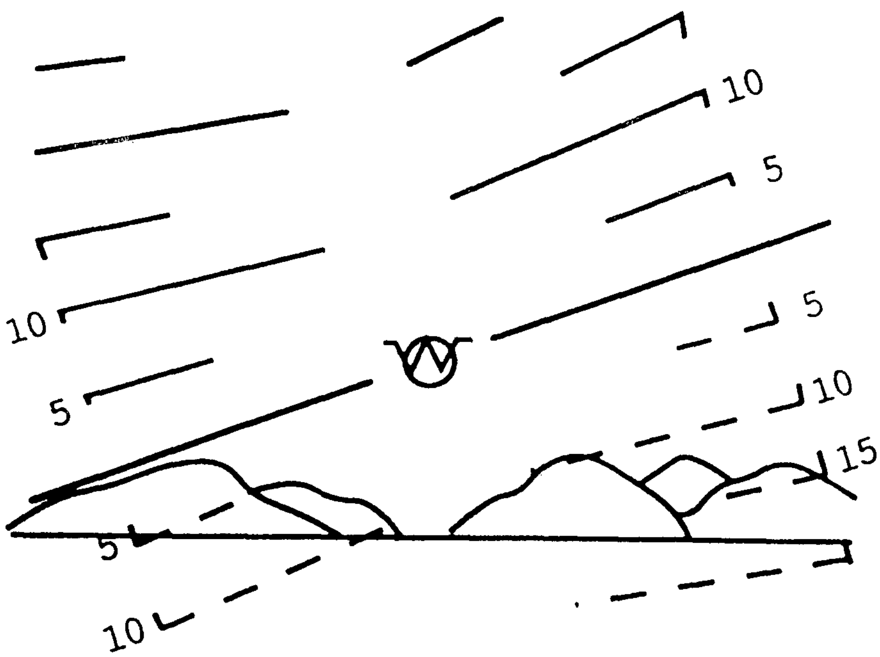


Elbit DASH HMD Symbology (Source: Elbit Corporation)

Figure 2.7. *Additional Helmet-mounted display attitude formats*



(a) Conformal display presentation.



(b) Body-axis display presentation.

Figure 2.8. *Conformal and Body-axis HMD Attitude Symbology* (Source: Jones, Abbott and Burley, 1992)

view (90° to the left) out the cockpit of an aircraft which is banked to the right at 20° of roll. Here again, the body-axis format assumed the traditional moving-horizon representation, but the conformal attitude display was obviously a moving-aircraft (fixed-horizon) type display (note the small, *rotated* symbol in the bottom, right-hand corner of the conformal display [below the right-hand "5-degree marker"]).

Jones, *et al* found the body-axis format was the more effective HMD attitude display since it resulted in fewer attitude estimation errors. The researchers also concluded from subjective results the body-axis display did not cause attitude confusion. The most interesting result applicable to the investigation of OKCR was the disparity between attitude estimation errors. Jones, *et al* found considerably more roll estimate errors than pitch estimate errors. In addition, the ratio of roll-to-pitch estimation errors for the body-axis format was 10:3 (over three times as many for roll than pitch), while for the conformal display this ratio was only 19:11 (less than twice as many for roll than pitch). What these results seem to suggest is there may have been an interaction effect between type of display and the specific component of spatial orientation (roll and pitch). It appears the conformal format was comparably better for resolving roll than for resolving pitch - which implies moving-aircraft representations may be superior for HMD-based aircraft roll resolution. Unfortunately, this point was not discussed in the paper.

As a final note, the results of the two HMD attitude reference studies further reinforce the fact the human system is less adept at resolving spatial orientation and reacting to changes in the *roll* plane than in the more natural pitch and heading planes of motion.

Recent debates on the subject of aircraft cockpit displays have suggested complete elimination of the HUD in favor of HMDs with superior field-of-view and optics. If HMDs do replace HUDs, an attitude display on the HMD will no longer be simply a reference but one of the *primary* sources for attitude information. This alone should be a prime driver for determining a safe and functional attitude display for HMDs.

For comparison, Figure 2.9 again shows the same scenario as shown in Figure 2.5 except that now the pilot in both right and left scenes has a head tilt based upon the predicted OKCR response. In addition, the left scene demonstrates the pilot's forward view while using a *moving-aircraft* (outside-in) type of HMD attitude reference. The model-environment reversal disappears when the moving-aircraft display is employed; the position of both display elements reflect the position of their counterparts in the real environment. At the heart of the moving horizon representation is the presupposition the pilot maintains head and body alignment with the aircraft (in the z-axis) during all maneuvers. For this reason, all attitude displays on the aircraft have been in a vertical, up-down orientation and placed centrally near the pilot's forward view of the cockpit instrument panel. Current studies (Patterson, 1995; Smith 1994) have shown this assumption is now incorrect for simulated flight. Further investigations need to be accomplished in aircraft to determine the extent of the optokinetic cervical reflex during actual flight. This study will provide a springboard for subsequent work required for the design of attitude displays which are representative of and compatible with aviation spatial orientation behavior.

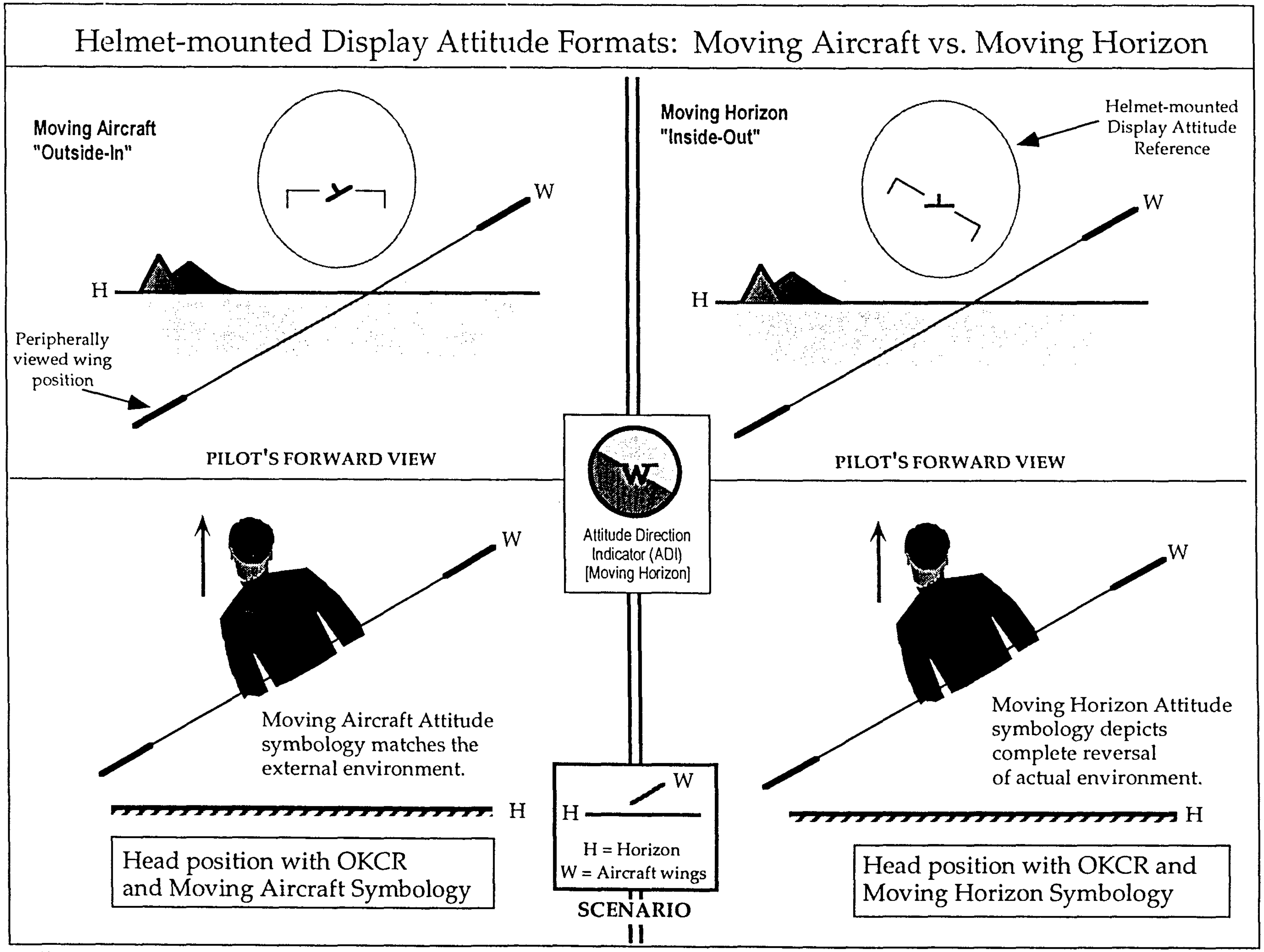


Figure 2.9. *Comparison of attitude display formats (Moving-horizon vs. Moving-aircraft) from HMD's when OKCR is exhibited*

3.0 DEVELOPMENT OF HYPOTHESIS

Based upon results from prior aircraft simulator studies, it is hypothesized that pilots of high-performance jet aircraft attempt to align their eyes with the horizon (when it is visible) to maintain a stabilized retinal image of important visual cues (i.e., the horizon). Pilots derive necessary orientation information from these visual cues, which reduce the occurrences of spatial disorientation (SD) and increases situation awareness (SA). This hypothesis is contrary to the prevalent assumption that pilots keep their heads aligned with the aircraft's Z-axis. Formally stated:

H_o: no head tilt observed

H_a: head tilt observed at all angles

Rejection of the null hypothesis will suggest pilots have a preferred head alignment with respect to the horizon. Furthermore, it is proposed head alignment will be dependent upon the phase state of aircraft bank. That is, whether the aircraft is entering a bank or returning to wings-level. This investigation will test these hypotheses via the collection of real-time pilot head and aircraft orientation data obtained from actual high-performance jet maneuvers.

4.0 METHOD

4.1 Subjects

The investigation required the voluntary participation of nine United States Air Force operational fighter test pilots stationed at Nellis Air Force Base, Nevada. Each pilot was male with six to twelve years experience flying high-performance fighter aircraft and were currently actively flying the F-15 aircraft. All pilots were instrument qualified. The pilots read and signed a consent form explaining all risks and benefits of the investigation. In addition, the pilots were advised the purpose of the study was to evaluate normal pilot reflexive actions during various phases of flight. This was a blind investigation and therefore the pilots were not briefed on the actual variables until the completion of the study. There was no remuneration for participation in the study. None of the pilots participated in or were aware of either the Smith (1994) or Patterson (1995) studies.

4.2 Equipment

The subjects piloted F-15C aircraft based at Nellis Air Force Base, Nevada. As this investigation involved actual (not simulated) flights in high-performance fighter aircraft, it was imperative non-invasive methods of data collection were employed. Two F-15 aircraft were equipped with Polhemus MAGNETRAK magnetic head tracker systems which allowed the collection of pilot's head motion parameters without interfering with the pilot's tasks. This satisfied the requirement for passive, non-invasive data collection techniques. The head tracker has a resolution of 0.088 degrees based upon 12-bit accuracy. Technical specifications on the Polhemus MAGNETRAK system are located in Appendix A. Coincidentally, the scenario in the OKCR simulator studies (Patterson, 1995; Smith 1994) was also the Nellis Air Force Base air ranges in which the subjects flew a *simulated* F-15 aircraft. Therefore this investigation matches the basic flight environment conditions of the previous work.

4.3 Experimental Design

This was an observational study and therefore no experimental task was designed. All data were collected from normal, day-to-day aircraft sorties and missions flown at a Nellis Air Force Base. All missions occurred during VMC (visual meteorological conditions) flight. These sorties and missions were not specific to this study. Pilot subjects flew sorties during which various maneuvers and engagements took place. Both aircraft position data and pilot head orientation data were simultaneously recorded via telemetry during the flights.

4.4 Data Collection Methods

The collection of data was a multi-step process involving (1) initial collection of raw data, (2) isolation of important events to be studied and (3) creation of data point subsets from initial raw data. See Figure 4.1.

① During the actual mission flown, pilot head orientation and aircraft dynamic parameters were continuously sent from the aircraft to ground stations via near-real-time electronic telemetry signals. These parameters were then stored as raw data on magnetic tapes for each pilot and mission. The data sampling rate was ~10 samples per second (or approximately one data point every 100 milliseconds). Typical missions were approximately 45 minutes and fit on one tape; longer missions required two tapes. Each tape contained approximately 150 megabytes of data.

② The raw data tapes were then used with a graphics workstation to playback the mission. The application on the workstation projected a three-dimensional (3-D) view of the ground and airspace showing all active aircraft on the flying range. The software allows the "observer" free movement of the point-of-view (POV) in three-space to observe the mission scenario from any vantage point (including a bird's-eye view). In addition, the observer can "attach" the POV to the tail of any aircraft in the scenario and

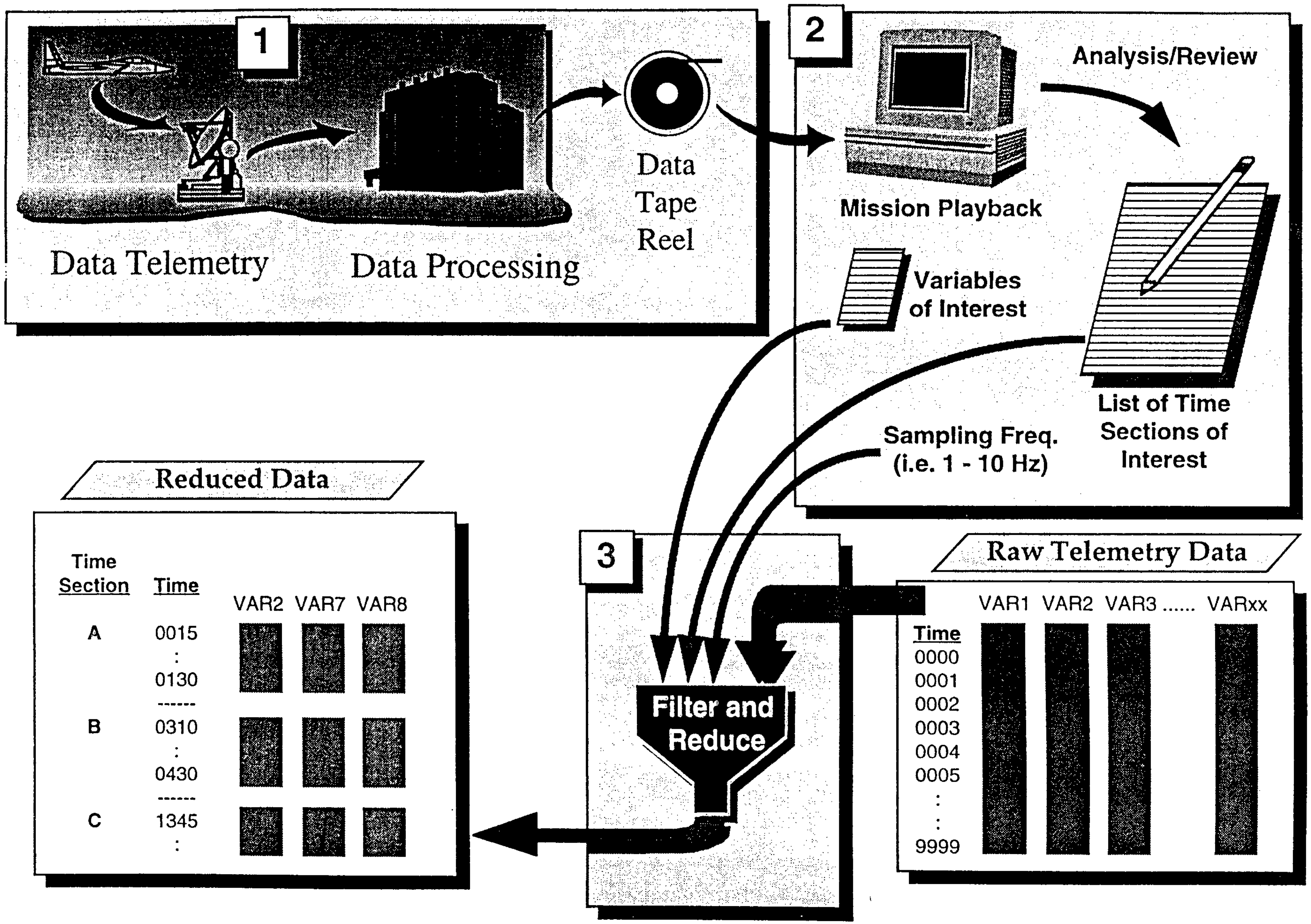


Figure 4.1. *Data Collection Process*

follow that aircraft throughout the mission essentially "viewing" what the pilot had seen from the cockpit.

In order to replicate, as closely as possible, the task conditions used by Patterson (1994) and Smith (1994) in their simulator studies, the investigator made all attempts to discard data during which the pilot was obviously engaged in active pursuit of another aircraft. The investigator studied the mission to isolate time periods during which the pilot had performed basic, simple flight maneuvers, preferably when the pilot was *not* engaged in a mode where the primary visual stimulus was another aircraft in the airspace. Since it was impossible to know where the pilot was looking in every instance, some of the time periods may have included part or all of an engagement. These time periods were recorded as a list for each pilot/mission.

③ Finally, the time intervals recorded in the second step were used in conjunction with data reduction techniques to create blocks of data for which only the independent and dependent aircraft and head orientation parameters of interest were retained.

4.5 Analysis Methods

Preliminary analysis was accomplished via numerous plots of the raw data to examine the data for any graphical trends and possible dependent variables. The initial candidate to determine factor effects was the two-factor repeated measures ANOVA.

The dependent variable, ROLL, was the pilot head tilt angle as measured from body vertical; a negative ROLL values corresponded to a lateral flexion tilt to the left (Figure 4.2). The two independent variables were BANK and PHASE. BANK was the aircraft angle of bank with respect to the Earth's horizon; negative BANK values correspond to a left aircraft bank (Figure 4.2). The second independent variable, PHASE, was a qualitative variable with two values: INTO and OUT_OF. To investigate if subjects' head tilt response may have been dependent upon the phase of the aircraft turn, the data was divided into two categories: head tilt while

Note: in both figures the object is facing out of the page

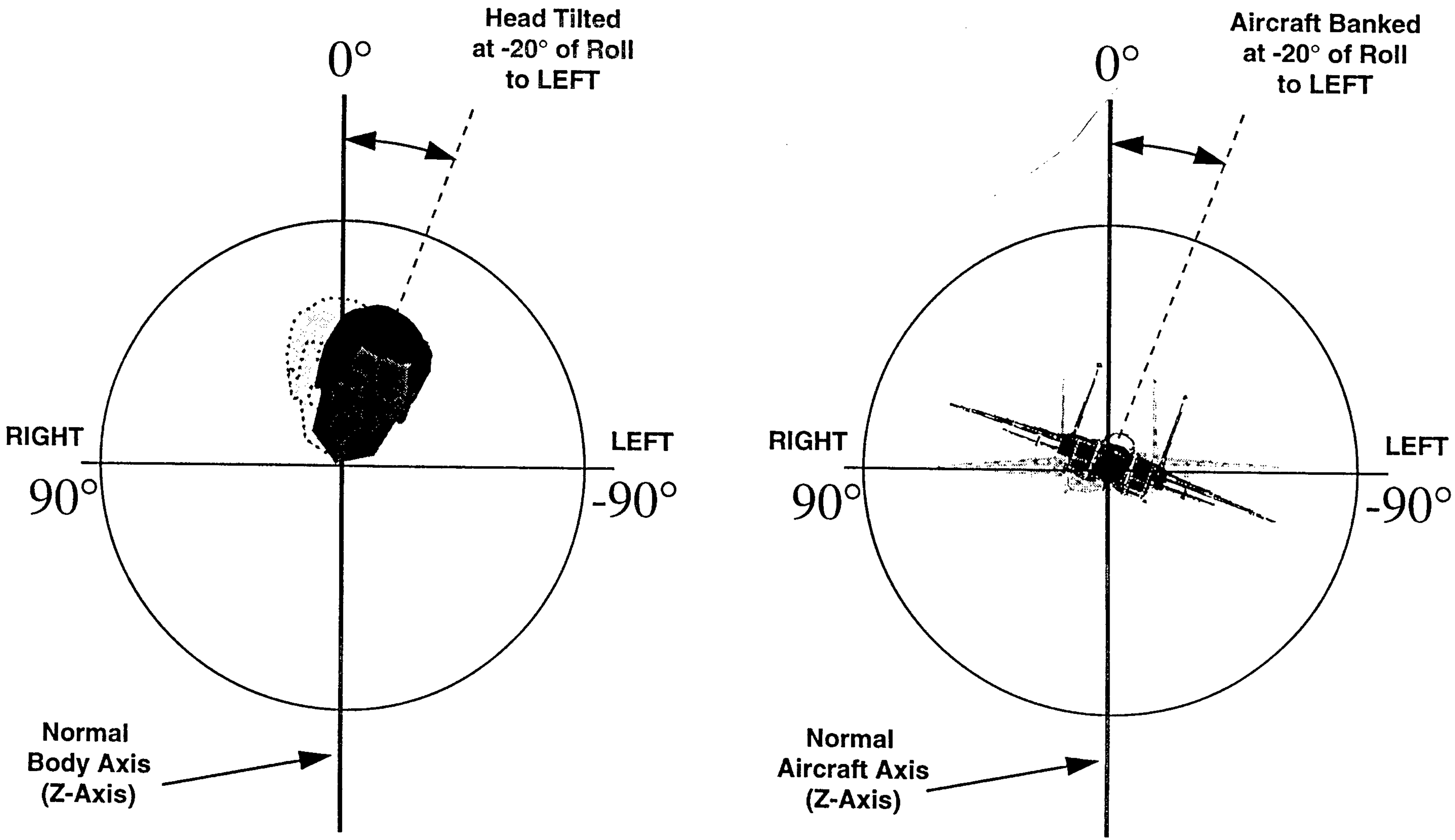


Figure 4.2. *Head Tilt Angle and Aircraft Bank Angle measurement conventions.*

entering (INTO) the banked turn and head tilt while exiting (OUT_OF) the turn. The complete matrix was a 37 x 2, repeated measures ANOVA experimental design.

The nine pilots in the study were considered to be a random sample from the population of possible pilots. The aircraft bank angle, broken down by 5° levels were considered of interest in themselves and were therefore fixed.

Table 4.1 below shows an abbreviated 9 x 37 matrix with one independent variable: aircraft BANK angle, and nine subjects. The dependent variable, ROLL, was the angle of head tilt, noted in the matrix as the symbol: $\Phi_{n,\theta}$. In this study each treatment (aircraft BANK) was applied to each subject multiple times. The value, Φ, is the mean response (head tilt) for pilot n, at aircraft BANK angle, θ'. The BANK angle is actually a range of angles where:

$$\left[\theta - \frac{\Delta}{2} < \theta' \leq \theta + \frac{\Delta}{2}\right]$$

and Δ is the interval between treatment BANK angles (in degrees). For example, the mean head tilt for pilot 3 at aircraft BANK angles between 82.5° and 87.5° (Δ=5°) is: $\Phi_{3,85}$.

Table 4.1. *Data collection matrix*

	Aircraft BANK (each level contains five [5°] degrees)								
	- 90°	**-85°**	**-80°**	....	**0°**	....	**80°**	**85°**	**90°**
Subj 1	$\Phi_{1,-90}$	$\Phi_{1,-85}$	$\Phi_{1,-80}$						$\Phi_{1,90}$
Subj 2	$\Phi_{2,-90}$	$\Phi_{2,-85}$							
:						$\Phi_{n,\theta'}$			
Subj 9	$\Phi_{9,-90}$								$\Phi_{9,90}$
$\Phi_{\bullet,\theta'}$	$\Phi_{\bullet,-90}$	$\Phi_{\bullet,-85}$							$\Phi_{\bullet,90}$

The mean head tilt (ROLL) was calculated using the following formula:

$$\Phi_{n,\theta'} = \left[\sum_{k=1}^{m} \phi_{n,\theta',k} \Big/ m \right]$$

where m was the total number of observations for pilot n at aircraft roll range θ'. The $\phi_{n,\theta',k}$ represents the k^{th} observed head ROLL angle for pilot, n, in aircraft BANK angle range, θ'.

The total number of observations, m, was typically higher for aircraft bank angle ranges closer to zero and at the extreme angles of bank angles around ±60-90°. This occurred for obvious reasons: during all aircraft banks, the aircraft necessarily passed through all the bank angle ranges from zero to the maximum bank angle both during and following the turn as pilots flew "straight and level" when not banking the aircraft. Also, while turning a high-performance jet, pilots maintained as large a bank angle as possible to safely yet quickly accomplish the turn.

One disadvantage of the repeated measures analysis is the fact the pilot head tilt was not independent from adjacent treatments. For example, the pilot's head tilt at 70° (following a 90° maximum bank) could have been influenced by his or her head tilt angle fractions of a second before, when the aircraft was at 80° of bank. This interference is sometimes called the carry-over effect. Since aircraft bank angle represents a continuous independent variable which cannot be assigned in random order to the subject, it was difficult to resolve this interference problem. For example, a pilot cannot encounter a 50° aircraft bank followed *instantly* by a -40° bank without first passing continuously through all angles between. This difficulty was partially resolved via carefully chosen statistical analysis techniques.

To test for treatment effects the following hypothesis was proposed:

$$H_O: \mu_1=\mu_2=\mu_3=\ldots=\mu_{37}=0$$

$$H_a: \text{not all } \mu_j \text{ equal zero}$$

where μ_j is the mean head tilt angle at the corresponding treatment (aircraft bank) j. Retaining the null hypothesis implied the pilots' head tilt angles did not differ significantly relative to the aircraft's angle of bank. By comparison, if H_a (the alternative hypothesis) was accepted, then it was implied the mean head tilt angle in each of the thirty-seven aircraft bank angles "bins" were not the same.

If aircraft bank angle had a significant effect on head tilt, a model for the response was developed. Data from Patterson (1995) and Smith (1994) suggested the OKCR response is sigmoidal in shape with a linear phase between ~±45° at which point it levels-off asymptotically. Trend analysis was used to determine the components of the model. Initially four forms were tested: linear, quadratic, cubic, and quartic. These were chosen since the sigmoid shape has a linear trend as well as two-reverse points. An F-test involving each of the four fundamental forms was accomplished. It was hypothesized the F-test would be significant for the linear and cubic components, but not for the quadratic or quartic forms.

5.0 RESULTS

All initial results were analyzed using Statistical Analysis System (SAS) release 6.09 on a VMS-based DEC Model 4000 mainframe system. All post-hoc analyses were conducted using the statistical functions of Excel 5.0 on a 68040-based Macintosh system with math co-processor.

5.1 Subject Data

All nine subjects completed a sufficient number of maneuvers (aircraft banking turns) to provide a quantity of raw data equivalent to or greater than that used in the simulator studies. Using the process described in 4.5, data were converted into a 2 x 37 matrix for each pilot. These matrices were then used for analysis. The *mean* head tilt for each pilot at each aircraft bank angle was the dependent variable in the matrices for two reasons: 1) this method provided a balanced ANOVA approach via one head ROLL observation per aircraft BANK angle, and 2) this was the method used to analyze the simulator study results. All analysis was conducted at a significance level of 0.05.

5.2 Missing Data Points

As there was no control over specific angles of bank during aircraft turns, the subjects employed each of the 37 levels of BANK (±90°) differently. In most cases there was a minimum of one head tilt (ROLL) data point for each of the 5° levels of BANK. However, four of the pilots had at least one BANK level empty:

- Two subjects failed to use aircraft bank angles in the -90° range,
- One subject had four missing data cells at -90° and the range from 80° to 90°,
- The fourth subject's matrix failed to register data in the 85° data cell.

Overall, there were seven missing data cells of a total 333 (37 x 9). Although this was a small percentage (2%) of missing data points, most statistical analysis procedures would completely remove all subjects with missing data from any ANOVA analysis; in this case four of nine subjects would have been removed. Therefore, the SAS procedure: GLM (general linear model), was used. GLM is the recommended procedure to use when compensating for an unbalanced ANOVA model - a model with unequal numbers of observations. Due to the missing values, only 326 observations were included in the GLM analysis.

5.3 Aircraft Bank Phase Interaction and Main Effects

See Table 5.1 for the ANOVA results of the two-factor design. The main effect for PHASE of the aircraft turn, characterized by the increasing or decreasing angle of aircraft bank, was not found to be statistically significant ($F(1,8) = 5.3176$, $p = 0.7169$). Furthermore, there was no significant interaction between BANK and PHASE. Therefore data were pooled, leaving a single factor, repeated measures model design.

Table 5.1 *ANOVA Results from Two-Factor, Repeated Measures Model*

Source	df	MS	F	*p*
PHASE	1	5.6883	0.14	0.7169
Subject **x** PHASE	8	40.3068		
BANK	36	15133.4431	15.43	0.0001
Subject **x** BANK	288	980.6711		
PHASE **x** BANK	36	106.5359	1.22	0.1924
Subject **x** PHASE **x** BANK	288	87.5298		

5.4 Aircraft Bank Angle Main Effects

There was a significant effect of aircraft BANK angle upon the subjects' head ROLL angle: ($F(36,325) = 1.4534$, $p \leq 0.0001$). See Table 5.2 for the pooled data ANOVA results. The plot in Figure 5.1 shows the overall mean head tilt (for all subjects) at each level of aircraft bank angle. The maximum and minimum subject data at each aircraft bank angle level is also annotated via high/low bars.

Table 5.2 *ANOVA Results from Single Factor, Repeated Measures Model*

Source	df	MS	F	*p*
BANK	36	2082.951	23.19	0.0001
Error(BANK)	288	89.838		

5.5 Regression Analysis Results

Following the significant results of aircraft BANK upon the pilot head ROLL angle (tilt of head), a regression procedure was used to determine the coefficients of the response. As predicted, the linear and cubic parameters were found to be statistically significant ($p = 0.0002$ and $p = 0.0013$, respectively), while the quadratic and quartic components were not statistically significant ($p = 0.1550$ and $p = 0.0992$, respectively). These results were produced via the POLYNOMIAL option in the SAS GLM procedure.

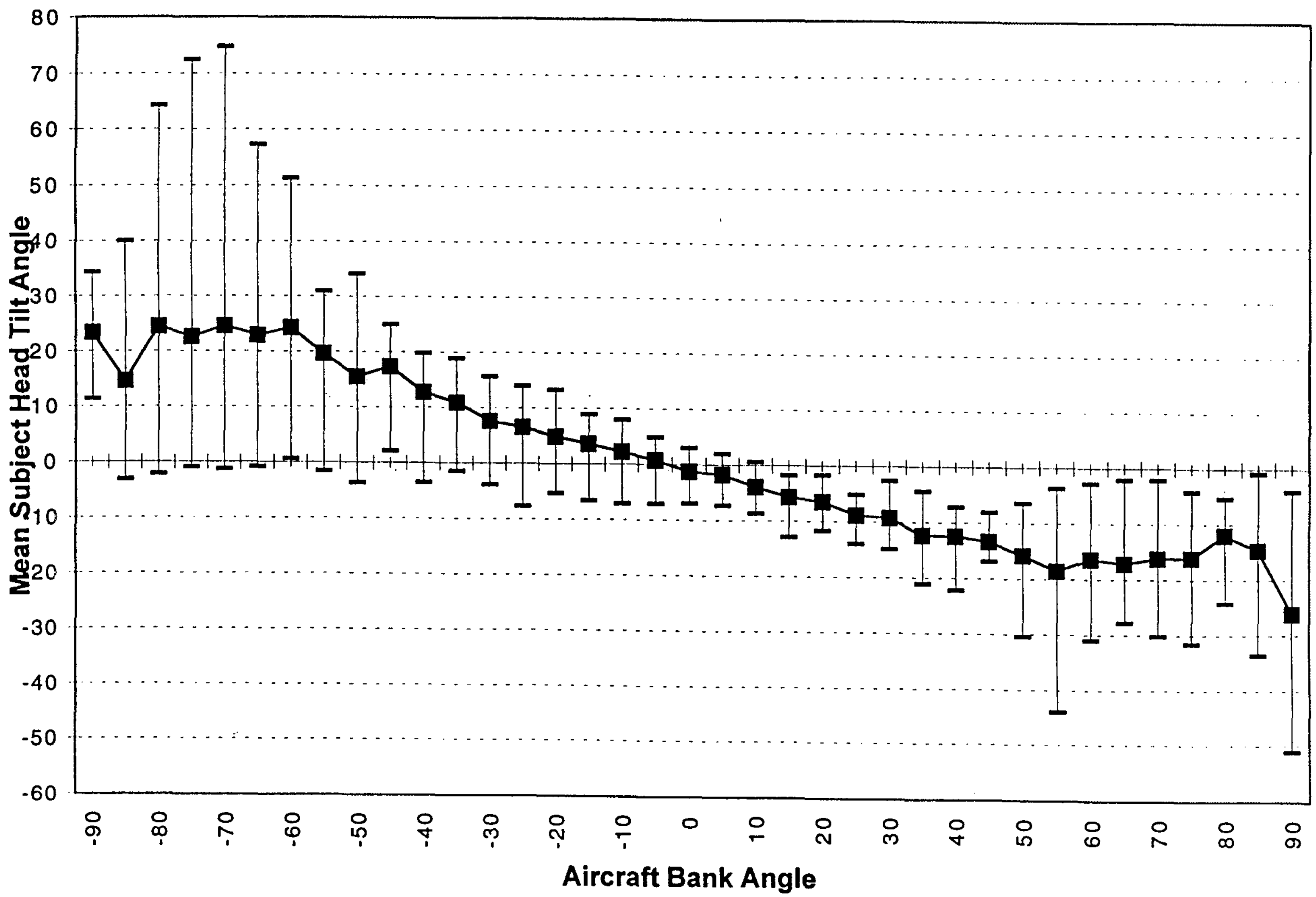


Figure 5.1. *Plot: Mean Head Tilt vs. Aircraft Bank Angle*

As mentioned in section 4.0, the data was to be fit to a fourth order model. Since the quartic term was found not significant, the regression model was then reduced to a third order equation. The equation used to fit the model was:

$$\mathbf{ROLL} = \beta_0 + \beta_1 \times \mathbf{BANK} + \beta_2 \times \mathbf{BANK}^2 + \beta_3 \times \mathbf{BANK}^3$$

The results of the regression procedure are in Table 5.3 (ANOVA) and Table 5.4 (parameter estimates). Figure 5.2 shows the plot of the predicted polynomial response based on the regression analysis. The model is indicated by the solid line with diamond "◊" markers; the individual pilot responses are annotated by the scatter plot of open squares.

Table 5.3. *Regression analysis ANOVA results*

Source	df	MS	F	p
Regression Model	3	2679.3129	300.879	0.0001
Error	33	8.9050		
R^2		0.9647		
Adjusted R^2		0.9615		

Table 5.4. *Regression Analysis Parameter Estimates*

Variable	df	Parameter Estimate	Standard Error	T for H_0: $\beta_x = 0$	Prob > |T|
INTERCEPT	1	-0.440250	0.73632766	-0.598	0.5540
BANK	1	-0.399810	0.02303284	-15.622	0.0001
$BANK^2$	1	0.000419	0.0001926	2.176	0.0368
$BANK^3$	1	0.000016988	0.00000412	4.122	0.0002

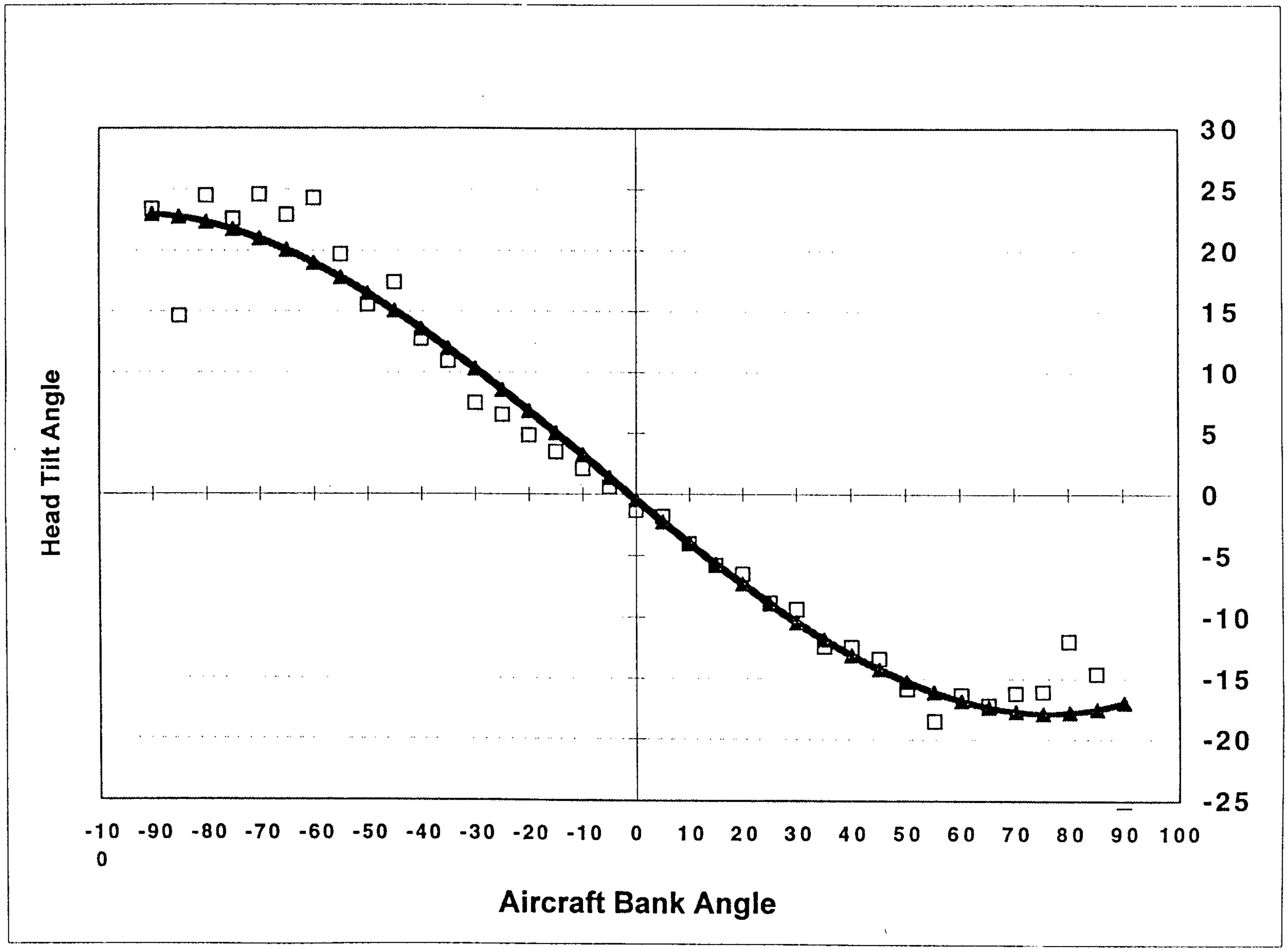


Figure 5.2. *Plot: Head Tilt vs. Aircraft Bank Angle Polynomial Plot*

6.0 DISCUSSION

6.1 The Optokinetic Cervical Reflex Effect During Actual Flight

The results of this study indicate the optokinetic cervical reflex is an irrefutable behavior of pilots in high performance jet aircraft. This objectively confirms the subjective observations as well as validates the work completed in the simulator studies. Figure 6.1 shows a plot of the four OKCR models for comparison. Each line is a plot of head angle versus aircraft bank angle. The four models are: this study's third-order model, Patterson's (1994) third-order model and Smith's (1994) active and passive fourth-order models. Graphical inspection indicates a very good match between all four models.

In order to compare the actual flight data against the simulator models, the method of standardized residuals was utilized. Each subject's mean head tilt response at every aircraft bank angle (from actual flight data) was compared with the predicted head tilt from the (simulator) models. This resulted in a residual matrix (37 x 9) for each of the three simulator OKCR models. Next, each matrix was normalized and standardized residuals were determined. Finally, the standardized residuals were analyzed as follows: residuals which fell within $|\sigma| < 2$ were considered normal results. Residuals in the range $2 \leq |\sigma| < 3$ were considered moderate outliers. And residuals in the $|\sigma| \geq 3$ were labeled as extreme outliers. Surface plots (Figures 6.2 through 6.4) are graphical visualizations of the data from the three matrices. A minimum of 95% of all the standardized residuals fell within the normal range for each of the three models considered. Therefore, the OKCR flight data was found to be statistically comparable to the results from the previous simulator studies.

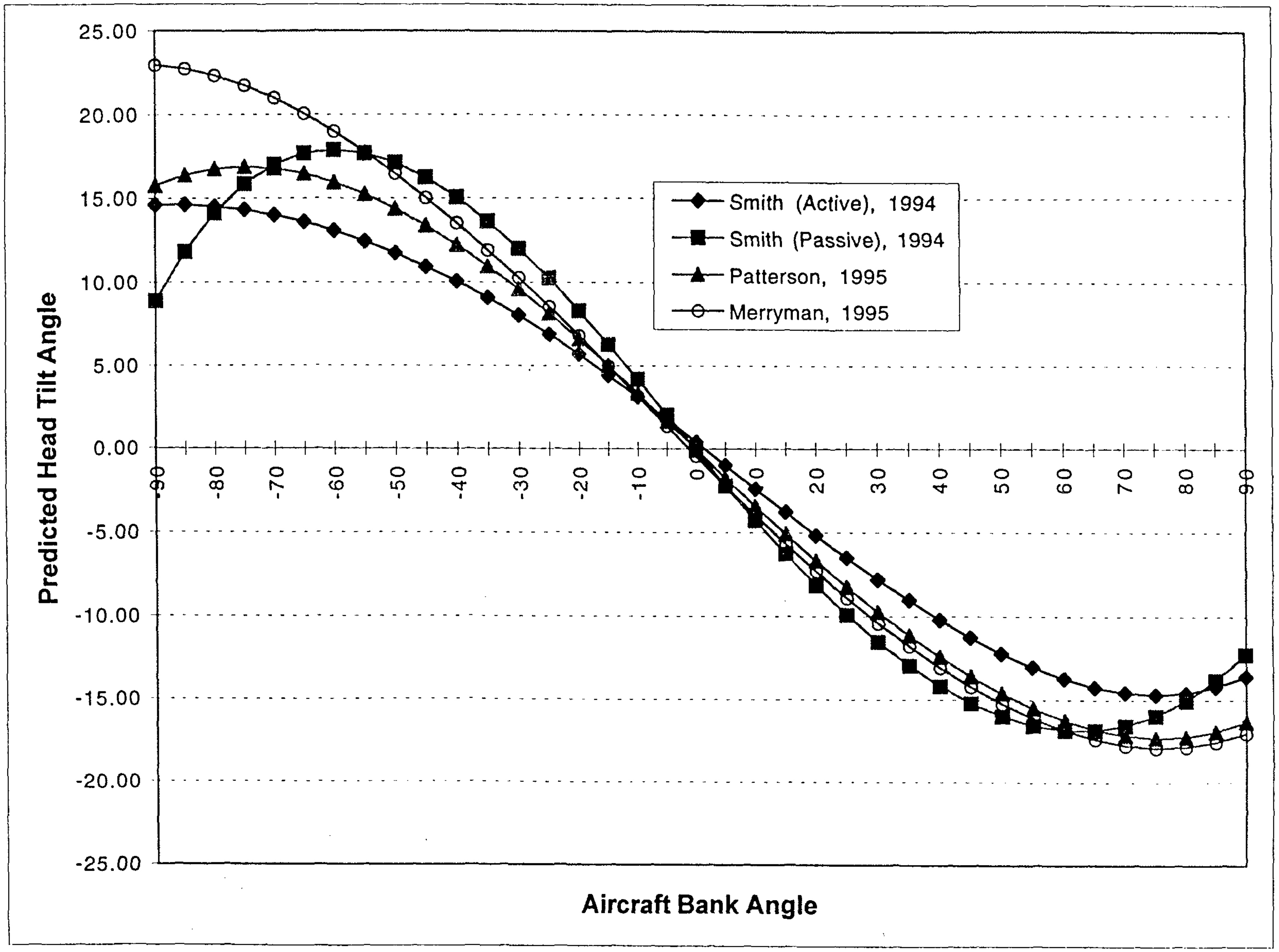


Figure 6.1. *Plot: Four OKCR Response Models*

Note: gray-level represents distance of standardized residual from mean.
Black = extreme outlier, Gray = moderate outlier, all other data are normal.

Figure 6.2. *Standardized Residual Comparison to Patterson Model*

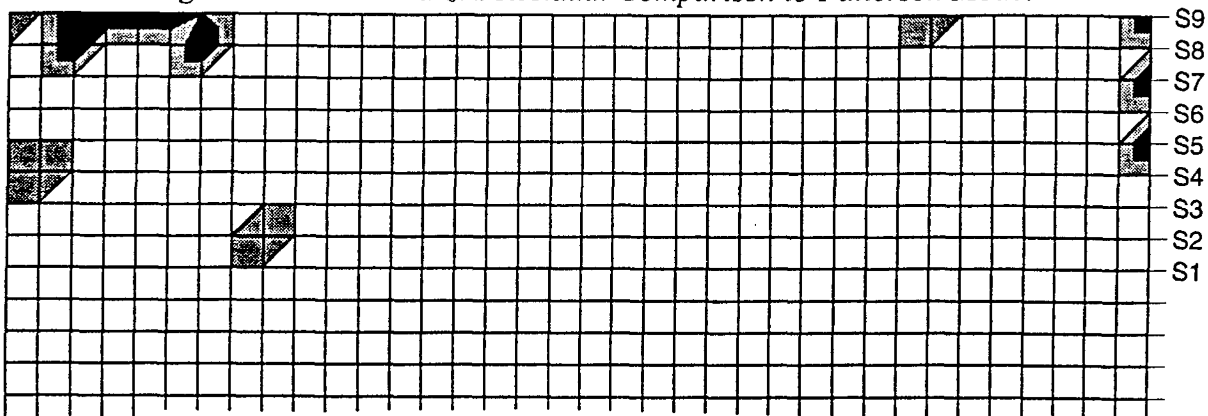


Figure 6.3. *Standardized Residual Comparison to Smith (Active) Model*

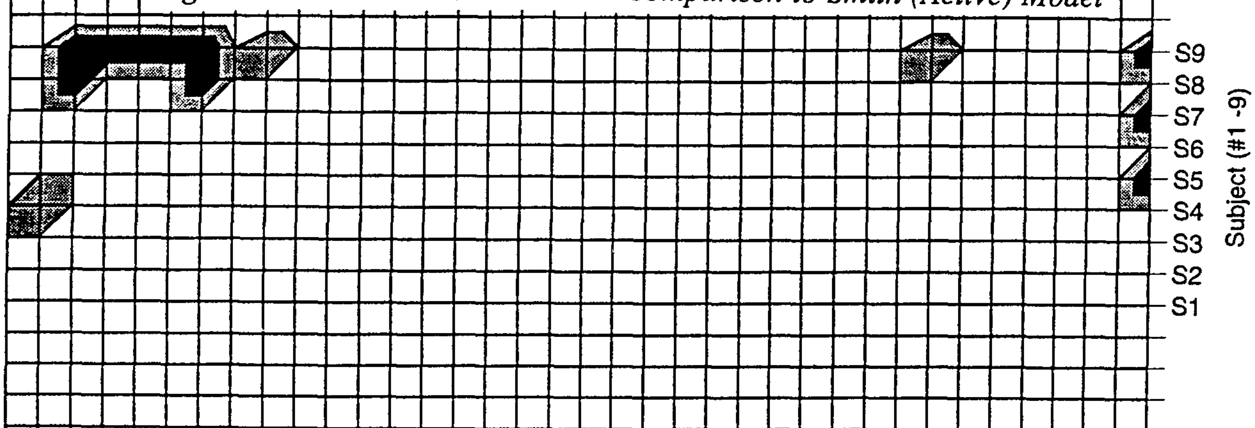
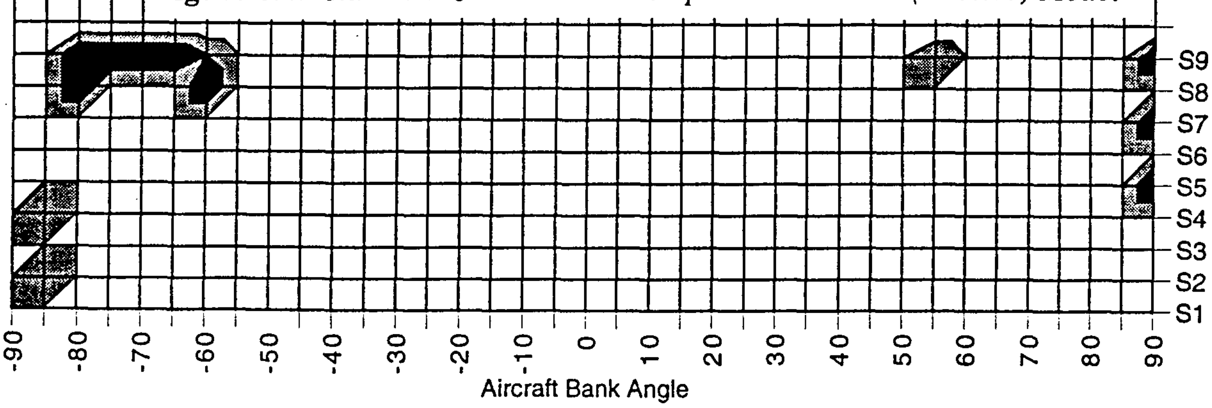


Figure 6.4. *Standardized Residual Comparison to Smith (Passive) Model*



As expected, most of the extreme outliers occurred at the tail ends of the aircraft bank angle - those angles between ±80 and 90°. There was greater variance of the data at the higher bank angles due to the smaller number of observations. An exception was a single subject who had numerous extreme outliers in the left aircraft bank data cells. This subject appears to have exhibited extremely high head tilt angles during aircraft banks to the left. Further investigation into this subject's data determined this range (extreme left aircraft bank) was the *only* region for which this anomaly existed. Removal of this subject's data did not result in any graphical change in the overall OKCR response for the group, except at extreme left aircraft bank angles. Any number of confounding variables could explain this response: poor data collection, pilot was visually tracking (or engaging) another aircraft, the helmet system rotated during flight and was subsequently un-calibrated for a portion of the mission. The extreme tail end, for left aircraft bank, of this study's third-order model is therefore suspect and should be interpreted as a possible product of the extreme outlier data.

6.2 Strength of the OKCR Effect

Despite the many confounding factors (see previous section) possible in an observational study such as this, the optokinetic cervical reflex was significant enough to overcome these extraneous variables. An approximation of the simulator studies results was hypothesized, but the actual level of coincidence between the three studies was extremely surprising. The fact the OKCR can be induced in a simulator, without the true physical and vestibular effects of actual flight, also suggests the reflex is a powerful, natural behavior based primarily on visual inputs.

6.3 Significance of Aircraft Bank Phase Results

The results of this investigation suggest the OKCR response is not dependent upon whether the pilot is entering into a bank or returning from one. The plot in Figure 6.5 graphically indicates there are no hysteresis effects between the two phases. This result should be accepted cautiously, however. Since this was a relatively non-controlled, observational study, other confounding variables may have prevented any phase effect from becoming apparent. A controlled experimental task in which pilots flying actual aircraft, follow a prescribed flight path, should provide a better set of data from which the bank phase effect can be studied.

However, if the bank phase is, as this study has shown, independent of the OKCR then this is a critical finding since it can reduce the complexity in the design of future displays. Attitude displays which will compensate for OKCR effects will be much simpler if the only inputs are the aircraft's and the pilot head's orientations. If the phase of the bank was a significant variable, this would greatly complicate the design.

6.4 Differences in Natural Head Tilt Angle

Interestingly, most of the pilots exhibited what appeared to be a natural head tilt different from zero. At zero degrees of aircraft bank (wings level), one would expect the mean head tilt for a pilot to be near zero. But, in actuality, this value varied up to seven degrees and was typically between two and three degrees. There are two explanations for this effect. The first is all humans have a natural head tilt which is either the result of adapting to an imperfect vestibular system or the tilted head has caused the vestibular system to adapt to the tilt throughout development. This is certainly plausible since each human is a unique being. The second explanation is the head tracker system used was either tilted on the pilot's head (imperfect fit) or was not calibrated correctly in the roll axis. It is very possible both explanations are affecting the results. Regardless as to the cause, the actual effect of individual natural head tilt on the overall OKCR results was nullified by sample size.

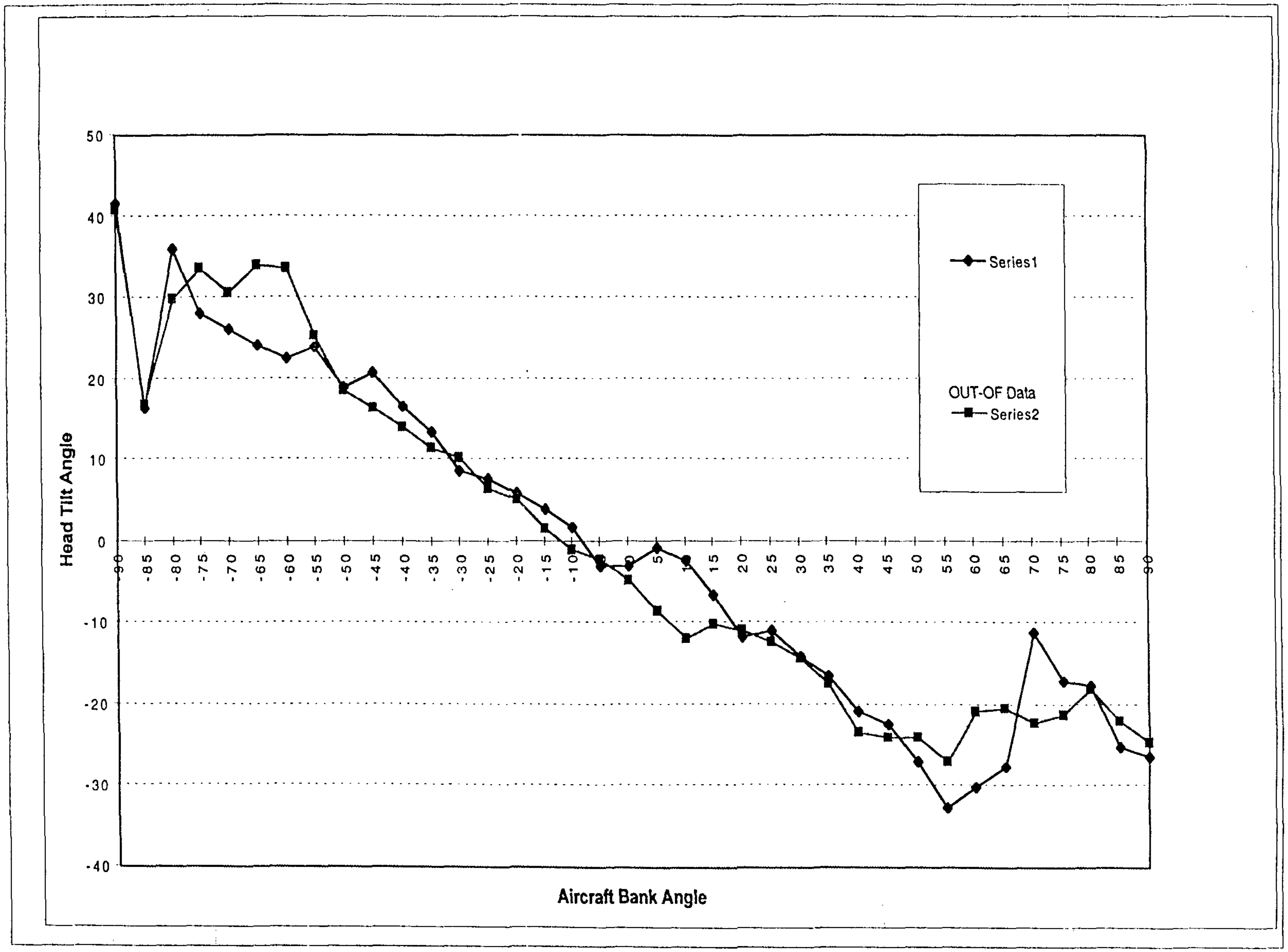


Figure 6.5. *Plot: Mean Head Tilt vs. Aircraft Bank Angle - Phase Effect*

6.5 Analysis of Linear Segment of OKCR Response

Figure 6.6 shows a plot of the linear segment of the OKCR response between ±30 degrees of aircraft bank. The three lines represent the linear regressions from the actual flight data and from Smith's (1994) simulator data. The simulator data has two lines: one the OKCR exhibited by the subject *actively* controlling the simulator; the other the reflex exhibited by the subject who was *passively* observing the auto-piloted flight. Smith found a significant difference between the slopes of the passive and active simulator data. Since the F-15 flight data for this investigation involves pilots flying single-seat fighter jets, it was hypothesized that the linear regression line should match Smith's *active* data and not the passive data. Graphically, the flight data correlates well with Smith's active data.

Two t-tests were conducted, comparing the linear regression slopes from each pilot to each of Smith's active and passive slopes. Table 6.1 summarizes the t-test procedures and results. The t-tests revealed a significant difference between the flight data and the passive simulator data (p = 0.0023), while the difference between the flight data and the *active* simulator data was found to be non-significant (p = 0.4762). These results indicate the actual flight data corresponds extremely well with the appropriate simulator data, which further validates the simulator OKCR research.

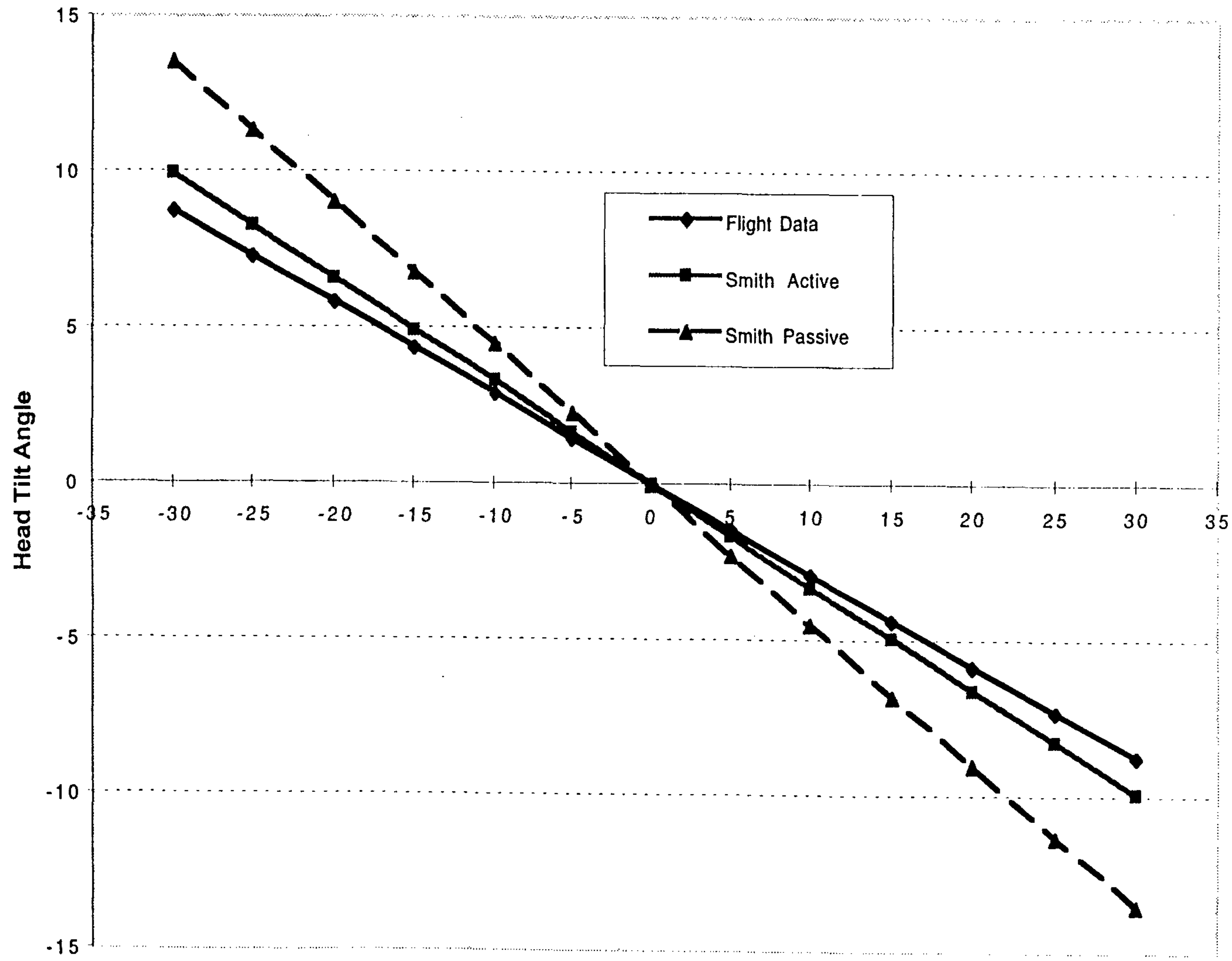


Figure 6.6. *Plot: OKCR Linear Response Analysis*

Table 6.1. *T-test (two sample, unequal variance) results from analysis of linear regression slopes between ±30 degrees for actual flight data and simulator data.*

Subject	Actual Flight Data	Smith: Active in Simulator	Active-Actual Difference	Smith: Passive in Simulator	Passive-Actual Difference
1	-0.29	-0.33	0.04	-0.45	0.17
2	-0.09	-0.33	0.24	-0.45	0.36
3	-0.34	-0.33	0.00	-0.45	0.12
4	-0.23	-0.33	0.10	-0.45	0.22
5	-0.31	-0.33	0.02	-0.45	0.14
6	-0.33	-0.33	0.00	-0.45	0.12
7	-0.38	-0.33	-0.05	-0.45	0.07
8	-0.45	-0.33	-0.11	-0.45	0.01
9	-0.34	-0.33	-0.01	-0.45	0.11
Mean Response	-0.31	-0.33	0.02	-0.45	0.15
			0.22	Sum	1.32
			0.09	Sum of Squares	0.27
			0.01	$(\text{Sum})^2/n$	0.19
			0.08	SS about Mean	0.08
			0.01	S_d^2	0.01
			0.75	t_8	4.40
			1.86	Critical at 0.05	1.86
			0.4762	*p*-value	**0.0023 ***

* indicates a significant mean difference

6.6 Analysis of Asymptotic Effects in the OKCR Response

According to Patterson (1995), the optokinetic cervical reflex is a natural attempt to stabilize a retinal image of the horizon to provide a reference stimulus. This true horizon image is theorized to provide the primary spatial reference for maintaining spatial awareness. The OKCR response behaves in a linear fashion at smaller angles of aircraft bank. During these low angles (< 40°) the pilot maintains an almost fixed visual orientation with respect to the horizon--the aircraft and pilot's body act as a separate "system," moving independently from the pilot's head. But, as higher angles of aircraft bank (>40°) are encountered, the OKCR response begins to level and the pilot's head starts to move *with* the aircraft and *against* the horizon image. This reflects a significant transition in visual orientation cues and reference frame.

The asymptotic limit of the pilots' head tilt was in the range of 15 to 20° of latero-flexion (reference Figure 6.1). Recent studies have found the mean maximum latero-flexion angle for males (non-military) to be 41° with a standard deviation of 7° (reference Table 2.3 of this document; Woodson, *et al*, 1992). There is at least a 20° difference between the maximum OKCR head tilt and that of the Woodson, *et al* research. The question then posed is: what are the mechanisms and drivers for the limited head tilt and why does it occur at approximately 40° of aircraft bank? Patterson (1995) has suggested the asymptotic limit is an anatomical limit; the pilots reach a maximum neck flexion in the coronal plane. But, in light of the anthropometry findings, there appears to be other plausible mechanisms since the pilots are far from the mean male extreme head tilt angle. The remaining part of this section will be spent discussing the proposed interpretations behind the asymptotic effect.

The proposed interpretations fall under two categories: physiological/physical and cognitive. The physiological and physical explanations will be discussed first.

6.6.1 Physiological/Physical Interpretations of the OKCR Asymptotic Response

The exhibited limit to head tilt is obviously not a *true* physical limit as much as it may be a *comfort* level limit. The anthropometry results (Woodson, *et al,* 1992) were for *extreme* head tilt, not a comfortable head tilt. It may be true that, if asked to tilt their head to a *comfortable angle,* subjects would exhibit a head tilt on the order of 15 to 20°. This should be investigated. Another proposed interpretation is *normal acceleration attenuated* neck flexion. At extreme aircraft angles of bank (AOB), the normal accelerations on the pilot may be greater than 6g. It is possible that the high G-loading on the neck prevents full flexion of the neck. The addition of a helmet may further inhibit full latero-flexion. However, since the OKCR asymptotic limitation was observed in simulators without acceleration forces, this interpretation is suspect. Although, it is possible that the pilots anticipated a G-load from experience and reacted accordingly. A simulator investigation using subjects without flight experience (have never flown, have never used a flight simulator or computer flight program) needs to be accomplished to resolve the factor of flight experience as applied to OKCR in simulators.

The actual visual limitations imposed by the frame of the aircraft (see Figure B.1 in Appendix B) may be another factor to consider. In both this investigation and the simulator studies the aircraft flown was an F-15. The cockpit structures in the simulator were very close, in position and size, to those actually found in the F-15's used in this investigation. Also, the HUD field-of-view (FOV) was comparable between actual aircraft and simulator. Due to this parallelism, if aircraft structures forced a limitation on OKCR-induced head tilt, then the same asymptotic limits should be seen in both studies - which is what occurred. Furthermore, it is possible that the asymptotic value of head tilt would be greater or less in other aircraft which have a cockpit structure much different from the F-15. For example, in the F-16 aircraft, the pilot sits much higher above the aircraft frame and experiences less visual blocking cockpit structures. Therefore, since the optokinetic cervical reflex is primarily a visually driven response, any differences of a visual nature may affect the magnitude of the reflex.

6.6.2 Cognitive Interpretation of OKCR Asymptotic Response

There is an interesting angular lag between the OKCR head tilt response and the aircraft AOB. Prior to the asymptotic limit of head tilt, the image of the horizon upon the pilot's retina is slowly rotating as the aircraft increases AOB. The plot in Figure 6.7 shows the OKCR response (g) and the aircraft AOB (♦). Also shown (Δ) is the difference between the OKCR and AOB. This difference is essentially the angular displacement between the pilot's head and the perpendicular axis from the earth below. If there was *perfect* compensation for the aircraft bank, the OKCR response would be equivalent in magnitude (still opposite in direction) to the AOB, until a limit of head tilt was encountered. This would bring the difference between OKCR and AOB much closer to zero during low AOB. However, this is not the case and in reality a lag exists.

The asymptotic limit occurs around 40 - 45° AOB. At this AOB the angular displacement between the pilot's head angle and the horizon is approximately 30°. It is proposed that, at this point, the pilot can no longer normalize the image of the horizon. By normalize, I refer to the cognitive recognition that the horizon represents a horizontal frame of reference. This is predicated on the theory the human visual system is not a rotationally invariant pattern recognition "system" (Kabrisky and Rogers, 1989). The "pattern" in this case, of course, is a straight line in the visual

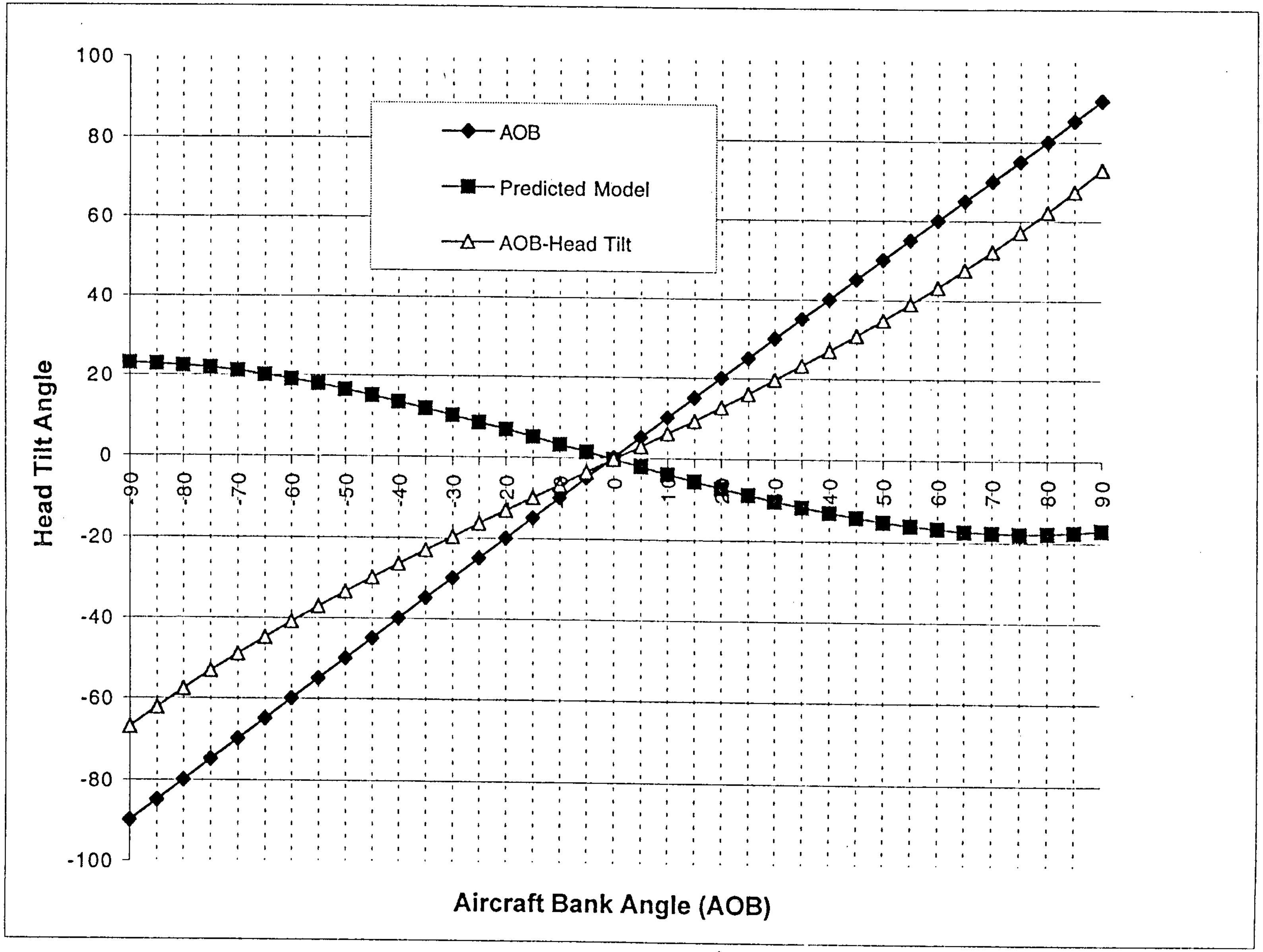


Figure 6.7. *Plot: Relative OKCR Head Tilt*

field. When the horizon is displaced from its normal, ground-viewed orientation of 0°, at some point (perhaps at 30°) it is no longer a "horizon" and consequently cannot be used as the primary visual cue to maintain spatial orientation.

The images in Figure 6.8 illustrate the inability of the human visual system to fully recognize a rotated stimulus. Upon first impression, a subject will undoubtedly recognize the two images are of a human face - rotated by 180°. The subject, however, will fail to notice that the left figure contains grotesque distortions in the facial components. Not until the figure is rotated to some angle away from 180° does the subject recognize that the face has indeed been modified. In other words, the subject failed to normalize the complete image, otherwise the modification would have been instantly obvious.

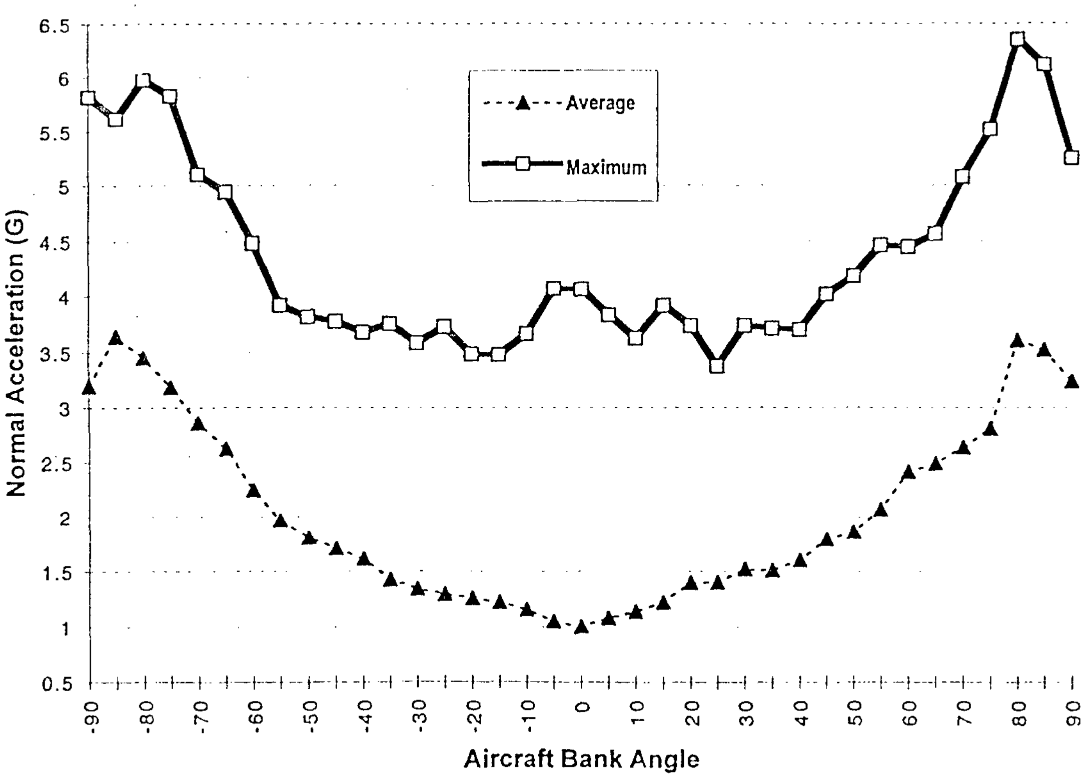
This also supports Patterson's (1994) proposal that, upon reaching the asymptotic limit, the primary and secondary visual cues are switched. At low AOB the horizon can be normalized and therefore used as a primary cue. At higher AOB the pilot no longer sees a horizon, but senses the motion (rotation) of the horizon in the peripheral vision and this is used as a secondary visual cue for maintaining spatial orientation.

6.7 Normal Acceleration (Gz-Forces) Consideration

The normal acceleration level (g-forces in the *z*-axis) was considered as the third primary independent variable for this study. Unfortunately, this variable was removed from the study since it violated the statistical principles of multicollinearity. Figure 6.9 shows the Gz forces are *highly correlated* with aircraft bank angle. This graph indicates both the maximum and average normal acceleration for the subject group at each level of aircraft bank. The higher the aircraft bank, the higher the resulting g-forces. There was no method of decoupling these two variables, and therefore g-forces could not be used in the statistical analyses.

Figure 6.8. *Image Demonstrating Relative Rotational Invariance Limitations* (In Howard, I.P., 1982)

Figure 6.9. *G-forces vs. Aircraft Angle of Bank (Multicollinearity Plot)*



7.0 CONCLUSIONS

7.1 OKCR in the Actual Cockpit

This investigation verified that the optokinetic cervical reflex does occur in the cockpit of high performance aircraft. It is a seemingly natural response to a very unnatural stimulus: rotation in the roll (coronal) plane during airborne motion. As Patterson (1995) stated, it is theorized that this response is an attempt to stabilize the *retinal* image of the visible horizon. The stabilized image becomes the primary source of visual information used to maintain spatial orientation. OKCR is a logical reflex considering, to a pilot flying in an aircraft, there is only one physical visual stimulus which can be used to determine body orientation: the Earth. And the best discriminator on the earth's surface is the *horizon*, the natural divider between the ground and the sky - the pilot's medium. Therefore, the pilot reflexively seeks to maintain a relatively fixed head-horizon orientation as long as possible. While this accounts for spatial orientation of the human portion of the system, the pilot is still attached to an aircraft. Keeping the aircraft from impacting the ground is a prime concern for the pilot and therefore the pilot must also account for the spatial orientation of the airframe with respect to the earth. To accomplish this, Patterson (1994) has suggested that the aircraft wing tips (and other aircraft structures) act as *peripherally* viewed secondary sources of information by which pilots detect the independent motion of the aircraft relative to their own head.

In summary, during low angles of bank (AOB) pilots maintain a *head-horizon orientation* from which spatial awareness is determined. Once the maximum OKCR head tilt is exceeded (corresponding to high AOB), the pilot's head becomes "attached" to the pilot's body and aircraft. The complete system is now rotating during the aircraft bank. The pilot is now maintaining a *head-aircraft orientation.* When returning to a "wing's level" attitude, the pilot maintains a head-aircraft orientation until the aircraft AOB is about ±45° at which the pilot maintains a head-horizon orientation. The transition between head-aircraft and head-horizon orientations represents a critical change in the pilot's cognitive view of the world since the frame of reference changes instantaneously

The results of this study and the previous studies impact many aspects of flight. The following is a synopsis of those issues and suggested approaches.

7.2 The OKCR in Pilots of Large Aircraft

Although Smith (1994) suggested that the aircraft experience of the pilot (fighter or transport) was not a significant factor in the OKCR response, actual data from transport aircraft was not studied. This study, and the previous simulator studies, have documented the OKCR in high-performance aircraft systems. The control-response time lag in high-performance jets is small and aircraft roll is almost instantaneous when the flight stick is moved. In contrast, the time lag in large aircraft ("heavies") such as transport jets and commercial airliners is greater. The aircraft does not roll (or bank) as quickly as a fighter jet. While the OKCR is hypothesized to exist in any aircraft, the actual magnitude and frequency response may be affected by control-response time lag.

7.3 Impact on the Use of Simulators and Simulated Flight

The fact the OKCR response was found to be almost equivalent between the actual flight data and the simulator data lends credibility to the use of simulators for realistic training and as experimental research tools. Given the high costs and logistical difficulties involved in actual flight testing, the use of simulated flight methods is a necessary and desirable alternative. Since the simulators used were full, 360° dome-style units, the effects of reducing field-of-view on the OKCR is not known, therefore the recommendation to use simulators is limited to full field-of-view, dome simulators. Although the actual OKCR simulator studies were limited to 180° of visual information, since the pilots were not tasked to use information from the rear hemisphere, it was essentially a full field of view system as viewed by the subject.

7.4 Impact on HMD and Display Design

The recognized existence of the OKCR should, at a minimum, be a principal consideration in the design of all aircraft attitude displays. Current HMD attitude symbology sets still reflect the old assumption of pilot head orientation during flight. As was shown by the Model-Environment Reversal effect, applying the traditional attitude display to HMDs may result in the serious consequences of pilot spatial disorientation and control reversal error. Since HMDs are now in their infancy, the correct design of attitude symbology *today* can save aircrew lives and prevent costly re-engineering subsequent to production in the future. The most important issue is the fact HMDs have a *relative* frame of reference, mainly the pilot's head, and that the pilot's head is subject to the OKCR response which *changes* the pilot's cognitive frame of reference during flight. We would be remise to not take full advantage of the head position data provided by modern head-mounted trackers in the cockpit. This information, in conjunction with physiological and human factors models of the OKCR, can result in attitude display formats which are compatible with the pilot's spatial orientation cues and will increase the pilot's spatial awareness and reduce the incidences of spatial disorientation.

7.5 Impact on Training Issues

The first step of the training process should be education. Education in the research community, the engineering community and most importantly, the pilot community. An incorrect presupposition has persisted for over sixty years, and this will be a difficult challenge to overcome. First, pilots need to be trained that it is *natural* to tilt the head during banking maneuvers. Furthermore, this OKCR head tilt should not induce cross-coupling (the Coriolis effect). If pilots are aware of this reflex, it may also reduce the incidence of spatial disorientation as they transition between external and internal (cockpit displays) visual spatial orientation cues.

For the research community, the existence of the OKCR should be recognized in the design of future experiments involving flight. Subjects should be allowed full freedom of motion of the head to permit the OKCR to occur naturally. This holds for both actual and simulated flight. It is critical the natural spatial orientation cues are not blocked or altered, unless of course, that is the primary intent of the study.

For the engineering community, the design of future displays, especially helmet-mounted displays, must include provisions for adapting to the OKCR. Current attitude displays, when coupled with the OKCR response, can magnify spatial disorientation effects and induce control reversal errors. New attitude display symbology of the moving aircraft (outside-in) type or a frequency-separated type may help by providing a frame of reference which matches that seen by the pilot. The area of display design is probably most mired in the convention of the old theories regarding pilot head alignment. While modifications of the *cockpit* attitude displays are unlikely to occur in the near future, the ease by which the symbology of new displays (i.e., *helmet-mounted displays*) can be changed makes them the prime candidates for "OKCR-friendly" design changes. Caution must be taken, however, since multiple attitude displays of *differing* types may prevent resolution of spatial disorientation. Therefore, all attitude displays within the vehicle should be compatible with a singular frame of reference and this frame of reference should be determined experimentally and include the OKCR response.

7.6 Impact on Pilot Injury and Safety

While spatial disorientation remains a paramount concern, the existence of the optokinetic cervical reflex may affect the physiological aspects of flying as well. There are numerous physiological effects possible as a result of the OKCR. In particular, if pilots tilt their heads during normal accelerations greater than 1g, this may place additional strain on the lateral muscles of the neck. With helmet-mounted displays, the combined head+helmet system center of gravity (CG) may be different than the pilot's normal head CG. This difference could cause significantly greater strain during OKCR-induced head tilt and high-G maneuvers. Also cervical damage has been cited as another possible source of OKCR-induced injury in pilots (Patterson, 1995)

Another physiological effect centers on the methods pilots use to combat the deleterious results of enduring high levels of g-forces. Pilots can only endure up to a certain level of normal acceleration before losing consciousness due to hypoxia--the severe reduction in oxygen concentration in the brain tissues. The high-g's prevent the blood from reaching the brain and therefore the pilot "passes out." This is called G-induced loss of consciousness (GLOC). G-suits are just one method pilots may use to raise their G-tolerance. Another method is called the Valsalva maneuver, or "high-G straining technique." By rhythmically taking short breaths, grunting and constricting muscles in the neck and abdomen, holding a column of air in the trachea, a pilot can usually gain up to an extra 1g of tolerance. Since the OKCR occurs during aircraft turns and therefore under higher-g conditions, this may reduce the effectiveness of the Valsalva maneuver. During OKCR, the pilot's trachea and blood vessels may be constricted, thus preventing the maneuver its full effect.

7.7 Future Work

This investigation and the two previous simulator studies are the proverbial "tip of the iceberg" with respect to aviation spatial orientation. Although, the optokinetic cervical reflex has been shown to be a real effect during flight, additional work is required to focus on the specific details of the reflex.

Numerous studies are documented in the literature regarding eye motion resulting from changes in body orientation and the external environment. The countertorsion of the eyes resulting from tilting the head (Schöne, 1962; Miller and Graybiel, 1971; Petrov and Zenkin, 1973; Crone, 1975) is one such effect found in a laboratory setting. It is desirable to know if eye movement and eye scan patterns play a part in the OKCR. *Eye tracker studies* would answer many questions regarding the actual visual and vestibular mechanisms driving the OKCR.

A variable not measured in any study yet is that of *upper body tilt*.. Does the pilot supplement head tilt by rotating the torso as well? Head tracker systems only measure the overall orientation of the head within the cockpit, but this is not necessarily the *actual* tilt angle between the neck and head. This information is important in order to determine the effects of Gz loading on the cervical spine region.

The *effects of g-forces* on the OKCR needs to be studied as well. Since g-forces are highly correlated with aircraft angle of bank, another method of investigation needs to be devised. The interaction of g-forces and OKCR with the Valsalva method should also be studied. One possible experiment would be to expose subjects to higher levels of g-forces in centrifuges and determine the objective or subjective effectiveness of the Valsalva maneuver at head tilt angles similar to what results from the OKCR.

As was alluded to above, each of the three OKCR studies provided the subjects with full 360° field-of-view (FOV). It may be true that, with a reduced FOV, pilots will not exhibit the same magnitude of OKCR. Or the reflex may be completely absent. Simulator studies involving *modifying the field-of-view* are required to clarify the relationship between OKCR and FOV. The results of such studies would be instantly applicable to night vision goggle and other virtual reality research where the user's FOV may be reduced or modified.

Finally, other methods of analyzing the OKCR should be investigated. One such method would involve *frequency analysis*.. This method can be used to study the time effects of the OKCR. Possible results could include: *response latency* (the time difference between initiation of aircraft bank and the subsequent OKCR response), and the *frequency response* of the OKCR head tilt (head roll rate). These results may be particularly illuminating and lend insights into OKCR mechanisms as well as provide the necessary inputs for new aircraft/spacecraft attitude and virtual reality display designs.

8. APPENDIX

MAGNETRAK™ SPECIFICATIONS

SYSTEM COMPONENTS & PHYSICAL CHARACTERISTICS

SENSOR (HELMET MOUNTED)	0.9″ L × 1.1″ W × 0.7″ H	0.7 oz
SOURCE (VEHICLE MOUNTED)	2.4″ L × 1.4″ W × 1.4″ H	5.5 oz
AIRCRAFT PROM	4.3″ L × 1.3″ Diameter	5.3 oz
SYSTEM ELECTRONICS UNIT	11.13″ L × 4.88″ W × 6.85″ H	11.3 lb
HELMET DISPLAY RETICLE GENERATOR	2.0″ × 0.5″ Diameter LED CROSS-HAIR PATTERN WITH 4 OR 8 PERIMETER CUEING DISCRETES	1.0 oz
PARABOLIC VISOR	COMPATIBLE WITH HGU 33, 34, 55 AND SPH-4, -5 HELMETS	

PERFORMANCE

UPDATE RATE	50 Hz SINGLE COCKPIT 25 Hz DUAL COCKPIT		
RESOLUTION	ANGULAR TRANSLATION	1.75 mrad, 0.1° 0.1″	
ACCURACY	"HUD" BOX OVERALL COVERAGE	2 mrad (RMS) 4—10 mrad (RMS)	
OPERATIONAL ENVELOPE		OVERALL	HUD BOX COMPARISON
	AZIMUTH	±180°	±10°
	ELEVATION	± 90°	±10°
	ROLL	±180°	±10°
	MOTION BOX		
	X (FORE-AFT)	± 16″	± 3″
	Y (LEFT-RIGHT)	± 10″	± 3″
	Z (UP-DOWN)	± 6″	± 1.5″
DISPLAY	EXIT PUPIL FIELD OF VIEW CONTRAST RATIO	16mm 6° 1.2:1 AGAINST 15,000 fL	

RELIABILITY/MAINTAINABILITY

MTBF	3000 HOURS (217C PARTS COUNT)
BITE	DETECTS 95% OF ALL PERFORMANCE DEGRADING FAULTS
"O" LEVEL	LINE REPLACEABLE UNIT ISOLATION 95%
"I" LEVEL	SHOP REPLACEABLE UNIT ISOLATION 97%
"D" LEVEL	CONTRACTOR DEPOT REPAIR

I/O INTERFACE

1553B DUAL REDUNDANT BUS
RS 232-C SIGNAL LEVEL, ASCII OR BINARY
SPARE SLOT FOR SPECIAL PURPOSE INTERFACES
OUTPUT FORMATS
- EULER ANGLES
- DIRECTION COSINES
- QUATERNIONS
- POSITION X, Y, Z

SYSTEM CONTROL (TRACKER AND DISPLAY)
- VIA 1553B INTERFACE
- OPTIONAL CONTROL PANEL

POWER REQUIREMENTS

PRIME POWER CONSISTENT WITH MIL-STD-704

115V	0.7A (PRIME POWER)	400 Hz	SINGLE PHASE
28V dc	0.1A (RELAY POWER)		

ENVIRONMENTAL CONSIDERATIONS

SEU FORCED AIR COOLING—COLD WALL CONSTRUCTION
MIL-E-5400 CLASS 2 EQUIPMENT
- −54°C to +71°C CONTINUOUS
- −54°C to +95°C INTERMITTENT
- 70,000 ft ALTITUDE

APPLICABLE MIL STANDARDS

GENERAL CONSTRUCTION	MIL-E-5400
ENVIRONMENTAL	MIL-STD-810
ELECTROMAGNETIC INTERFERENCE	MIL-STD-461

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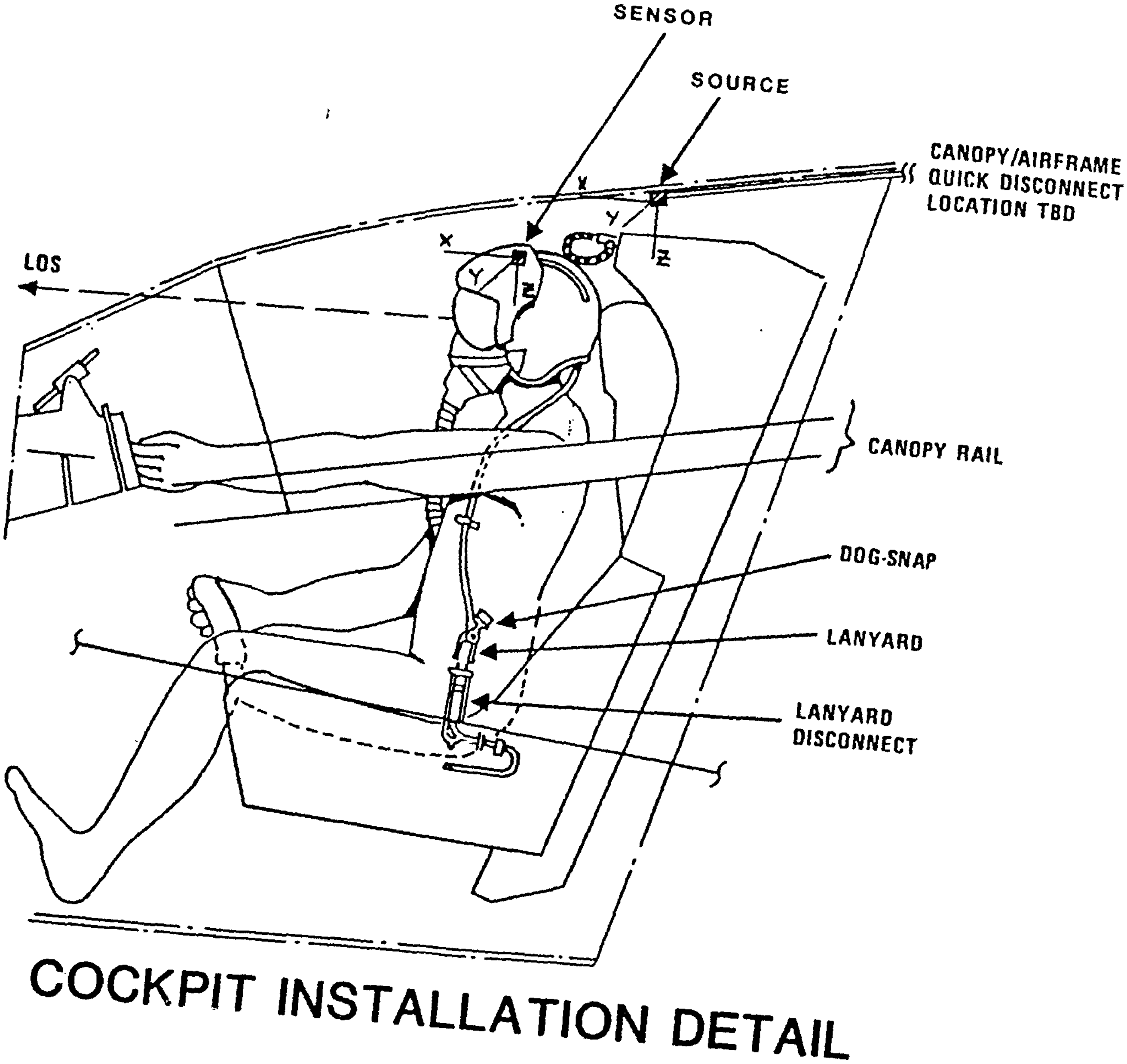

Figure 8.1. *Helmet-Mounted Tracker System (HMT) in F-15*

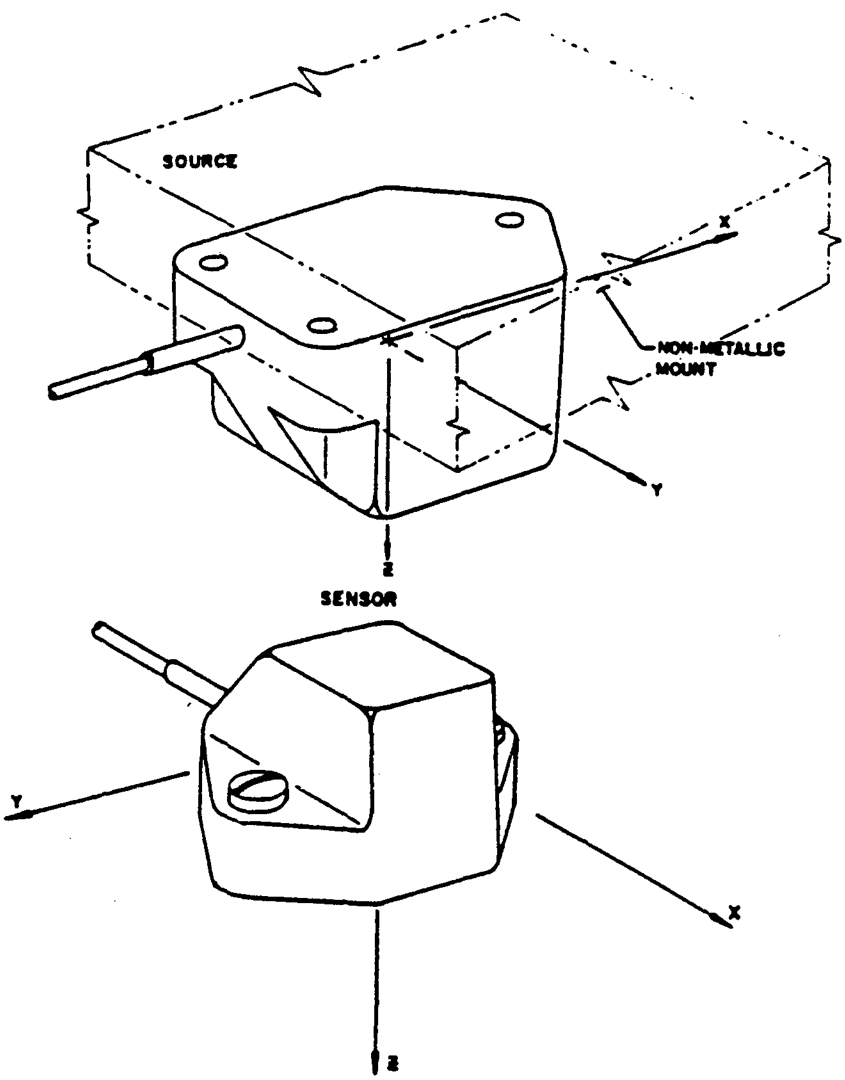

Figure 8.2. *MAGNETRAK HMT Source and Sensor*

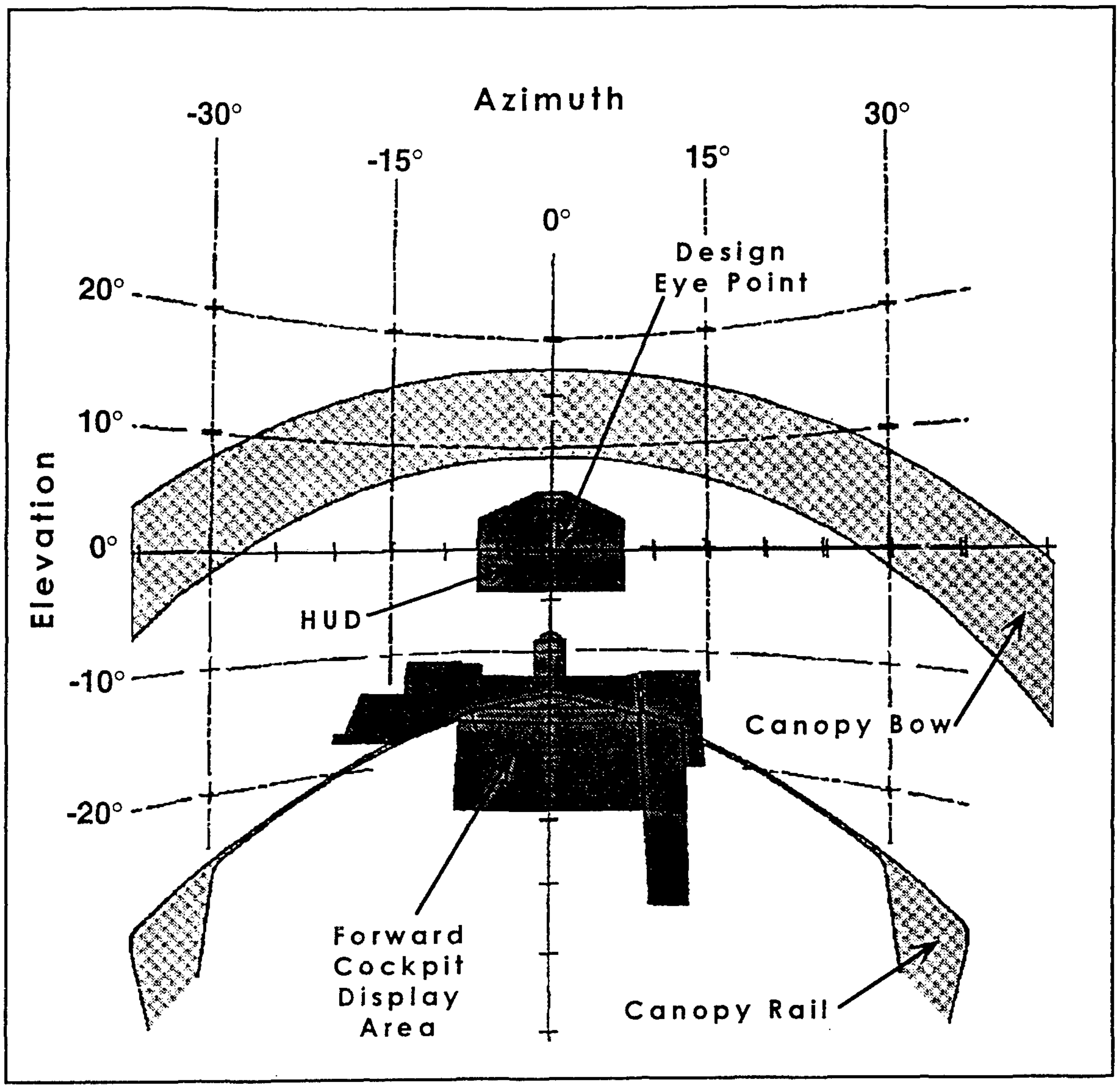

Figure 8.3. *Forward view of F-15 cockpit from design eye viewpoint showing structures which may block external visual objects. (adapted from McDonnell Douglas Aircraft original image)*

9. GLOSSARY

AOB - Angle of Bank

attitude - the angular position of an aircraft, determined by its orientation in pitch, roll and heading with respect to some reference point (usually the earth below).

Coronal Plane - the roll plane; that human plane which divides the anterior of the body from the posterior.

FOV - Field of View

G-forces - normal acceleration value measured in g's

Gz - the normal acceleration (in g's) in the body axis which runs from head to foot

g - unit of gravitational force; 1g = force of gravity on Earth = 32.2 ft/sec^2

head-mounted tracker - a system worn by a user which provides an output being the orientation of the user's head.

helmet-mounted display - a system worn by a user which projects a continuous image, usually visible only to the user, yet allowing freedom of motion of the head.

HMD - Head or Helmet Mounted Display

HMT - Head Mounted Tracker

HMCS - Helmet Mounted Cueing System

HUD - Head Up Display

IFR - Instrument Flight Rules, conditions during which the pilot uses internal aircraft displays to fly and control the aircraft.

IMC - Instrument Metereological Conditions (*See* IFR)

NVG - Night Vision Goggles

OKCR - Optokinetic Cervical Reflex (also: Opto-Kinetic Cervico Reflex)

SA - Situational Awareness; or Spatial Awareness

SD - Spatial Disorientation

symbology - term used to describe the graphical representations (or symbols) on displays such as those found on aircraft computer displays.

system - the combination of human and physical components. As defined by human factor engineering, the human operator is included as component of the full system.

telemetry - system by which data is transmitted via electrical signal from an active device to a recording device. For example, aircraft data can be sent to a ground station where it is recorded for later use.

VCS - Visually Coupled System

virtual reality - the attempt to create a realistic, three-dimensional environment or synthetic immersive environment in which the user(s) can function and interact (see, hear, touch, feel, smell, sense, taste).

VFR - Visual Flight Rules, conditions during which pilot uses external visual objects to fly and control the aircraft

VMC - Visual Metereological Conditions (*See* VFR)

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