Modeling and Mitigating Spatial Disorientation in Low G Environments: Year 1 Report

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Executive Summary

This report describes the goals and progress of the project entitled "Modeling and mitigating spatial disorientation in low g environments" for NASA's National Space Biomedical Research Institute (NSBRI) by the team of Alion Science and Technology Corp., and the Massachusetts Institute of Technology's (MIT's) Man Vehicle Laboratory. The report captures the team's first year accomplishments during this four-year project and articulates the team's Year 2 plans and beyond.

The goal of this collaborative industry-university research and technology development project is to extend Alion's spatial disorientation mitigation software – originally developed for aviation – to NASA applications in the Space Shuttle, Crew Exploration Vehicle, the International Space Station, Altair lunar lander, and Mars exploration mission. Extensions to Alion's software include adapting and adopting algorithms from MIT's spatial orientation models, as well as Frame-of-Reference Transformation (FORT) theory concepts.

The four overall specific aims of the project, and first year progress on each, are as follows:

1. Extend Alion's Spatial Disorientation Analysis Tool (SDAT) by enhancing MIT's *Observer* models and incorporating a version into SDAT. Enhance SDAT with pilot head movement data, and visual attention cues. Validate enhancements with existing and new flight data sets.

   Progress: We have extended the MIT Observer model so it predicts linear velocities and displacements in a world coordinate frame, it can operate in 0-g and partial g cases, and it mimics specific spaceflight illusions. Visual inputs are being incorporated. We are evaluating how the Observer algorithms could best be incorporated into SDAT. In addition, we designed a visual FORT model. We have obtained spaceflight data sets (from the Space Shuttle and lunar lander simulators) and still have more to obtain (e.g., Apollo data) with which we will verify and validate the enhancements.

2. Extend SDAT assessments to include typical space vehicle illusions: Inversion, Visual Reorientation, Tilt Gain, and Otolith Tilt-Translation Reinterpretation. Validation will include assessment of Shuttle landing data, and Altair simulator data.

   Progress: In addition to the related accomplishments mentioned above, we devised scenarios to examine predicted perceived orientation via SDAT and Observer analyses, and have begun those analyses of Shuttle and Altair simulator data sets. SDAT has been enhanced with additional illusion sequences, specifically for somatogravic and lateral drift perception illusions.

3. Further extend SDAT by examining alternative visual reference frames. FORT is used to predict the cognitive cost of transitioning between reference frames. Validation of Aims 1-3 for SDAT will include parabolic flight experiments.

   Progress: We designed a FORT model and will incorporate its cost portion into SDAT. We have begun to plan flight and simulator experiments to validate all enhancements to SDAT.

4. To further enhance SDAT assessor performance, pilot multi-sensory workload is considered in countermeasure selection. Validation experiments are not detailed, but will involve evaluations in ground-based simulators.

   Progress: Still being planned. Once we have verified and validated our models, we will assess the efficacy of various countermeasures triggered by SDAT during years three or four, based upon the scenarios devised in Aim 2, above.

Introduction

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Problem addressed by this research project

Astronauts, like aircraft pilots, may experience profound spatial disorientation (SD) during various flight phases, such as ascent, free fall, extra-vehicular activity, reentry, and landing. In contrast to the aviation environment, fortunately, there have as yet been no fatal accidents due to SD in space; however, there have been incidents caused, at least in part, by SD. Examples include:

- the Apollo 15 Moon landing that buckled the engine nozzle because of a misjudged crater slope and edge (Mindell, 2008)
- the Progress-MIR space station collision that was due, in part, to inadequate displays and frame-of-reference transformation problems (Ellis, 2000)
- several off-nominal Space Shuttle landings, starting with STS-3, some with very high sink rates due in part to commanders over-controlling pitch (McRuer, 1992)
- numerous cases of space motion sickness that interfered with operations, beginning with Apollo 7 (Mindell, 2008)
- extra-vehicular activity (EVA) height vertigo
- International Space Station (ISS) visual reorientation illusions (VRIs). A VRI is when a crewmember moves between two ISS modules and is confused about his or her orientation. The hazard of a VRI is that an astronaut may not be able to quickly evacuate the ISS in an emergency.

After returning to Earth, re-adaptation problems for long-duration space flight include balance problems, and otolith tilt-translation reinterpretation (OTTR) and tilt-gain illusions. An OTTR illusion is when otherwise stationary astronauts, re-adapting to 1 g, tilt their heads and feel as though they have moved (translated) a large distance in the opposite direction. A tilt-gain illusion is when it feels like one’s head has tilted to a greater angle than it actually has (Oman, 2007). Both illusions are most pronounced immediately after the transition from micro-g to 1 g; after several hours they usually dissipate completely.

Finally, vision plays a dominant role in human orientation. Visual cues often nullify the confusion from conflicting vestibular or proprioceptive cues; at other times, confusing visual cues exacerbate an SD event. In particular, we examine frame-of-reference transformation (FORT) problems. These problems are characterized by a human operator controlling a vehicle or manipulator (e.g., a robot arm) whose orientation or direction of motion is not aligned with the same coordinate system as the human operator’s body. Of course, such FORT challenges are not limited to space activities, but we focus only on such activities in this project.

Many of these SD problems are momentary and have few practical consequences (e.g., EVA height vertigo). Others have significant implications for the manual control of spacecraft (e.g., during docking or landing phases), for navigation within space stations, and for the critical control of space subsystems (such as robotic manipulator arms).

Original goals

The goal of this collaborative industry-university research and technology development project is to extend Alion's spatial disorientation mitigation software – originally developed for aviation – to NASA applications in the Space Shuttle, Crew Exploration Vehicle (CEV), ISS, Altair lunar lander, and Mars exploration mission. Extensions to Alion's software include adapting and adopting algorithms from MIT's spatial orientation models, as well as FORT concepts. Alion's and MIT's tools will be explained in detail later; for now, a brief introduction to each is necessary to understand the project's overall goals.

Alion has two patent-pending tools for SD applications: (1) The Spatial Disorientation Analysis Tool (SDAT) is for *post hoc* analyses of aircraft trajectory data (Small et al., 2006). SDAT has been useful in analyzing mishap data sets from the U.S. Air Force, Navy, and National Transportation Safety Board (NTSB) to determine the presence or absence of vestibular SD. It has a 75% SD detection accuracy rate. (2) The Spatial Orientation Aiding System (SOAS) is a real-time *in situ* cockpit aid that has been evaluated in simulators with rated pilots (Wickens et al., 2008). SDAT and SOAS use common software as much as practical. Both incorporate models of the vestibular system and assessor heuristics to predict the epoch and probability of an SD event such as the Leans, Coriolis, or Graveyard Spiral illusions, as well as any other significant disparities between actual and perceived pitch attitude (e.g., due to somatogravic illusions), roll rate, or yaw/heading rate. SOAS also assesses the human operator's multi-sensory workload to determine the types of countermeasures to trigger during a detected SD event and when to trigger them. For example, if the operator's visual workload is high, SOAS will emphasize auditory or tactile cues.

MIT's *Observer* is a set of models, developed over many years, whose purpose is to compute the human's central nervous system (CNS) integrated estimation of "down" in any gravito-inertial environment (Young et al., 1969, 1984, 1986; Oman, 1990, 1991, 2003; Merfeld et al., 1993; 2002). Observer uses published experimental results to combine vestibular, visual, and proprioceptive cues into an overall CNS response to body tilt and translation motions by estimating a resolved gravito-inertial force at any given time.

With the above as a brief background, the goals of this four-year project are to:

1. Enhance Alion's SDAT/SOAS by including algorithms from MIT's Observer model, particularly those for vestibular and visual sensory cues. Also SDAT/SOAS will adapt and adopt from Observer its CNS gravito-inertial force resolution for perceived tilt and translation estimates. We will validate enhancements using existing and newly acquired aerospace data sets.
2. Extend the models to describe 0-g maneuvers, as well as Shuttle and Altair landing illusions. We will validate the extended models using Shuttle and Altair simulator data sets, current theories, and archived Apollo lunar module data, if available.

3. Extend SDAT/SOAS to consider multiple visual frames of reference, the effects of visual attention and sensory workload, and the cognitive costs of mental rotation and reorientation. The enhanced SDAT/SOAS from goals 1-3 will be validated via simulator or flight experiments, or both, in Years 3 and 4.
4. Tailor SOAS for lunar landings, using multi-sensory workload to choose appropriate countermeasures and their timing. Countermeasures will include one or more of the following, as conditions warrant: control command displays; 2D and perspective synthetic/enhanced vision displays; attitude indicator formats tailored for physically redirected off-velocity-vector viewing; auditory cues and commands; and, tactile cues and commands.

As context for explaining Year 1 accomplishments and Year 2 plans, we next describe the background of the three key components of this research: SDAT/SOAS, Observer, and FORT.

Alion's Spatial Disorientation Analysis Tool (SDAT) and Spatial Orientation Aiding System (SOAS)

Alion's SDAT and SOAS began as a multi-sensory solution to aviation SD, funded by the Air Force Research Laboratory (AFRL). The goal was to develop a cockpit system, SOAS, to help pilots recognize when they were disoriented and to help them recover from SD events. Because of the difficulties in developing and certifying a cockpit system, Alion also pursued an intermediate step, SDAT, to help us better understand and characterize SD events. For both tools, the keys to helping disoriented pilots are to reliably detect such events and then to apply appropriate countermeasures to prevent the adverse consequences of SD (Figure 1). Our AFRL research concentrated on fixed-wing aircraft because they are much more prevalent in the Air Force, and because helicopter data sets (for in-depth analyses) were difficult to obtain. Furthermore, our focus was on fixed-wing aircraft because our resident subject matter expert (SME) was a retired USAF fixed-wing pilot.

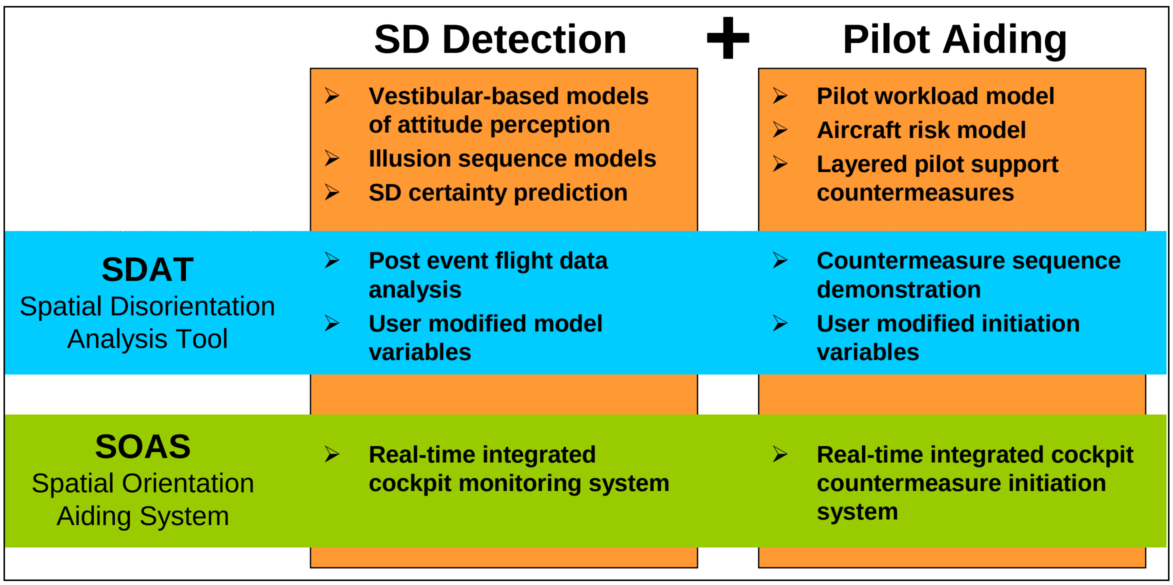

Figure 1. SDAT and SOAS philosophies and commonalities.

To detect SD, we focused on four conditions that relate to known susceptibilities of the human vestibular system:

1. Aircraft motions that are below the human threshold of detection. So, the aircraft attitude or direction of motion changes, but the pilot does not detect the change.
2. Sustained aircraft rotations (typically turns in the heading axis) that are no longer sensed by the pilot's vestibular system because the aircraft's angular velocity has stabilized, and the fluid in the semi-circular canals (SCCs) gradually returns to its original neutral position. Thus, as the aircraft continues to turn the pilot's SCCs no longer register the turn (assuming a constant-rate turn).
3. Stopping sustained turns (as when rolling-out on the desired heading) that yield erroneous sensations of turning in the opposite direction. This illusion is due to the SCCs acting as accelerometers, so that stopping a turn is a deceleration.

4. Airspeed changes that feel like pitch changes as sensed by the otoliths. The otoliths, like the SCCs, act as accelerometers. When airspeed increases, it may be misperceived as a pitch increase. When airspeed decreases, it may be misperceived as a pitch decrease. (For details about vestibular physiology in flight, the reader should consult DeHart & Davis, 2002; Young, 1984; Cheung, 2004.)

In addition to modeling these four conditions, SDAT/SOAS models common aviation illusions, such as the Leans, Graveyard Spiral, Coriolis, and somatogravic illusions. For details, interested readers should review the final report for our AFRL project (Small et al., 2006).

Once an SD event is reliably detected, appropriate multi-sensory countermeasures must be applied to help the pilots recover. SOAS's approach is that countermeasures should be applied in sensory channels that are available for processing critical information, and should only be applied when detection confidence is high and when the consequences of the SD event are unacceptable. These notions merit further explanation; first the multi-sensory nature of countermeasures, and then the severity of the SD event.

For multi-sensory countermeasures, SOAS provides recovery guidance in a sensory channel that is presumably not overloaded in the present circumstances (Wickens et al., 2008). For example, if the pilot is pulling a large g-load during an SD event and his/her vision is consequently narrowed, SOAS will use auditory cues to help with the recovery. If the auditory channel is overloaded due to radio chatter, then tactile recovery cues are more appropriate. SOAS also cues recovery actions in multiple channels to maximize the pilot's chances of noticing the cues and executing swift corrective actions. For example, auditory and tactile cues reinforce each other, as do visual and auditory cues. In many cases, all three cue modes will be used, if the situation warrants. This approach was experimentally validated with Air Force F-16 pilots in a simulator (Wickens et al., 2008).

SOAS also assesses the severity of the situation while selecting countermeasures. For example, if the SD event is at high altitude and only results in minor erratic control of the aircraft, then less intrusive countermeasures (e.g., visual cues) are triggered. However, if the pilot is so disoriented that aircraft control is lost and the aircraft is hurtling toward the ground, then more intrusive countermeasures are warranted. Such countermeasures would include all three of the above (visual, auditory, and tactile), and would progress to auto-recovery (if the aircraft is so equipped), and even to auto-ejection in order to save the pilot's life if the aircraft is damaged and unable to recover.

To summarize the AFRL research, SDAT/SOAS modeled the anticipated responses of the SCCs and otoliths to detect SD events, and to enable multi-sensory countermeasures based upon the situation and the pilot's multi-channel workload to help pilots recover from SD events.

To verify and validate our models, we used SD mishap data sets, we conducted pilot-in-the-loop experiments for countermeasure efficacy tests, and we analyzed data sets where an SD occurrence was unknown (to us at least). Early data sets and those generated by the Alion research team using desktop simulators, were used to fine-tune our models. Later data sets were used to verify and validate SDAT and SOAS (Small et al., 2006).

The challenges for the current research are to extend SDAT and SOAS into the space domain. Toward that goal, we have discussed space SD situations with domain experts, acquired actual space vehicle and simulator data sets, and have begun enhancing SDAT/SOAS with additional illusion models, as further explained in the Year 1 Accomplishments section.

MIT's Observer

Observer is a tool developed using Matlab/Simulink (release 2008a) to predict the time course of 3D human spatial orientation and eye movements in response to complex angular velocity and linear acceleration stimuli. As compared to earlier research versions, the current version of Observer is designed to be more easily used by sensorimotor investigators, human factors engineers and by disorientation incident/accident investigators. Although originally validated using 1-g human and animal data, the model is being extended to predict responses in 0-g, 1/6 (lunar) g and 3/8 (Mars) g, and the presence or absence of visual cues. It can also mimic head movement contingent vertigos events after spaceflight. Inputs to Observer are time series data supplied via Excel spreadsheet using a specific format. After each simulation, Observer displays a family of 2D plots of model inputs and outputs. A separate 3D visualization window dynamically displays the time course of Observer model "down" and "azimuth" estimates.

Observer model history

The non-visual, 1-g aspects of Observer largely derive from our 1993 multidimensional spatial orientation model (Merfeld et al., 1993) and subsequent structural and parameter value refinements by Haslwanter and colleagues (2000), and Merfeld and Zupan (2002). The idiotropic bias calculation is partly derived from Vingerhoets and colleagues (2007), and concepts articulated by Mittelstaedt (1983) and others. Visual bias effects are based on vector models suggested by Oman (2003), Laurence Harris (personal communication), and Groen and colleagues (2007). Simulations of astronaut OTTR and Gain illusions are from anecdotal descriptions and the ROTTR hypothesis proposed by Merfeld (2003).

The notion that human spatial orientation could be phenomenologically and mathematically described using "Kalman Filter" techniques borrowed from estimation and control theory was first demonstrated by Young and coworkers (Borah et al., 1979). Subsequent MVL modeling efforts (e.g. Bilien, 1993) showed that human orientation perception dynamics may not be truly "optimal" in a theoretical sense – much faster dynamics of a different order would be expected than are actually seen. Nonetheless, as noted by Oman (1991) the more general "observer" concept of state estimation – updated by sensory conflict signals derived from internal models of body and sense organ dynamics – remained useful, even if the human was not truly an "optimal" observer. The "sensory conflict" notion also provided a parsimonious hypothesis for the essential stimulus for motion sickness. Observer-based models currently underlie the widely accepted sensory-motor conflict theory for motion sickness (Reason, 1978; Oman, 1990), and several related theories (e.g., Bos & Bles, 2002).

Observer models for vestibular cue interaction have been validated using perceptual and eye movement data from humans, and eye movement data from animals, all of whom were passively accelerated (i.e., they did not control the motions they experienced). The models capture the main features of response data for a variety of different stimuli in a 1-g environment, including off vertical axis rotation (OVAR), linear acceleration, and centrifugation with a single set of up to five free parameters. In this sense, Observer models have emergent properties, and can play a useful role in quantitative hypothesis testing and refinement. For example, it can be applied to the current debate (e.g., Merfeld et al., 2005) as to whether or not the human vestibular-ocular reflex (VOR) is as closely coupled to orientation perception as originally suggested by the models of Haslwanter and Vingerhoets.

Observer describes the input-output relationships learned or genetically prewired in CNS neural networks, which presumably function without the explicit vector and quaternion mathematics used by the Matlab simulation. As noted by Oman (2007), electrophysiological and anatomical evidence supports the notion of brainstem “velocity storage” neurons, and limbic head direction, grid and place cells coded in a 2D horizontal plane whose orientation is apparently determined by the perceived direction of “down.” However, the components of the present Observer model that represent the effects of vision must be considered preliminary, and require further validation. Only visual orientation and angular velocity cues are presently being considered; landmark distance cues and ambiguities in visual frames of reference due to “frame” and “polarity” cues (Oman, 2003; 2007) are not yet incorporated.

Figure 2 is a block diagram of Observer. Observer uses a quaternion vector integrator to calculate the perceived “down” vector. For rotations about the axis of gravity, the primary drive to this quaternion rotator comes from the angular velocity estimate, weighted by a gain (“kwf”). The estimated azimuth is calculated by integrating the estimated angular velocity in a plane perpendicular to the estimated gravitational vertical. During off-gravitational-vertical-rotation of the head, the changing otolith signal provides an additional cue to angular rotation. Observer compares actual and expected otolith signals, and computes the vector difference between them. This vector, weighted by the gain “kf,” provides a second important “down” rotational input to the quaternion rotator. Since the GIF error vector also provides a cue to angular motion, this is weighted by a gain, “kfw,” and added into the angular velocity estimation. During constant velocity OVAR, this pathway creates sustained rotation sensations, and ultimately contributes a constant bias component to the VOR, long after SCC cues have disappeared.

In 1-g, the interaction between semicircular canal and otolith cues in the Observer model is thus determined by the four observer parameters (ka, kf, kw, and kfw) in both humans and monkeys (Merfeld et al., 1993; Vingerhoets et al., 2007). A fifth GIF gain, “kwf,” has been added so the model will mimic post-landing tilt-gain illusions in astronauts returning to 1-g from space. Otolith-tilt-translation-reinterpretation (OTTR) illusions after spaceflight can be approximated by setting the GIF feedback gain, kf, to a low value (e.g., 0). Observer accounts for the dynamics of these illusions; for example, it mimics the anecdotal descriptions by returning astronauts that a sustained head tilt does not yield a sustained perception of motion, only an initial illusion.

Some outputs of Observer are as follows. Observer’s *visualization* feature opens an animated vector plot of actual (red) vs. estimated (blue) direction of g and azimuth over time (Figure 3). Observer describes all head motions using a right-handed head-fixed inertial coordinate frame, with the X axis pointing forward, the positive Y axis pointing out the left ear, and the Z axis pointing upwards as noted in Figure 4.

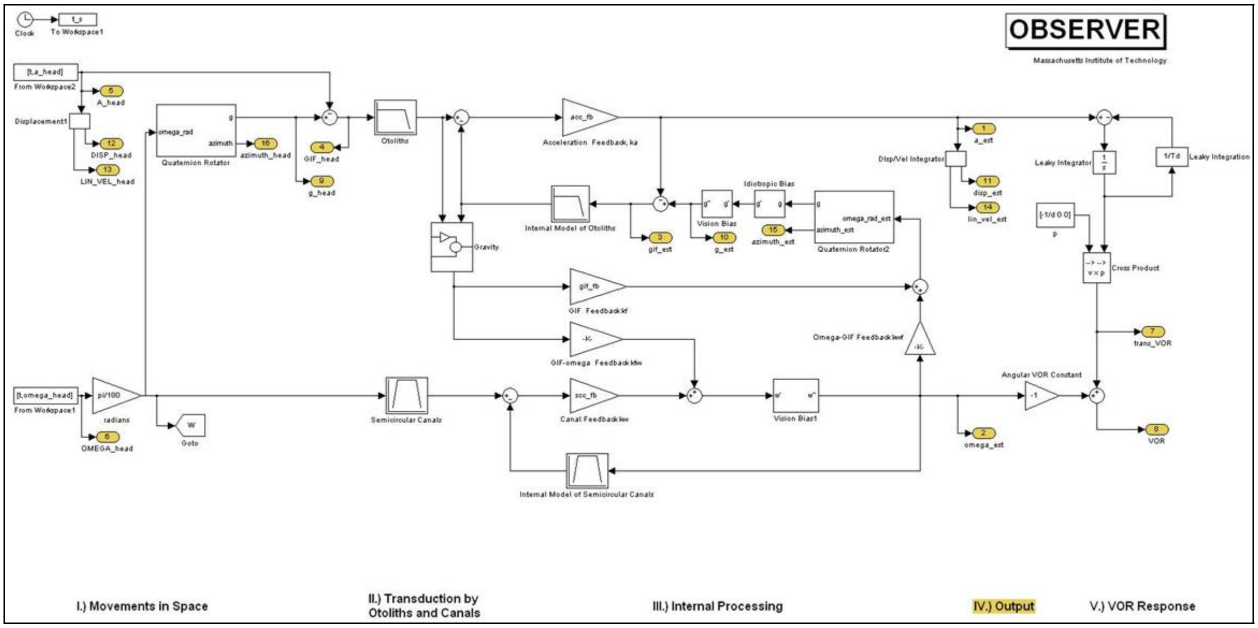

Figure 2. Observer block diagram.

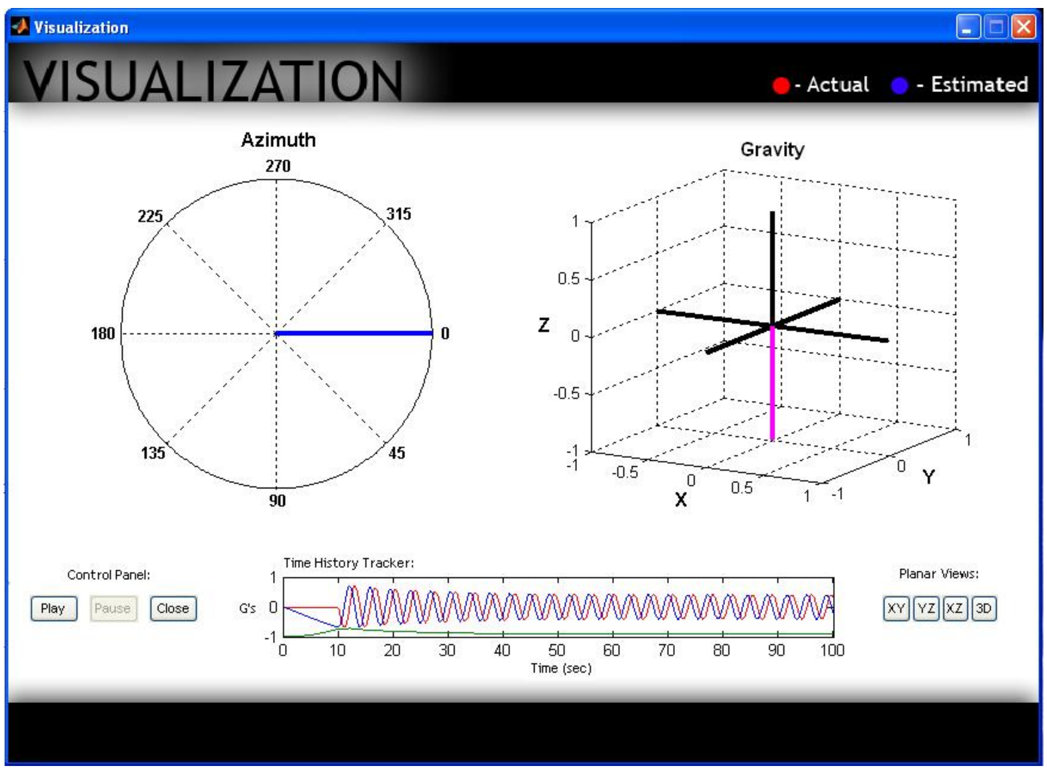

Figure 3. Observer output of estimated azimuth and "down" (labeled as Gravity).

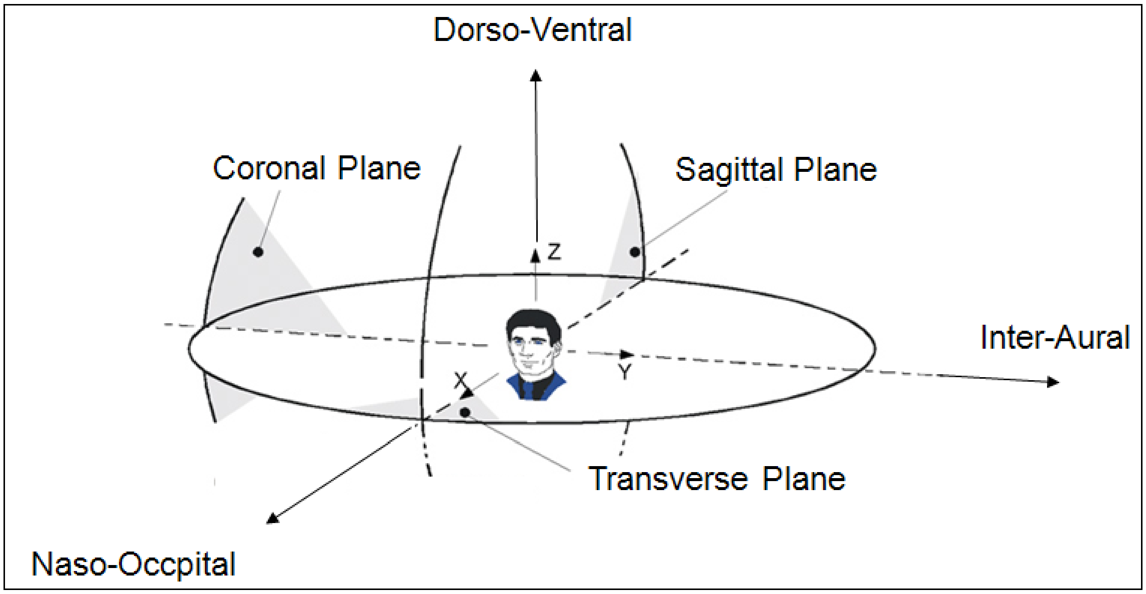

Figure 4. Observer coordinate system.

In summary, Observer models are founded on human and animal experimental results, as well as anecdotal observations of specific phenomena. As such, Observer complements SDAT's less theoretical approach to assessing motions for their potential to create orientation difficulties. In contrast to SDAT's applied focus, Observer does not suggest disorientation countermeasures *per* se. The two approaches are complementary and point toward the original goal of combining them to potentially detect disorientations more accurately, using Observer, and then applying appropriate countermeasures using SDAT/SOAS.

The newest element that will impact both the Alion models (SDAT/SOAS) and the MIT MVL models (Observer) is FORT – a frame-of-reference transformation theory that accounts for the disorienting potential of working in multiple visual frames of reference.

Frame-of-Reference Transformation (FORT)

To set the context for the FORT model, we suggest a scenario in which a crew is 200 miles above Earth as a Shuttle steadily approaches the ISS for docking. The commander, using reaction control jets, moves his translational hand controller (THC) to carefully align the spacecraft with the docking port, while viewing the error of alignment at an off angle – because the status and position display is oriented 90 degrees from the axis of control and of the approach as shown in Figure 5. At the last moment, just before contact, the commander moves the THC in the wrong direction from that intended. The Shuttle's docking ring fails to engage the docking receptacle, rebounds, and is damaged by the off-axis impact.

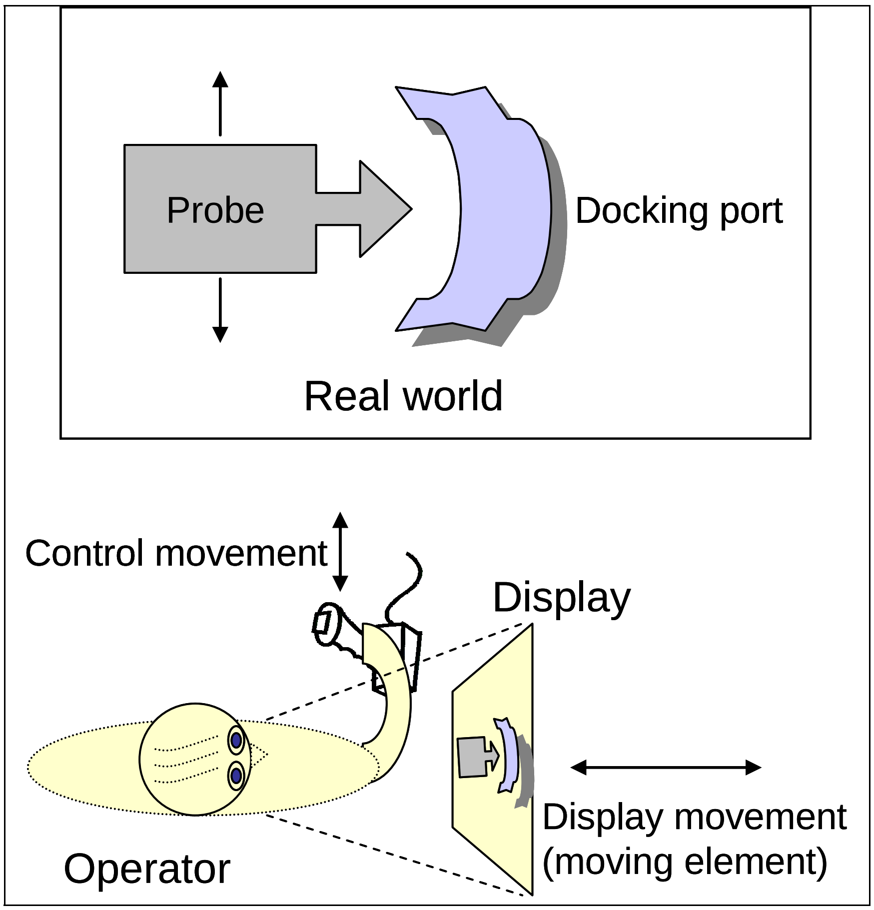

Figure 5. Docking task: reality vs. display-control alignments.

It is quite likely that such a hypothetical but plausible error could have been due to spatial disorientation, since the axis of control did not correspond to the axis along which the error was perceived. The human operator was required to make a frame-of-reference transformation (FORT). FORT theory is designed to understand the nature and cause of such errors. Below, we describe the theory and our efforts to translate this into a usable computational model.

FORT is designed to predict the response time or speed, the error likelihood (including both discrete and continuous errors), and the mental workload imposed in any circumstance in which the astronaut needs to translate from one frame of reference to another.

FORT theory, and the FORT model described below, can be applied to two general classifications of tasks: (1) **image comparison** tasks, such as those when the astronaut examines a diagram or map and tries to establish how items on the diagram or map correspond to those in the real world; and (2) **control** tasks, for example the continuous alignment task described above. Furthermore, these two tasks can be carried out in any of the following three situations:

1. Self orientation: either out of vehicle (EVA) or in vehicle (IVA). In the former case, astronauts may be navigating to a particular landmark on the spacecraft. In the latter, they may be deciding which exit to take to go from one ISS node to another.
2. Vehicle navigation and control: for example (a) rendezvous with another vehicle from a distance, (b) docking with another vehicle, or (c) guiding and landing a vehicle on a lunar surface.
3. Robotics control.

We also note three important uses of the FORT model, designed to predict astronaut performance in these environments:

1. Using a task analysis, we can identify "red flags" or particularly challenging control-display configurations with specific tasks, which will invite errors. In some circumstances we will be able to predict the time required to perform certain FORT maneuvers, a critical prediction in certain time-critical, time-limited situations (e.g., approaching a landing or docking; executing emergency procedures).

2. Embedded within FORT theory are costs associated with transformations. Given this, it should be straightforward to use the model to identify various countermeasures when such red flags appear; countermeasures that may vary in their feasibility and degree of success. In the case of the misaligned display cited at the outset (Figure 5), it may be that a full repositioning, so that the error is viewed straight on, is impossible because of other physical constraints. But, relocating the display 20 degrees toward the operator's trunk alignment and axis of control movement in Figure 5 will mitigate some control-display confusion problems.

3. FORT can be used as a retrospective mishap analysis tool, analogous to the manner in which SDAT is employed, so long as certain key data are available, regarding the interface design and a time record of actual control activity and system state.

Elements of FORT

Fundamental to the frame of reference theory and model is the notion of a **disparity** between the frame of reference of perception and that of the world (for image comparison) or of action (for control) (Wickens, Vincow, & Yeh, 2005). For example, the disparity most relevant to many aviation SD mishaps is that between perceived (ego) and actual (world) gravitational upright. In fact this is just one of a larger set of six dimensions along which a disparity can lie (pitch, roll, yaw alignment, and X, Y, Z translation). A disparity in Z occurs when the perceived altitude is different from the actual altitude; in aviation such a disparity invites the possibility of a hard landing, for example. FOR disparities also include the first and second derivatives of each of these six axes, yielding a total of 18 variables that could enter into a vector of *FOR disparity*. FOR disparities become even more complex in much of vehicular travel (typical of space operations) when a separate FOR can be defined for the Earth (or moon or planetary body), for the vehicle, and for the operator. Additional frames may be defined around robotic manipulators (particularly as these are mounted with cameras), and around the head as separate from the trunk; for example, when astronauts and pilots engage in off-boresight viewing.

The focus of FORT theory is to model the costs resulting from FOR disparities. Typically these costs can be measured as operators attempt to **transform** one FOR into another (e.g., "how do I move my control to move the probe upward?") (Wickens, 1999). Such costs are reflected in human error (if the correct transformation is not accomplished), in time costs, and in mental workload costs. The classic example of such a cost is manifest in the yaw axis when a navigator is using a north-up map to navigate in a southerly direction (Aretz & Wickens, 1992; Olmos et al., 1997). The navigator employs 2D mental yaw rotation of 180 degrees to assure that left and right in the forward view (ego frame) correspond to desired headings on the map (world frame). The rotation showed in Figure 5 is a 90-degree rotation. Such mental rotation costs are found to increase generally monotonically with the degree of disparity, to cause added mental workload (competing with other tasks) (Wickens et al., 1996), and to occasionally lead to reversal errors in control and spatial judgments.

Six additional levels of complexity imposed on FORT theory are:

1. As noted above, there are actually 18 components along which disparities may be defined. Thus even at a simple level, one could speak of the degree of FOR disparity scaled from 0 to 18 depending on how many components are affected.
2. Disparities along different axes are not all equally serious. For example, disparities along the pitch axis are less serious than those along the yaw axis (Cizaire, 2007). Thus it is easy to follow a map, whether it is held vertically or horizontally because the transformation from vertical to horizontal is simple (Franklin & Tversky, 1990; Wickens et al., 2005). However it is considerably more demanding to navigate with a map that is rotated 90 degrees in the yaw axis (so that, for example, forward in the world is right on the map). Thus different transformation components should be weighted differently. In Figure 6, we depict the smaller mental rotation cost translating between a fore-aft axis and a vertical axis, than transformations involving the lateral (left-right) axis.
3. Also, as shown in Figure 6, across the three rotational components of transformation (pitch, roll, yaw), the function relating human performance cost to degree of disparity is not linear, but appears to be an "S" shaped or ojival function. Again, as a straightforward example, both vertical and lateral mental rotation costs are disproportionately small for small angles, but show non-linear increases as disparity increases toward, and then above, 90 degrees (Wickens, 1999; Hickox & Wickens, 1999; Schreiber et al., 1998).
4. Top-down knowledge-driven strategies sometimes appear to override the rotation operations. This phenomenon becomes quite prominent when mental transformations at or near180 degrees are required, as shown in Figure 6. Here people often adopt a verbal "left is right, right is left" or "up is down, down is up" strategy, thereby allowing shorter response times than those predicted by a full 180-degree mental rotation. For example Cizaire (2007) observed that a 180-degree rotation in pitch required no more time than a

90-degree rotation in the same axis. Such knowledge-based strategies appear to become more prominent in known and human-constructed environments, with designated walls, ceilings and floors, such as is typical when moving about a space station (Cizaire, 2007).

5. One particular FOR difference, that is also knowledge driven, is the understanding or mental model of what is "fixed" and what is "moving" on a display. Thus, in aviation, pilots have differing degrees of control effectiveness depending on whether controlling attitude with a moving aircraft or moving horizon display (Previc & Ercoline, 1999; Roscoe, 2002; Kovalenko, 1991). Confusion between the perceived FOR can cause undesirable control reversals, which could produce potentially catastrophic results in precision maneuvering (e.g., final approach to docking as described at the start of this section and in Figure 5).
6. While FORT can be costly, it is sometimes better to maintain a consistent control-display (or display-display) transformation across different systems or different components of a single system, than to require the astronaut to switch (inconsistently) from one relationship to another (Andre & Wickens, 1992).

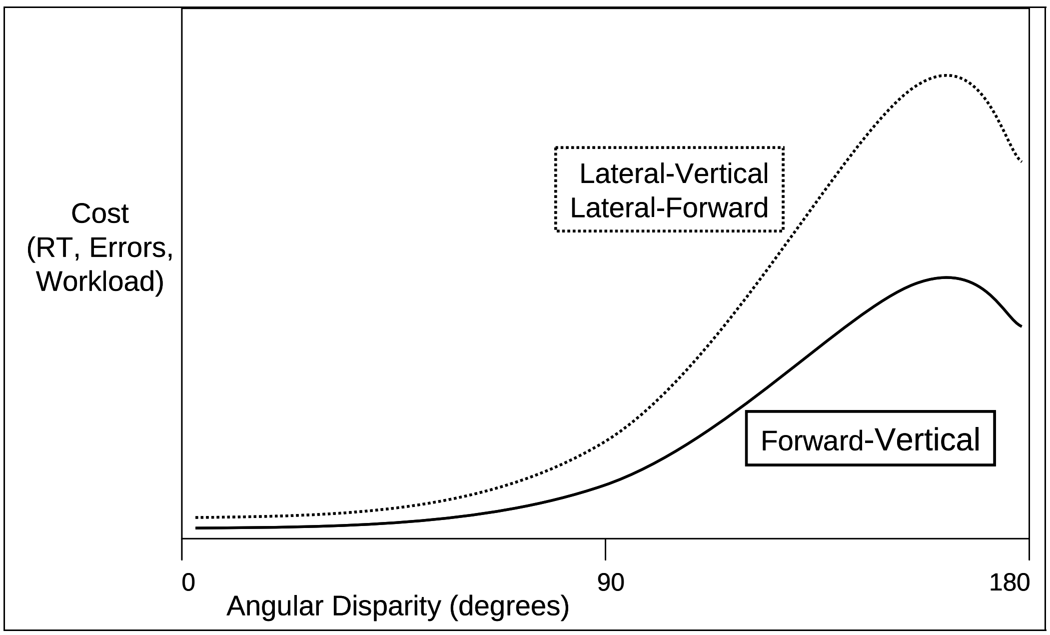

Figure 6. Costs of frame of reference transformations.

A FORT model based upon FORT theory can serve two interacting goals. First, given any definition of spatial task requirements and specification of visual information sources (displays, and out-the window views), it will predict the cost vector imposed by required transformations. This vector can be characterized by delays in making spatial decisions (including those necessary to exercise control), increased interference with concurrent tasks (reduced capacity for multi-tasking), and increased likelihood for errors. Second, the model can predict the effectiveness of particular display formats or augmentations in reducing or minimizing transformations, and hence minimizing workload (Gillingham & Wolfe, 1986). As a straightforward example, FORT predicts the substantial gains in flight control performance associated with synthetic vision system (SVS) displays (Alexander, Wickens, & Hardy, 2005). Such displays can be either status displays or command displays (Andre & Wickens, 1992). It is important to note that any display suite is typically required to serve more than one task. For example, a landing display must support both trajectory and speed controls, as well as obstacle awareness. FORT can help guide the designer on the choice of an appropriate display suite, or compromise display, that can minimize the aggregate FORT costs for a set of tasks (Wickens, 2000a; Wickens et al., 1996).

While formal algorithms have not yet been developed for a FORT model, the approach will be to analytically capture the curvilinear relations in Figure 6. Net costs for simple rotations can be modeled by establishing the angular disparity along each axis and summing across axes, using a 50% weighting for forward-vertical transformations, and unity weighting for the other two transformations. The FORT cost model could be more complex by considering first and second derivatives, as well as translations. For this project at this stage, though, we will keep the cost model simple until we have more data and a greater need for the added complexity. Calculation of specific time costs will use the data reported below in FORT Research Results.

FORT Research Results

In addition to the above development of FORT theory and modeling, we have accomplished the following two major goals:

1. We have surveyed the literature on mental rotation in space, and using space-like tasks and observed that:
    - Mental rotation costs in space appear to be little affected by the micro-g environment, and show roughly the same costs as on Earth, about 1-2 seconds for 180 degrees of rotation (Kanas & Manzey, 2008; Leone, 1998).
    - The cost of single axis rotations is different across axes in typical astronaut tasks (Cizaire, 2007).
    - There is an important distinction between the mental rotation of objects, and the mental rotation of self within an environment. The former is referred to as object rotation, the latter as “perspective taking” (Kozhevnikov & Hegarty, 2001). This distinction and its implications are outlined in more detail below. Importantly, the costs of self rotation are at least as great as those of object rotation, the paradigm for which the greatest amount of data are available. For example, object rotation studies have been carried out in 0-g environments (Kanas & Manzey, 2008) whereas self rotation studies have not.

2. We have examined how FORT can be integrated with SDAT. This application will predict online (or from an accident data base) when FOR disorientation is a likely occurrence. This will be based on three components:
    a) a “trigger event” reflected in control activity,
    b) an initial frame of reference mismatch, and
    c) dynamic FOR changes.

    These three components are elaborated upon as follows.

    (a) **Trigger event** as a control activity: Two types of control activity are strongly suggestive of FOR disorientation:

- Control reversal. Here a control action is made that amplifies, rather than reduces, an error. To diagnose this, we need a continuous measure of the error in the relevant error-nullification (tracking) task, such as the disparity between robot manipulator and target. We also need a continuous reading of control activity, and an estimate of the time lag (e.g., transfer function) of the control system. In the absence of these three channels of information, it is possible to make a less confident assessment from the control data alone, for example, if there are high frequency reversals.

- Control delay. FOR mismatch may also be sensed if there is a delay in moving the control, **under conditions when it should be moved** (e.g., error and error velocity of the same sign). This indicates a hesitation as the operator is trying to decide how to control. Here again, the system needs a continuous error measure.

(b) **Pre-existing conditions**. The static FOR misalignment describes the fixed properties of a workstation, and considers the angular rotation, along the three axes of space, between the control movement, and the display movement as depicted in Figure 5. For convenience, we describe the three axes as lateral (left right), forward (fore aft), and vertical (up down), or L, F, and V. Within each axis, a geometric function of mismatch increases to 150 degrees and then decreases to 180 degrees of rotation. Furthermore, of the three axis pairings (LF, LV and FV), the first two, involving mapping to the lateral axis, are weighted twice as heavily as FV, reflecting the major left-right confusions in axis mapping. Weighted mismatch values are summed across all three axis pairs.

(c) **Dynamic misalignment**. This term reflects the fact that FOR disorientation is amplified if mappings continue to change. For example, an astronaut manipulates a fore-aft joystick mounted to a swivel chair or space suit such that fore-aft, when facing a forward display, becomes L-R, if the workstation is swiveled 90 degrees. Dynamic misalignment at any given moment is computed exactly as static misalignment above (e.g., integrated across axes). However, a running integrator of dynamic FOR change accumulates the amount of change over the previous X minutes to assess the degree of dynamic change.

Alternatively, in the above, pre-existing conditions could just be re-defined as the momentary misalignment vector at the time of computation, with the dynamic component adding to this disorientation cost proportional to the extent of change over the past X minutes.

In implementing FORT within SDAT, the idea is that the static and dynamic components will create a static and or time-varying predisposition to FOR disorientation. If this predisposition is high, then the control event classifier will be more likely to classify a given control reversal (or control absence) as evidence of FOR disorientation; or, alternatively, be likely to classify a small reversal as evidence.

Further development for FORT model

Currently there are only two frames of reference to be matched, with mismatch between these defined by the 3-component rotational vector represented in Figure 6. It is possible that effective control may require three frames: control frame, display frame, and end-effector frame (e.g., robot arm). This need for three frames will occur when the display depicts motion relative to the human trunk that is in a different vector from the actual end effector motion. For example, a display of forward motion mounted at a 45-degree offset from forward, or viewing the end effector (i.e., the controlled element; e.g., a robot arm) through a head-mounted display while looking off-boresight. With three such frames, we may want to sum or average the vectors of mismatch between each pair of frames (where each vector itself contains the three-axis components). We will also be extending FORT to accommodate additional spatial awareness biases, which can create visual illusions for astronauts in landing approaches or in lunar surface navigation (Wickens, 2002). These biases include estimating velocity, biases in global optic flow, surface slant overestimation, display size, or 3D display compression. Most of these biases can be expressed within the framework of FORT, to the extent that all 18 transformations are considered.

Object rotation vs. perspective taking

The distinction between object mental rotation (MR) and ego perspective taking (PT) is potentially important as an ability, a strategy, and a task, although such distinction will be shown not to have any substantial impact on the currently evolving FORT model. We note at the outset that because this distinction **is** clear, we will now and henceforth refer to “misalignment cost” rather than “mental rotation” within the FORT model, as characterizing the cost when there is a disparity in frame of references. Thus, consistent with the potential importance of the MR vs. PT distinction, MR now refers to one of three possible approaches to dealing with misalignments:

1. **As an ability**. Kozhevnikov and Hegarty (2001) have shown that mental rotation and perspective taking have much in common. A high correlation (r=0.69) is found between tests of the two abilities, indicating that roughly 50% of the variance is shared between them. In contrast, the set of four tests that differ between them appear to account for only about 10% of the variance (e.g., unique to PT, not shared by MR). Thus in general, correlation **differences** between PT and navigation tasks and MR for the same navigation tasks appear, at most, to be about 0.30, and in most cases there are no such differences. The most important such difference appears to be in finding a shortcut back to the navigational starting point, which is correlated significantly with PT (r=0.30), but not with MR (r=0.11). For the other three navigation task tests, examined by the researchers, the correlations are not different.

   Another feature of the data reported by Kozhevnikov and Hegarty (2001) is that smaller disparity angles (less than 90 degrees) generally show minimal costs in either perspective taking or mental rotation, hence conforming to the general non-linear findings of performance costs with alignment differences in the FORT model.

2. **As a task**. The interesting finding from Kozhevnikov and Hegarty (2001) is that the PT task shows **more profound** costs of misalignment at large angles (160 deg) than does the MR task, as if the former are more susceptible to the classic Shepard effects, wherein two

geometric figures are compared to see if one of them, rotated into alignment with the other, is identical to the other. Alternatively, it is possible that the verbally mediated reversal strategy (“left is right, right is left”) which works for both tasks at 180 degrees, can also be applied more fluently with the MR task, as angles approach 180 (e.g., 160). Note that our recent research with NTU in Singapore which used a distinct PT task both in navigating within 3D buildings (Liu, 2008) and in using hand held displays in naturalistic environments (Tan, Helander, & Wickens, in preparation), also showed profound misalignment effects at angles nearing 180 degrees.

3. **As a strategy**. It is unclear the extent to which people can adopt the two different (PT and MR) strategies when given the identical task. However some data from Kozhevnikov and Hegarty (2001) suggest that they can, and indeed may spontaneously, shift strategy to invoke whichever one best serves the task at hand.

Applications to and relevance of the PT-MR distinction for FORT model. Most of the data from our Illinois lab from which we developed a FORT model (Wickens, 1999; Wickens, Vincow & Yeh, 2005) appear actually to have used PT tasks rather than MR tasks (Aretz, 1991; Aretz & Wickens, 1992, Wickens et al., 1996; Olmos et al., 1997; Williams, Hutchinson, & Wickens, 1996; Hofer & Wickens, 1997; Hickox & Wickens, 1999). This research dealt primarily with pilots, navigating with maps that were misaligned from the environment. It is not entirely clear (because we never asked them) whether the pilots took the **perspective** of themselves traveling southward (or eastward or westward) on a north-up map, or **mentally rotated** the map to a south-up (or east-up or west-up) perspective. However, whichever strategy was used, the costs of misalignment were typically profound. In only one study did we examine ability differences. These were not assessed by performance on PT vs. MR tests as in Kozhevnikov and Hegarty (2001), but rather by whether pilots spontaneously rotated their map, or held it north-up (about a 60-40 split). One might posit that those who held the map north-up were better able to take a different perspective. In any case, this group was superior to the map rotators in their acquisition of survey knowledge (ability to reconstruct the map of the terrain through which they had traveled). Interestingly, the two groups did not differ in their ability to draw a direct line back to their starting place (an analogy to the “short cut” task used by Kozhevnikov and Hegarty (2001)).

In conclusion, given the **more profound** misalignment costs in PT than MR observed by Kozhevnikov and Hegarty (2001), and given the substantial misalignment costs observed in most of our research in aviation (pilots in simulators), these data do not seem to mitigate the importance of the misalignment costs we have been assigning in the FORT model. Hence we will continue to use these non-linear misalignment cost functions in the model, but pay particular heed to MR vs. PT differences when the paradigm and strategy analysis allows us to do so, and when such differences might lead to divergent predictions. We remain most interested in the influence of three additional top-down factors as they may influence misalignment costs: (1) the well documented “verbal reversal strategy” (e.g., saying “up is down and down is up”); (2) the qualitative differences among the three axes of rotation (e.g., greater left-right than fore-aft confusions) highlighted by Franklin & Tversky’s (1990) work; and, (3) the emerging importance of “wall-ceiling” differences and other distinct landmarks, revealed by Cizaire’s dissertation

(2007) and closely related grid biases, when misalignment occurs within man-made rectangular structures (Tan, Helander, & Wickens, in preparation).

Now that we have explained the three major components of this research (SDAT/SOAS, Observer, and FORT), we proceed to articulate the project team's Year 1 accomplishments.

Year 1 Accomplishments

During the project's first year, as intended, we focused on: understanding the domain and astronaut susceptibility to various disorienting situations; explaining SDAT/SOAS and Observer algorithms to each other; obtaining vehicle data sets for verification and validation tests; and, designing a visual frame of reference transformation (FORT) model. Each of these accomplishments brings us closer to achieving the overall project goals stated in this report's introduction.

The following major sections describe the project's first year results in the context of the five specific aims that the team pursued, which were to:

1. Understand astronaut SD issues.
2. Devise realistic scenarios that lead to astronaut SD.
3. Update Observer to predict perceived velocity and displacement in "world" coordinates; extend model to 0-g and partial-g applications, incorporating visual cues; and, plan for adapting and adopting Observer models into SDAT (with the plan to be executed during the first and second years of the project).
4. Design a frame-of-reference transformation (FORT) model and plan for its incorporation into SDAT, and perhaps into Observer, as well.
5. Plan how to verify and validate all models during the project's next three years.

Understand astronaut SD issues

The team reviewed relevant literature and discussed astronaut SD issues with our astronaut consultant. During the course of the first year we also spoke with several current and former astronauts in concert with separate work on the Orion program and at various meetings (e.g., the "Go for lunar landing symposium, Tempe, AZ, March 2008). The most important source of understanding astronaut SD issues at the level of detail required is to analyze relevant data sets using SDAT and Observer, which we have begun to do as we obtain more and more data sets from space vehicles (e.g., Shuttle) and simulators (e.g., VMS). However, unlike aviation data sets, the space vehicle data sets do not have corresponding subjective assessments of whether or not the astronauts experienced SD (more about this issue later).

Our astronaut consultant relayed his experiences, especially with EVAs and height vertigo, as well as Shuttle docking maneuvers with multiple visual frames of reference. Controlling the Shuttle and ISS robotic arms also present intriguing frame-of-reference challenges. Furthermore, he interviewed Apollo 16 commander, John Young, about his lunar landing experience; Young reported no SD events during powered descent and landing.

Our Apollo 16 interviews, however, yielded a very fruitful discussion with retired General Charles Duke, the Lunar Module (LM) pilot, who described an intense (potentially somatogravic) SD event that he experienced when he launched from the Moon. Since the launch was vertical and the horizon was always visible at his window, it was particularly disorienting when the LM pitched over to enter lunar orbit for docking with the command module (CM) and his window was filled with the brightly lit lunar surface. Duke said that he felt that the LM ascent stage had pitched completely over and was diving back to the Moon. The overwhelming visual cue (with the lack of a visible horizon) and the perhaps more than expected vestibular sense of rotation make this scenario worth exploring further. Therefore, as we solidify our relationship with the NASA-Ames Vertical Motion Simulator (VMS) staff, we will request data sets from lunar ascents, not just landings (of which we have six data sets now). We are also trying to obtain archival Apollo lunar landing and ascent data sets via NASA-JSC colleagues.

We have been working with Dr. Karl Bilimoria of NASA-ARC to obtain several trajectory data sets from Dr. Bilimoria's recent lunar landing simulations in the VMS. Our plan is to analyze these trajectories with our tools to quantify the types of accelerations and velocities involved in lunar landing maneuvers, and use our models to identify those epochs where SD episodes are likely. Working with Dr. Kevin Duda of the Draper Laboratory, we have also obtained trajectory data from Draper's Autonomous Landing Hazard Avoidance Technology (ALHAT) program lunar landing simulator. Furthermore, we have contacts at NASA-LaRC from whom we will request data sets from their lunar lander simulator.

With the assistance of our astronaut consultant, we have obtained Shuttle mission data sets from JSC, but they have proven difficult to interpret, as the variable names are poorly documented for outside users, and there is a huge volume of data to sort through. We have also had preliminary discussions with Dr. Steven Moore of Mt. Sinai, a new NSBRI Sensorimotor Adaptation PI, about possible collaborative experiments in the VMS examining Shuttle landing scenarios.

Another potential source of space vehicle data is a desktop tool, EagleLander3D, which claims to have realistic Apollo LM vehicle dynamics. We have been working with its creator to develop a capability to record landing and ascent trajectories from human-in-the-loop simulations. The main advantage of such a tool is that we can "fly" trajectories that we suspect would induce SD, and capture the trajectory data for analyses. With such an inexpensive tool, we can "fly" multiple variations to test trajectory boundary conditions to ensure that our SD detection algorithms are robust.

Finally, we recognize that one limitation of model-based trajectory analysis is that, except in rare cases, data sets are of suspected SD events; we rarely receive pilot or astronaut reports of their subjective experiences of SD with a particular data set, to confirm an SD event. In the case of aviation data sets, we do have safety board conclusions about the likelihood of SD. To the extent that the models quantitatively predict what pilots are likely to experience based on a variety of well-controlled experiments in ground laboratories, these analyses will help us to identify the types of maneuvers where SD is likely. Such data set analyses in Years 1 & 2 will help us to design appropriate simulator and flight experiments to validate our models.

Devise realistic scenarios that lead to astronaut SD

Based upon discussions with astronauts and preliminary analyses of likely disorienting trajectories, the set of scenarios we selected to examine for their potential to induce SD are as follows:

1. Main engine cut-off at the end of launch phase;
2. Multiple visual frames of reference during rendezvous and robotic arm control tasks;
3. Visual reorientation illusions (VRIs) when moving between ISS modules;
4. EVA height vertigo;

5. Lunar landings with degraded visual cues (e.g., due to blowing dust or acute sun angles);
6. Lunar ascents and orbit entry pitch-over maneuvers;
7. Shuttle entries and landings;
8. Adaptation to micro-gravity; and,
9. Adaptation from micro-gravity to lunar g or 1-g.

We will pare this list to a manageable number for in-depth countermeasure research in years 2-4. For example, EVA height vertigo has fairly minimal consequences – lost productivity – and so may not be worth pursuing beyond Year 1.

Outlier Shuttle landings are of particular interest. Specifically, STS-090 represents the most extreme outlier with a descent rate of 6.0 fps at touchdown (where the desired rate is 3.5 fps and 5.0 is considered the maximum permitted). Whether or not the commander experienced SD during this landing is not known. We are still in the process of analyzing this data set, but its large size (almost 16,000 rows of data) is a significant challenge. In fact, we had to enhance SDAT to process such a large data set, as 5,000 rows was SDAT's previous limit.

As previously discussed, acquiring realistic data sets of trajectories for the above scenarios and their corresponding SD events for model validation, has been a challenge. We have made progress in this first year, but not as much as we hoped. Consequently, we have also sought rotary-wing aircraft data sets from actual aircraft and simulators. Specifically, we have requested actual V-22 and helicopter data, and have used X-plane (a commercial desktop aircraft simulator product) to fly paths that are known to induce SD. Rotary wing data sets are attractive to us because they are more easily obtained, and they represent a reasonably close analog to a lunar lander for testing our algorithms.

Another commercially available desktop simulator is EagleLander3D, which, like X-plane, gives us the capability to fly trajectories ourselves and test our algorithms with a larger quantity and variety of data sets than we could obtain otherwise. While the validity of X-plane and EagleLander3D simulations may be in question, there is no doubt that we could not obtain the test cases necessary to verify our algorithms in any other practical way. More about these desktop simulation tools follows.

Desktop simulation data sets

The desktop tools EagleLander3D and X-plane help us understand vehicle dynamics, and we use recorded data sets from simulation scenarios that we fly for SDAT algorithm development and system testing. These tools do not replace higher fidelity pilot-in-the-loop testing.

Part of the focus of the first year effort has been to determine what sort of changes need to be made to the current version of SDAT in support of spatial disorientation analysis for space and non-earth gravity flight. Focused initially on fixed wing aircraft, the models within SDAT were modified to support the vertical landing and take-off dynamics of lunar or Mars landers. One early step in support of these changes was to develop an understanding of the dynamics of such vehicles and to determine the types of data that could be supplied to SDAT. While we have not yet had success acquiring actual data from Apollo lunar missions, even when we do, there will only be six missions worth of data to analyze.

EagleLander3D (www.eaglelander3d.com) is a commercially available desktop simulation of the Apollo lunar landings. The web site claims that the tool represents a realistic rendition of the physics, flight dynamics and instrumentation of the lunar module for lunar landings and orbital docking maneuvers. (If we obtain Apollo trajectory data, we should be able to validate this claim.) Our intention is to create flight trajectories representing the SD events and visual obscuration reported by Apollo astronauts. We have acquired the tool and learned to fly both landing and docking sequences, but no data sets have yet been created for SDAT or Observer analyses due to the software's present inability to output data sets. Nevertheless, it has helped the team better understand lunar lander flight dynamics. We are working with the tool's developer to acquire a data recording and download capability.

Due to the current inability of EagleLander3D to output data, we found another simulator that provides a reasonable analog in terms of dynamics and data. The commercially available desktop flight simulator, X-plane (www.x-plane.com), includes several helicopter simulations. We had used X-plane to create SD-like flight trajectories for the previous (AFRL-funded) development of SDAT and were familiar with its capabilities (Small et al., 2006). The team flew and captured data sets for two helicopter sequences from take-off to landing. These included lateral drift and tilt translation illusions that a pilot might encounter with a vertical take-off and landing vehicle. These two data sets are being used to test the changes to the otolith model within SDAT's vestibular attitude calculator (Small et al., 2006) and the new somatogravic illusion sequences described in Appendix A.

MIT and Alion model enhancements and potential integration

This step involved upgrading and exchanging information about MIT's Observer and Alion's SDAT. First, we describe the enhancements to Observer, then to SDAT. This section concludes with analytical comparisons of these two models on common data sets from aviation SD mishaps.

Observer enhancements

As proposed, starting in October 2007, MIT developed an updated Matlab/Simulink 2008a version of Observer – a mathematical model for multi-dimensional human spatial orientation, based largely on the MIT team's 1993 model (Merfeld et al., 1993) but incorporating additional refinements suggested by Haslwanter and colleagues (2000), Vingerhoets and colleagues (2007), and Groen and colleagues (2007). The model describes how the CNS combines vestibular and visual cues for rotation and translation. The inputs to the Observer model are head linear acceleration and angular velocity time series; its principal outputs include perceived linear accelerations and angular velocities.

This newest version of the model includes a graphical user interface, so it can be run by users who are not fluent with Matlab, which makes Observer now potentially accessible to aeronautical accident investigators, as well as more suitable for use in teaching (e.g., a version of the model was made available this spring to graduate students taking the Harvard-MIT HST Bioastronautics program course HST514J on sensory-neural systems). The new GUI allows the user to load model stimuli, choosing from a variety of example cases (e.g., centrifuge, OVAR, post-rotational tilt dumping, and several aircraft accident cases), or to load tabulated data from external sources (e.g., X-plane or VMS simulator data). The user can also display all the inputs and outputs as time series, and present the instantaneous direction of perceived "down" and "north" in an animated window. Our Observer model is currently also being used by Andrew Rader, a PhD student in Dr. Merfeld's lab at MEEI.

Significant extensions of the existing Observer model were also incorporated this year specifically for this project. These include:

1. Variable strength of gravity, necessary for Moon and Mars landing simulations;
2. Inclusion of adaptation dynamics in the gravi-receptor portion of the model;
3. Estimation of perceived azimuth (heading) in addition to the perceived direction of "down";
4. Estimation of perceived linear velocity and displacement in a coordinate frame aligned with the perceived vertical via "leaky integrator" processes, including dynamics which account for the poor human ability to correctly judge motion in the gravitational vertical as compared to horizontal directions;
5. Static visual cues to perceived orientation; and,
6. An additional fundamental model parameter ("Kwf") describing the contribution of rotational cues to "down" perception. Our simulations suggested this parameter is needed to correctly represent the ROTTR hypothesis for post-landing OTTR and tilt-gain illusions in astronauts. In OTTR, a slight tilt of the head results in a large illusory translation in the opposite direction to head tilt. In ROTTR, the head feels it has tilted much further than it actually has. Our original Observer model included the parameters "Kfw" describing the gravi-receptor contribution to rotation perception, and "Kf" describing the contribution of gravi-receptor cues to "down" perception. To model the tilt-gain illusion we now add this third parameter, Kwf. Tilt-gain illusions result from an increase in Kwf, and OTTR illusions from a reduction in Kf. Our revised model also accounts for why the OTTR illusion sensation of linear velocity opposite to head tilt is of limited duration, and displacements are limited in magnitude, as noted by returning astronauts. A short paper describing the model extensions and ROTTR results is in preparation.

SDAT enhancements

Alion added otolith perception models to SDAT during Year 1 and will test them during the early months of Year 2 using preexisting aviation data sets, new rotary wing data sets, and simulated lunar lander data sets. It should be noted that SDAT uses an aircraft coordinate system, as flight data sets rarely have head position data, which would be ideal. We used the same vector formula as for our preexisting pitch perception algorithm (arctangent Gx/Gz) but tailored for the specific axis of motion, lateral or vertical. But, humans often err in judging the direction of vertical motion (Melvill Jones & Young, 1978), so we must account for this tendency. In addition, we applied a threshold acceleration of 0.005g to the longitudinal (X) and lateral (Y) otoliths, meaning that accelerations below this threshold are not detected. Cumulative small accelerations that yield a velocity of less than 20 cm/sec are also not detected; but, once the velocity reaches this value, the motion is detected (Melvill Jones & Young, 1978).

A review of the literature yielded linear acceleration detection thresholds of 0.005g for accelerations in the Gx and Gy planes (body axis fore and aft, X, and body axis left and right, Y); for the vertical body axis, Z, the detection threshold is 0.01g (DeHart & Davis, 2002; Cheung, 2004).

The threshold difference is usually explained as evolutionary, since humans, unlike birds, did not evolve to move in the vertical axis.

The initial version of the SDAT vestibular attitude calculator included a simple algorithm combining longitudinal (Gx) acceleration with the acceleration of gravity (Gz) for estimating the pitch angle misperception that can occur in flight (Small et al., 2006). Called the somatogravic illusion, a common example is of a high performance aircraft at take-off that maintains a forward acceleration of 1g. This results in the movement of the otolithic membranes erroneously registering this acceleration as if the head were tilted up at 45 degrees (DeHart & Davis, 2002). Since values for linear acceleration are not always included in the data sets, SDAT calculates Gx based on changes in airspeed. Some data sets do include the total gravito-inertial force felt by the pilot, often termed “normal load factor” or Gz. When this value is available, it is used in place of the 1 Gz assumed for Earth’s gravity in the above formula.

Some recent data sets from desktop simulators have included g-axial or longitudinal acceleration values representing the forces on the pilot along the long axis of the aircraft. Unfortunately, the SDAT pitch perception calculation is not the same when using computed Gx compared to Gx from the data set. We have not yet resolved this discrepancy, but are still investigating it.

While the misperception of pitch angle due to linear acceleration is common in fixed wing aircraft, the potential for similar misperceptions of roll angle can occur during lateral accelerations in vehicles capable of such lateral motions. Therefore, we have enhanced SDAT to use the same calculation to estimate roll angle misperceptions based on lateral accelerations, Gy. Some data sets include lateral speed; others include values for “g-side” or “side slip accelerations.” For now, SDAT uses arctangent (Gy/Gz) to calculate the roll angle (or tilt) misperception associated with lateral movements.

SDAT uses detection thresholds to determine when the pilot or astronaut may not perceive vehicle motions. Previously, SDAT only used SCC thresholds to calculate misperceived roll or yaw/heading rotations. Now SDAT includes thresholds for linear motion perceptions in our otolith effects models. Furthermore, since the otoliths “translate” linear accelerations into angle perception error (see above), it is the above threshold accelerations that result in misperceptions. That is, side-to-side supra-threshold accelerations may be misinterpreted by the otoliths as tilts in the roll axis. The important distinction here is that with SCC calculations, it is the sub-threshold motions that yield misperceptions; for the otoliths, it is above threshold motions that yield misperceptions.

Interestingly, when we use the 0.005g threshold in the arctangent (Gy/Gz) calculation, it yields a roll misperception of only about 0.3 degrees, which is insignificant in our experience to be a cause of SD even when sustained over a long duration. Therefore, for simplicity, SDAT now uses all Gy values to compute roll misperceptions. If we find that this simplification yields erroneous results, we can add an otolith threshold to our algorithms.

Furthermore, the results of experiments by Melvill Jones and Young (1978) suggest that there is also an otolith speed threshold (approximately 20 cm/sec), not just an acceleration threshold, similar to the well-known Mulder Product calculation for cumulative SCC rotation accelerations

(Previc & Ercoline, 2004). One SDAT application of this threshold is for calculating unperceived drift, as in the following example scenario. A helicopter or lunar lander pilot tries to minimize all horizontal motion relative to the surface prior to touching down. In the absence of visual motions cues – as can occur within the dust cloud created by helicopter rotor wash (called "brown out") or the lunar lander main engine – undetected horizontal motion (drift) can become a serious problem. Such drift can result in the lunar lander touching down on an unacceptably steep slope, or the helicopter striking an obstacle. Both problems may have potentially fatal consequences. SDAT should be able to detect when drift is below the 20 cm/sec threshold and that it has accumulated in a direction that may place the vehicle in a dangerous position. The difference between the intended landing location and the amount of undetected translation can be expressed as a latent position error due to SD. For speed changes below the detection threshold, SDAT could track how much translation error has occurred and provide a countermeasure to alert the pilot to the problem before the consequences become unacceptable.

Observer and SDAT results comparisons

While working to improve our respective models, the Alion and MIT teams also compared analyses of common data sets with Observer and SDAT, respectively, to compare and contrast the models. The differences between the two approaches are significant, and to be expected, given their respective derivations and developments. MIT's Observer model builds on decades of physiological and perceptual research. Its principal goal has been to reliably describe the relationship of angular velocity and linear acceleration cues, to the time course of eye movements and perceptions. The model was not specifically developed to detect and classify SD episodes. In contrast, Alion's SDAT/SOAS models have been designed and developed to use practical heuristics to estimate the probability of an SD episode based on aircraft trajectory data, and to classify the type of illusion experienced. The ultimate goal of SOAS/SDAT is to then determine the severity of the SD event and trigger appropriate countermeasures. So, if an SD event is fairly benign, then less intrusive countermeasures are warranted; for severe SD events (i.e., surface collision imminent), SOAS/SDAT triggers more intrusive countermeasures.

We have compared the analytical results from SDAT and Observer with two actual data sets – one from the Navy, the other from the NTSB. These two data sets represent incidents in which SD was suspected. Both sets were analyzed during the initial development of SDAT and the findings compared favorably with those of the incident investigation teams. Each of the following sets of graphs contains the analytical results from Observer and SDAT. In each graph, the blue line represents the actual aircraft flight dynamics from the data set. The red line represents the perceived value calculated by either Observer or SDAT. The yellow line is the difference between the actual flight data and the calculated perceived values (i.e., the absolute value of the difference between the blue and red values at each moment in time). In the MIT graphs the red line data is labeled 'Estimated' while, in the SDAT graphs, the red line is labeled 'Perceived'. While other values are important, the comparison is limited to the values of roll and yaw velocities as they are the values that both tools currently generate in common. The horizontal axis is time in seconds; the vertical axis is angular rate (roll or heading speed) in degrees per second. Positive values are rightward motions from the pilot's perspective; negative values represent leftward motions.

The first two graphs (Figure 7) show the roll velocity data as analyzed by the two tools for the NTSB (Strasburg accident) data set in which a small twin-engine aircraft's pilot experienced a graveyard spiral while flying in clouds and crashed into the ground killing all aboard. For the first three quarters of the time period the two tools show similarly small, but not identical, delta values (yellow line) between the actual roll velocity and the perceived roll velocity calculated by the tools. During this period the majority of the roll actions are relatively small. However, for the last quarter of the time period, the deltas diverge dramatically. During this time period, the aircraft is experiencing very high roll velocities as control is lost during the accident. Based on the fact that these large roll rates are well above the SCC detection thresholds, SDAT shows that the delta between actual and perceived roll velocity would be quite low. In contrast, Observer calculates very high roll rate deltas between the actual and the estimated values.

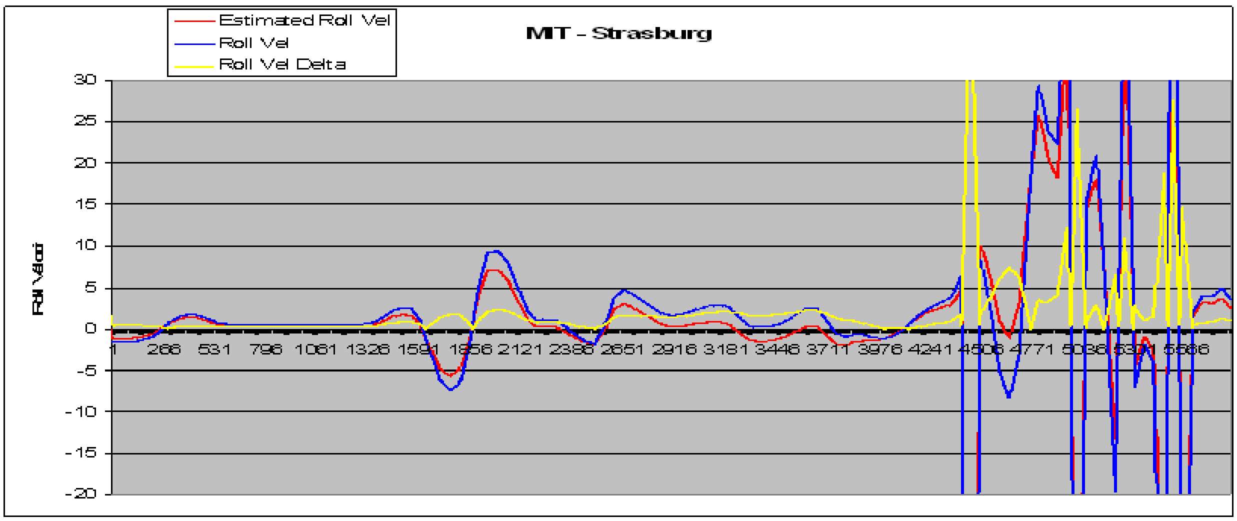

Figure 7a. Observer roll velocity for Strasburg (NTSB) accident data set.

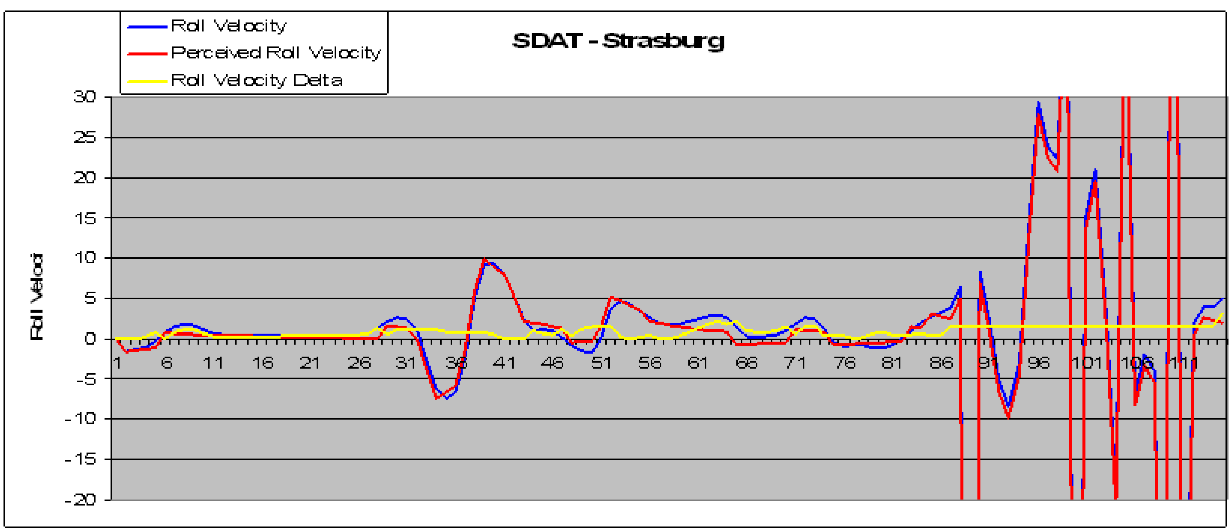

Figure 7b. SDAT roll velocity for Strasburg (NTSB) accident data set.

Figure 7. Comparison of Observer (MIT) and SDAT roll velocity for NTSB data set.

The next set of graphs (Figure 8) compares the yaw velocity calculations for the same accident data set (NTSB Strasburg). The graphs show that the aircraft slowly increased its rate of heading change (a graveyard spiral) until the apparent loss of control near the end of the accident. The MIT and SDAT models calculate very similar perceived yaw velocity values and associated deltas for most of the time period. Late in the data set, during the apparent loss of control, the values calculated by the two tools again diverge. SDAT (Figure 8b) shows that the above threshold yaw velocities are all perceived but maintain the accrued yaw velocity error delta. For this same time period, the MIT model (Figure 8a) shows large variations in the perception delta. The reasons for these differences between Observer and SDAT results are not presently known, but are being investigated.

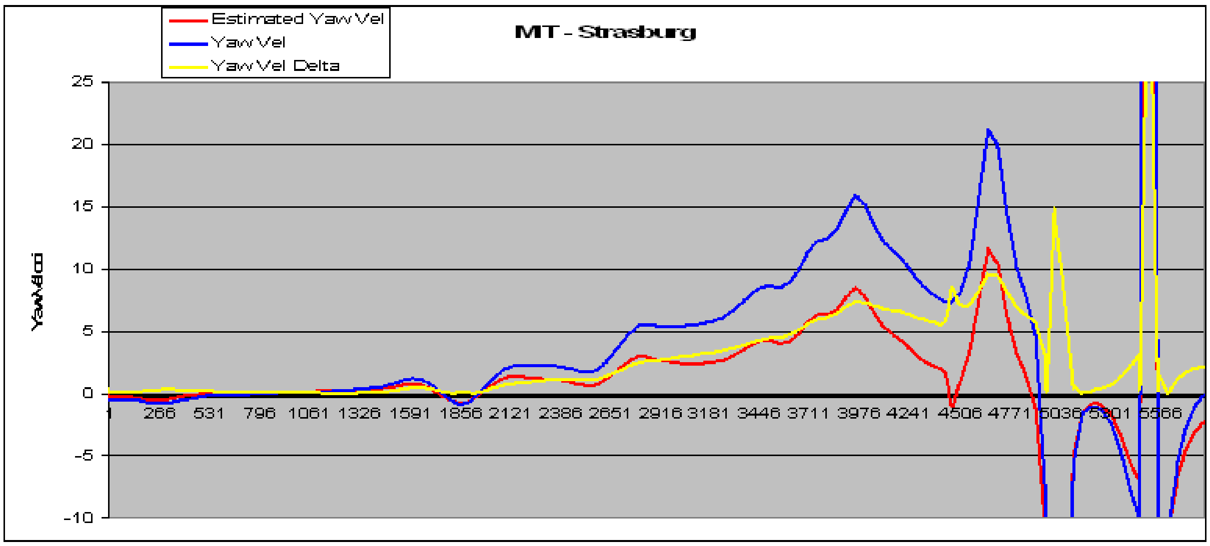

Figure 8a. Observer yaw velocity for Strasburg (NTSB) accident data set.

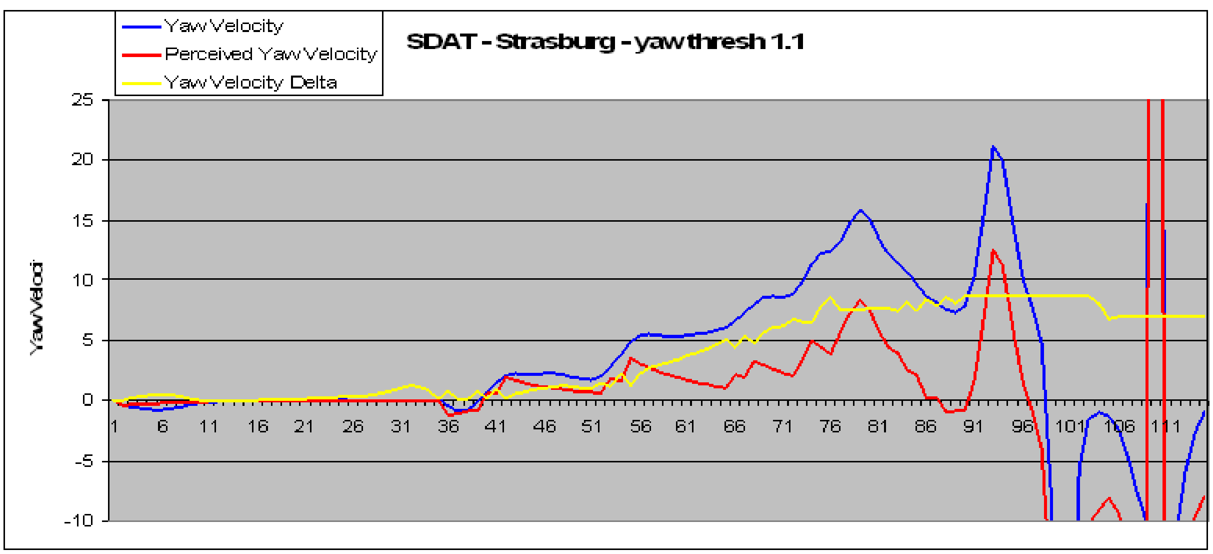

Figure 8b. SDAT yaw velocity for Strasburg (NTSB) accident data set.

Figure 8. Comparison of Observer (MIT) and SDAT yaw velocity for NTSB data set.

Next, we compared the two tools' analyses of a Navy mishap data set in which a sustained turn in the airfield traffic pattern is followed by a sudden dive into the ground, presumably caused by a pitch misperception SD event. The first set of graphs (Figure 9) show the roll velocity results. The MIT model indicates that the estimated roll velocity is generally much lower than the actual roll velocity. The SDAT model predicts that the perceived roll velocity more closely matches the actual values. While the magnitude of the calculated deltas differs, it is interesting to note that the general shape of the yellow delta lines are similar (meaning that the peaks and valleys mostly correspond), indicating some level of agreement about the general character of the perception deltas.

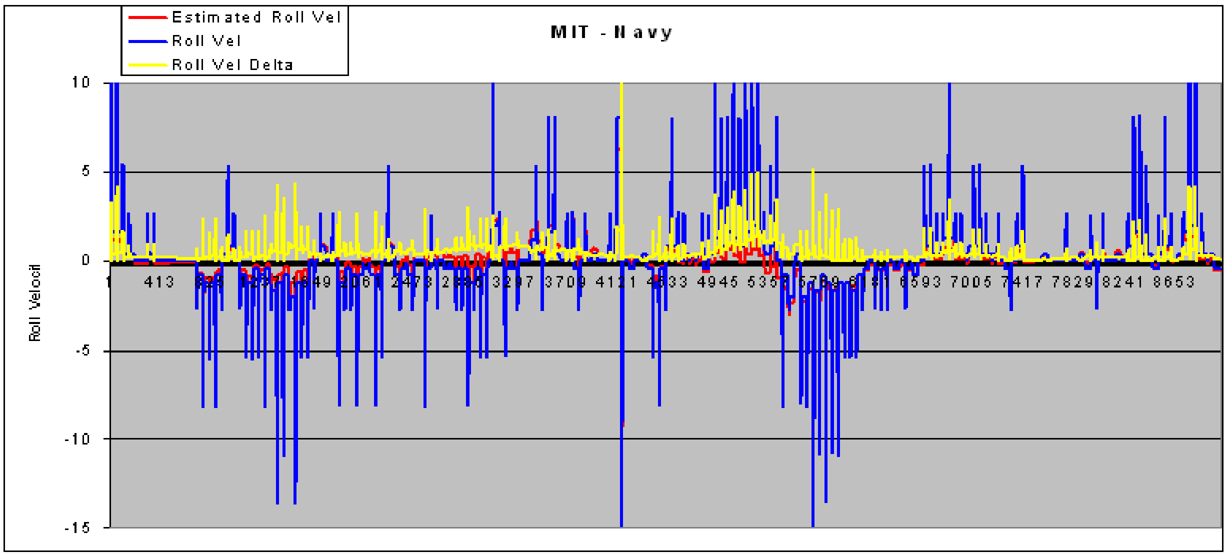

Figure 9a. Observer roll velocity for Navy accident data set.

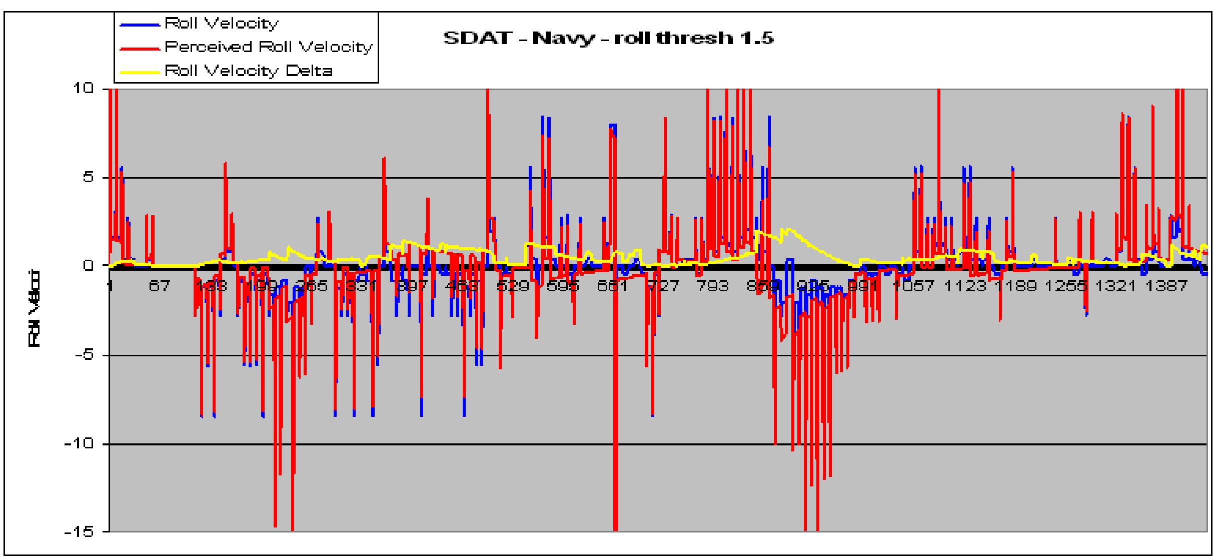

Figure 9b. SDAT roll velocity for Navy accident data set.

Figure 9. Comparison of Observer (MIT) and SDAT roll velocity for Navy data set.

Figure 10 shows the graphs for the yaw velocity of the Navy data set. The MIT model estimates that a small amount of the yaw velocity is perceived, with a maximum delta approaching 4 deg/sec. SDAT allows analyses using a range of threshold values; the first SDAT graph (Figure 10b) shows that at the default yaw threshold of 1.1 deg/sec, almost none of the yaw velocity would have been perceived. Figure 10c shows that, in order to obtain perception values similar to the MIT model, SDAT uses a 0 deg/sec threshold value, which is not supported by current vestibular research. Since Observer does not yet use thresholds in its estimation of yaw velocity perception, the contrast between SDAT and Observer results is not surprising. But, the lack of thresholds in Observer, alone, does not fully explain the differences between SDAT and Observer results. Discussions between the Alion and MIT teams are ongoing to understand the reasons for differences in the results.

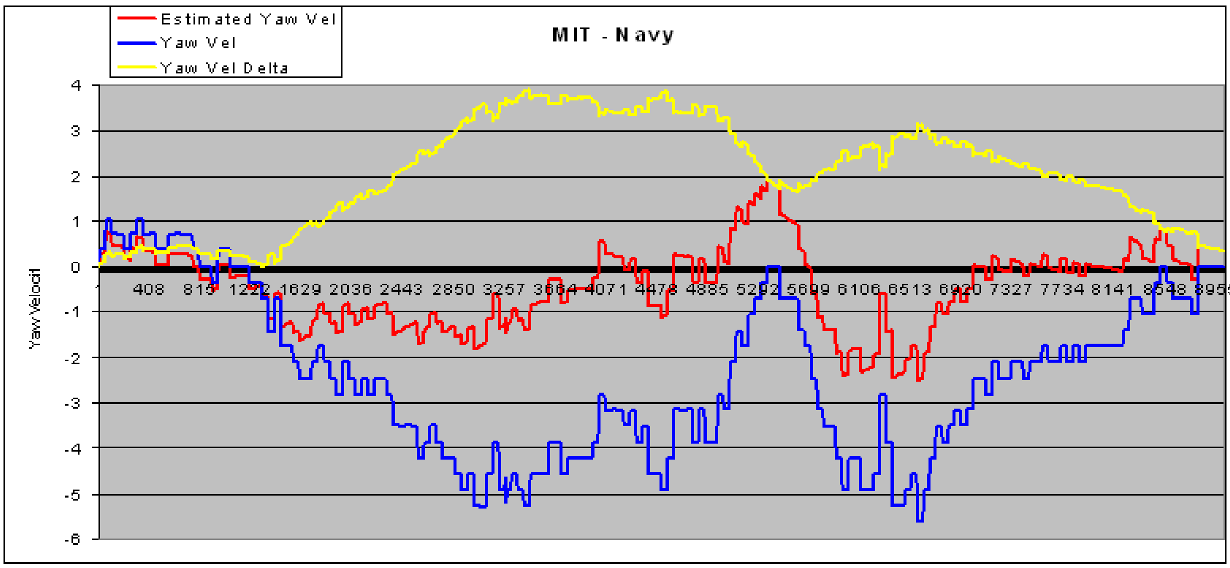

Figure 10a. Observer yaw velocity for Navy accident data set.

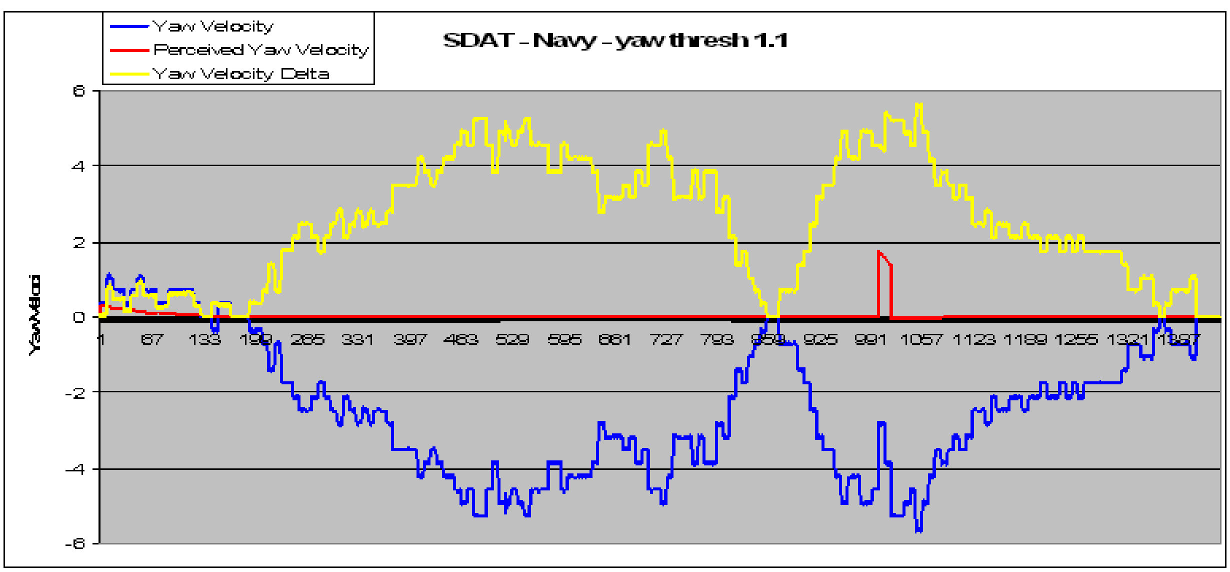

Figure 10b. SDAT yaw velocity for Navy data set at default 1.1 deg/sec threshold setting.

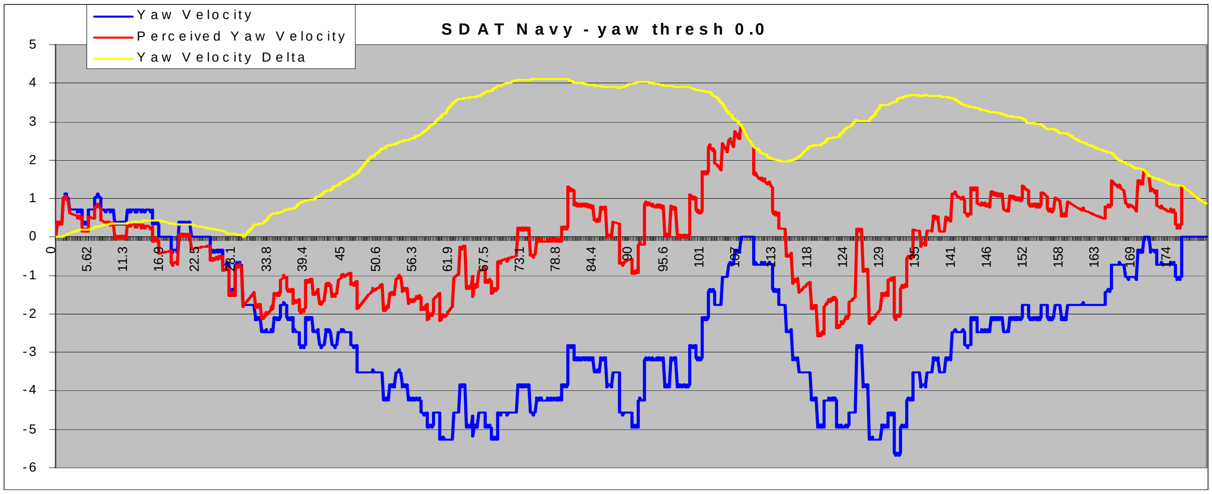

Figure 10c. SDAT yaw velocity for Navy data set at 0 deg/sec threshold for direct comparison to Observer.

Figure 10. Comparison of Observer (MIT) and SDAT yaw velocity for Navy data set.

While the similarities in the analytical results are encouraging, the differences require further investigation and discussion, which will be accomplished early in Year 2 of the project as we continue to conceptually (if not physically) merge the two tools.

It appears that the three major reasons for results differences are that (1) SDAT uses SCC thresholds whereas Observer does not (yet); (2) Observer has a canal-otolith interaction model whereas SDAT does not (yet); and (3) Observer links rotation (SCC) perception to lateral accelerations (sensed by the otoliths) to feed forward into a new perceived gravity vector. The first of these factors certainly contributes to the different results shown in Figures 7-10; the contributions of the last two factors is less clear, but needs further investigation.

Year 1 Accomplishments Summary

We now have access to Shuttle and NASA-Ames' vertical motion simulator (VMS) and other Altair simulator data sets. We are still pursuing Apollo data sets. To supplement these data sets, we have recently received helicopter data sets from Ft. Rucker. The reason we sought rotary wing data sets is that they represent the closest analogs to lunar landers here on Earth, and they are plentiful. Their lateral and vertical motions are significantly different from fixed-wing aircraft, thus giving us new data with which to verify and validate the enhancements to SDAT and Observer.

MIT's Observer has been enhanced with improved algorithms for calculating the perception of "down" and azimuth, as well as a more user-friendly graphical user interface (GUI) for condition selection of motion data inputs, and presentation of the perceived orientation estimation. Alion's SDAT has been improved by adding otolith perception models to our pre-existing semi-circular canal models, and by adding somatogravic illusion detection sequences.

Impact of Year 1 accomplishments on original goals

The scarcity of usable data sets required us to re-double our efforts to obtain relevant data sets with which to verify and validate improvements to SDAT and Observer. We also determined that Altair simulators would be suitable platforms for validation experiments, supplementing or replacing parabolic flight experiments, based upon Year 2 planning, cost considerations, and availability.

After designing a FORT model, we determined that it should not be incorporated into SDAT *per se*. Rather, the FORT *cost function* shown in Figure 6 should be used to help determine an astronaut's susceptibility to SD in a given situation, to help determine the severity of an SD event, and to help select countermeasures when a frame-of-reference transformation SD occurs.

We are also considering a change of strategy for enhancing SDAT: Rather than adopting and adapting Observer algorithms, we may use a suitably tailored version of Observer within SDAT to act as the source of calculated perceived attitude and motions. Then, SDAT would compare those Observer-calculated perceptions to the actual vehicle attitude and motions to determine the likelihood of the human operators suffering from SD. Therefore, the change of strategy is that SDAT would use Observer rather than its own algorithms to calculate perceived attitude and perceived motions.

Research Plan for Year 2

The main focus of our research is to understand astronaut SD events and to apply appropriate countermeasures to help astronauts who experience SD. In Year 2 we will focus more attention on verification and validation (V&V) with data sets, and designing validation experiments in parabolic flight and in suitable ground-based simulators (e.g., VMS). Parabolic flight experiments will borrow ideas from Borah and colleagues' TIFS experiments in the 1980s, which measured in-flight perception of both translatory motions and which way is "down" (Borah & Young, 1982; 1983).

Proposed research plan for Year 2

In the second year of this NSBRI sensorimotor adaptation project, the Alion-MIT team will:

1. Continue enhancing and merging SDAT and Observer, and continue comparing analytical results of common data sets. We will figure out why there are differences in our respective results and what to do about them. Observer will:
    - incorporate perceptual thresholds,
    - add static and dynamic visual cues for perception calculations,
    - focus on scenarios involving human perception of vertical and horizontal motions (as would be experienced during lunar landing and take-off scenarios), and
    - evaluate the impact of motion cues on perception in hovering lunar landers with the pilot's head located near the center of gravity (as in a training vehicle) vs. offset 8-12 feet above (as in Altair).

    SDAT will add more SD illusion sequences and may use Observer as a compiled module within SDAT to calculate perceived attitudes, angular and linear velocities, and displacements for comparison with actual vehicle values to assess the likelihood of SD.

2. Validate enhancements with previous flight data sets and new data sets (from actual vehicles and from simulators). Included will be Shuttle landing data outlier analyses (compared to non-outliers), and data sets from Altair and ALHAT simulators. Particular emphasis will be on data sets with lateral and vertical motions to test new functionality within SDAT.

3. Expand FORT to additional axes and higher derivatives (velocity and acceleration). Incorporate the FORT model's cost function into SDAT and develop a separate FORT design tool (if schedule and budget conditions permit, which should be decided in the first half of Year 2).

4. Plan in detail for simulator and parabolic flight validation experiments in Years 3 and 4. Flight experiments will focus on obtaining subjective perception data in low g environments. Simulation experiments will focus on countermeasure efficacy. Some suitable simulators (e.g., Ames' VMS) might be used for both purposes.

Plan how to verify and validate all models in the project's next three years

Originally, we proposed parabolic flight experiments to verify and validate our models. Our current thinking is that we will use a combination of parabolic flight, vertical motion simulator (VMS), or possibly other simulator resources for validation. Our goals are to test our SDAT and Observer perception and illusion sequence algorithms, and the efficacy of our real-time counter-measures, as well as our FORT model. Experimental testing of SDAT/SOAS should be done in two stages: the first to fine-tune our SD detection algorithms, the second to test our multi-sensory countermeasures once SD is detected. Clearly, for Earth-based simulators, we will be unable to validate algorithms that predict 0-g adaptation illusions, such as OTTR and tilt-gain.

During the first year we have identified several potential facilities for conducting motion experiments of different levels of fidelity. In each case, the goal is to stimulate human subjects with precise controlled angular and linear accelerations, and to measure the subjects' dynamic perceptions of orientation and motion sensations. The SDAT and MIT-Observer models will be programmed to accept the motion inputs and to produce predictions of the subject reactions. We are considering cooperative research with several laboratories, in the US and abroad, to achieve these goals.

For the verification of our models, we rely on data set analyses from actual vehicles and simulators. The data sets capture realistic SD scenarios, as described earlier, and nominal operations for comparison purposes and to ensure that we do not have false positives. Year 1 has focused on building relationships with data set providers within NASA, DoD, and the NTSB. We have not yet conducted in-depth analyses of the data sets we have obtained. We shall do so in Year 2 as part of our iterative design-develop-test process. A typical V&V effort would be to use half the data sets to develop and verify our algorithms, and the other half to test and validate them.

Conclusion

To conclude, we summarize our progress to date, and then articulate our plans for Year 2.

Task progress summary

Our four overall project aims, and progress on each, are as follows.

1. Extend SDAT by extending MIT's Observer models and incorporating a version into SDAT. Enhance SDAT with pilot head movement data, and visual attention cues. Validate enhancements with existing and new flight data sets.

   Progress: We have extended the MIT Observer model so it predicts linear velocities and displacements in a world coordinate frame, can operate in 0-g and partial g cases, and mimic OTTR and tilt-gain illusions. Visual inputs are being incorporated. The model has a GUI, so users do not have to be Matlab experts. We are evaluating how the Observer algorithms could be best incorporated into SDAT. In addition, we designed a visual frame-of-reference model. We have obtained new data sets (Shuttle, Altair and ALHAT simulators) and still have more to obtain (e.g., Apollo data) with which we will verify and validate the enhancements.

2. Extend SDAT assessments to include typical space vehicle illusions: Inversion, Visual Reorientation, Tilt Gain, and Otolith Tilt-Translation Reinterpretation. Validation will include assessment of Shuttle landing data, and Altair simulator data.

   Progress: In addition to the related accomplishments mentioned above, we devised scenarios to examine predicted perceived orientation via SDAT and Observer analyses, and have begun those analyses of Shuttle and Altair simulator data sets. SDAT has been enhanced with additional illusion sequences, specifically for somatogravic and lateral drift perception illusions.

3. Further extend SDAT by examining alternative visual reference frames. Frame of reference transformation (FORT) theory is used to predict the cognitive cost of transitioning between reference frames. Validation of Aims 1-3 for SDAT will include parabolic flight experiments.

   Progress: We designed a FORT model and will incorporate its cost portion into SDAT. We have begun to plan flight and simulator experiments to validate all enhancements to SDAT.

4. To further enhance SDAT/SOAS assessor performance, pilot multi-sensory workload is considered in countermeasure selection. Validation experiments are not detailed, but will involve evaluations in ground-based simulators.

   Progress: Once we have verified and validated our models, we will assess the efficacy of various countermeasures triggered by SOAS during years three or four, based upon the scenarios devised in item 2, above.

Glossary

2D	two-dimensional
AFHRL	Air Force Human Resources Laboratory
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
ALHAT	Autonomous Landing Hazard Avoidance Technology (Draper Lab project)
Altair	Orion program's next generation lunar lander
aka	also known as
ARC	NASA's Ames Research Center (in Sunnyvale, California)
BEA	French aircraft accident investigation bureau
CEV	Orion program's crew exploration vehicle
CM	command module
cm	centimeter(s)
CNS	central nervous system
deg	degree(s)
Desdemona	TNO's multi-axis 6DOF aviation research simulator
DoD	U.S. Department of Defense
DOF	degrees of freedom
EagleLander3D	desktop Apollo LM simulator
EVA	extra-vehicular activity
FOR	frame of reference
FORT	frame of reference transformation
fpm	feet per minute
fps	feet per second
G, g	force of gravity (on the Earth, about 32 feet/sec^2; one-sixth that on the Moon)
Gx	acceleration in the X axis (in units of g)
Gy	acceleration in the Y axis (in units of g)
Gz	acceleration in the Z axis (in units of g)
GIF	gravito-inertial force
GUI	graphical user interface
HUD	head-up display
HST	Health Sciences & Technology (joint Harvard-MIT program)
Hz	Hertz (cycles per second)
ISS	International Space Station
IVA	in-vehicle activity
JSC	NASA's Johnson Space Center (in Houston, Texas)
kts	knots
LaRC	NASA's Langley Research Center (in Hampton, Virginia)
LM	lunar module

m	meter(s)
MEEI	Massachusetts Ear and Eye Infirmary
MIT	Massachusetts Institute of Technology
MR	mental rotation
MVL	Man-Vehicle Laboratory (at MIT)
NASA	National Aeronautics and Space Administration
NSBRI	National Space Biomedical Research Institute
NTSB	National Transportation Safety Board
NTU	National Technical University of Singapore
Observer	MIT's human spatial orientation set of models
OTTR	otolith tilt translation reinterpretation
OVAR	off vertical axis rotation
PhD	doctoral degree
PI	principal investigator (leader of a research project)
PT	perspective taking
ROTTR	Rotation otolith tilt-translation reinterpretation
RT	response time
SCC	semi-circular canal
SD	spatial disorientation
SDAT	Alion's spatial disorientation analysis tool
sec	second(s)
SME	subject matter expert
SOAS	Alion's spatial orientation aiding system
STS	Shuttle Transportation System (aka Space Shuttle, or just Shuttle)
SVS	synthetic vision system
THC	translational hand controller
TIFS	total in-flight simulator (U.S. Air Force research aircraft)
TNO	Dutch aviation research agency
TRL	technology readiness level
U.S., US	United States
USAF	United States Air Force
V-22	tilt-wing aircraft used by U.S. Air Force, Marines, and Special Operations
V&V	verification (does the model function as intended?) and validation (does the model accurately portray the real world?)
VAC	vestibular attitude calculator (a module of SDAT/SOAS)
VMS	ARC's vertical motion simulator
VOR	vestibular-ocular reflex
VRI	visual reorientation illusion
X-plane	desktop aircraft simulator that outputs trajectory data; uses good fidelity aerodynamics models

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Appendix A. SDAT's New Somatogravic Illusion Models

During the first year of this four-year project, we enhanced SDAT with new illusion models or sequences that exercise our added otolith models, as follows. We have not yet tested these new illusion models, but will do so early in Year 2.

Take-off / Acceleration

The otoliths of a pilot during take-off (or other high acceleration) respond to the force of gravity and the forward acceleration such that the perceived direction of down is rotated from the vertical. Without visual input, this can be interpreted as being pitched up and the pilot may push the nose of the aircraft down in response to the unwanted pitch up sensation (DeHart & Davis 2002; Previc & Ercoline, 2004).

Examples:

- A high performance aircraft taking off with 1G of acceleration. This 1g of inertial force combined with gravity results in a displacement of the otoliths towards the back of the head in a position nearly the same as if the head were tilted up 45 degrees.
- Carrier launch aircraft experience pulse accelerations of +3 to +5Gx resulting in illusions of nose-high pitch angles persisting for 30 seconds or more. It is estimated that a +4Gx catapult launch can produce a 76-degree rotation of the gravito-inertial vector.
- Commercial aircraft take-off with accelerations from 100 to 130 knots over a 10-second period generates +0.16Gx, resulting in only 1.01G but directed 9 degrees aft, thus signaling a 9-degree pitch-up. Commercial aircraft may climb-out at 6 degrees or less, so a 9-degree correction would put the aircraft into a 3-degree descent.

Somatogravic Excess Pitch Illusion Model Sequence

This sequence will combine actual aircraft pitch values with perceived pitch values from SDAT's vestibular attitude calculator (VAC). Changes in airspeed will also be used as a secondary check on the timing of perception. Pitch rotation values will be used to assess the pilot's response to the perceived pitch-up delta.

- Initial conditions include an airspeed acceleration resulting in the perception of greater pitch than exists (not necessarily pitched up).
    - both actual and perceived could be positive
    - actual is negative and perceived in positive
    - both are negative
- The sequence includes a check for the airspeed change in addition to the pitch perception values.
- Event 1: Initial event combines the pitch perception difference with a specific delta that is maintained for a certain time period.
    - Initial trigger
        - Perceived Pitch > Actual Pitch (by some user-selected amount)
            - once this is true, record current time, current actual airspeed, and current pitch
            - If Perceived Pitch < Actual Pitch
                - Then reset values recorded for time, airspeed & pitch

- Event triggers
  - Perceived Pitch > Actual Pitch AND
  - Perceived Pitch Delta >= 5 degrees AND
  - CurrentAirspeed – InitialTriggerAirspeed > 30 kts
  - All three conditions existing together for >= 5 seconds
- Event 2: Pilot reacts to misperception and pushes the stick forward to bring the nose down.
  - The sequence will track the change in actual pitch degree starting from the recorded pitch value in Event 1.
    - Event 1 conditions exist AND
    - (CurrentActualPitch – Recorded Event1 Pitch) / (current time – recordedEvent1Time) < -2 deg/sec
  - Resulting in a Nose Low attitude
  - The sequence may still represent an SD if the result is nose up but not as potentially serious as nose down.
  - Included will be an assessment that airspeed is still increasing
- Event 3:
  - Actual Pitch < -3 degrees
    - Resulting in loss of altitude (check for negative vertical velocity)
  - AND
  - CurrentAirspeed – InitialTriggerAirspeed > 40 kts
- Event 4: VVI < -1000 ft/min or X seconds to ground impact for SD severity value.

Where specific values exist, these should be user selectable in the set-up tab's model description.

Landing / Deceleration

The reverse process occurs during deceleration, such as lowering the flaps for landing or a reduction in power. The pilot may feel tilted forward and interpret the sensation as an excessive pitch down. If the pilot responds by pulling up, then the resulting reduction in airspeed can increase the pitch down sensation (DeHart & Davis 2002; Previc & Ercoline, 2004). A continuation of this sequence can result in a stall.

<u>Somatogravic Insufficient Pitch Illusion Model Sequence</u>
This sequence will function much like the events for the Excessive Pitch sequence including pitch perception delta values, actual pitch changes, and airspeed changes.

- Initial conditions include deceleration resulting in the perception of less pitch than actual
  - both could be positive
  - perceived could be negative and actual positive
  - both could be negative
- The sequence includes a check for the airspeed change in addition to the pitch perception values.
- Event 1: Initial event combines the pitch perception difference with a specific delta that is maintained for a certain time period.
  - Initial trigger
    - Perceived Pitch < Actual Pitch

    - once this is true, record current time, current airspeed and current pitch
    - If Perceived Pitch > Actual Pitch
      - Then reset values for recorded for time, airspeed & pitch
  - Event triggers
    - Perceived Pitch < Actual Pitch AND
    - Perceived Pitch Delta >= 5 degrees AND
    - CurrentAirspeed – InitialTriggerAirspeed < -30 kts
    - All three conditions existing together for >= 5 seconds
- Event 2: Pilot reacts to misperception and pulls the stick back to bring the nose up
  - The sequence will track the change in actual pitch degree starting from the recorded pitch value from Event 1.
  - Event 1 conditions exist AND
  - (CurrentActualPitch – Recorded Event1 Pitch) / (current time – recordedEvent1Time) > 2 deg/sec
  - Resulting in a Nose High attitude
  - This may still represent an SD, but not be serious until the nose high attitude and airspeed combination approach a stall for the specific aircraft.
  - Included will be an assessment that airspeed is still decreasing.
- Event 3:
  - Actual Pitch > 15 degrees AND
  - CurrentAirspeed – InitialTriggerAirspeed < -40 kts

Inversion Illusion

The inversion illusion is a variation of the excess pitch sequence. The following is an excerpt describing the sequence:

> This occurs when the gravito-inertial force vector actually rotates backward so far as to be pointing away from the ground. It can occur when a steep climbing high-performance aircraft levels off abruptly. This subjects the pilot to –Gz centrifugal force from the arc flown just before level-off. As the aircraft changes to level flight, airspeed picks up rapidly adding a +Gx tangential inertial force. Adding the –Gz and +Gx to the 1-G gravitational force results in a force vector that rotates backward and upward relative to the pilot. This stimulates the otolith organs in a manner similar to a pitch upward into an inverted position. Even though the SCC should respond to the actual pitch downward, the conflict is resolved in favor of the otoliths, perhaps because the SCC response is transient while the otolith response persists, or because the information from the other mechanoreceptors reinforce the information from the otolith organs. The pilot responding to this condition, by pushing forward on the stick to counter the perceived pitching up and over, only prolongs the illusion by creating more –Gz and +Gx forces (DeHart & Davis 2002, chapter 8, pg 281).

Variations:

- Turbulent weather can contribute as downdrafts can be a source of –Gz.
- It can occur with airliners when the pilot pushes the nose down after experiencing the illusion.

- Jet upset is the name for the sequence that includes instrument weather, turbulence, inability to read the instruments, inversion illusion, pitch down control input, and recovery difficulty due to resulting aerodynamic or mechanical forces.

Aerobatic Inversion Illusion Model Sequence[1]
One option would simply be to identify situations when perceived pitch is really high while actual is really low or even negative. This assumes that the perceived pitch calculation within VAC will accurately respond to the combinations of -Gz and +Gx. This is something we haven't yet tested. The sequence will have to include a duration sufficient to avoid an event being triggered by transitory perceived spikes from Gx calculations with high frequency data. Other indicators include the increase in airspeed, the pushing forward on the stick (nose down pitch command) as part of the illusion response and loss of altitude. The sequence could include an increase in perceived pitch following pushing the stick forward.

- Event 1: Initial conditions are very high perceived pitch and very low or negative actual pitch (rather than simply a large delta) and increasing airspeed over a period of time.
    - Initial Conditions
        - Perceived pitch > 45 deg AND
        - Actual pitch < 5 deg
        - Once this is true, then record current time, airspeed, actual pitch and perceived pitch.
        - If Perceived pitch < 45 AND Actual pitch > 5 then reset these recorded values.
    - Event Triggers
        - Perceived pitch > 45 deg AND
        - Actual pitch < 5 deg
        - Current Airspeed – Initial Trigger Airspeed > 30 knots AND
        - All three conditions occurring together for > 5 seconds
- Event 2: Pilot reacts to the misperception by pushing the stick forward to get the nose down.
    - The sequence will track the change in actual pitch degree starting from the recorded pitch value from Event 1.
    - While conditions for Event 1 exist
    - (CurrentActualPitch – Recorded initial trigger pitch) / (current time – recorded initial trigger time) < -2deg/sec
- Event 3: Determine if pushing the stick forward has resulted in a worsening of the condition.
    - Does perceived pitch increase while actual decreases?
    - Perceived pitch > initial trigger perceived pitch + 5 deg AND
    - Actual pitch < initial trigger actual pitch - 5 deg AND
    - Both conditions occur together for > 3 seconds
- Event 4: Resulting in a Nose Low attitude
    - The sequence may still represent an SD if the result is nose up but not as potentially serious as nose down.

[1] This illusion is the aeronautical one, not the sustained inversion illusion experienced by astronauts in 0-g.

    - Included will be an assessment that airspeed is still increasing
    - Actual Pitch < -3 degrees AND
    - CurrentAirspeed – InitialTriggerAirspeed > 40 knots
- Event 5: Resulting in loss of altitude
    - Check for negative vertical velocity (VVI < -1000 fpm)
    - Or time to impact less than X seconds

G-Excess

The G-excess illusion is a false or exaggerated sensation of body tilt that can occur when the G environment is sustained at greater than 1G. In 1G, a 30-degree head tilt forward results in otolith displacement indicating that much angle. In a 2G environment the 30-degree head tilt results in an otolith displacement indicating much greater tilt, theoretically as much as 90 degrees (2* sin30 = sin 90 deg). Experimental evidence shows the phenomenon if not the theoretical magnitude. Perceptual errors of 10 to 20 deg are generated at 2G, and at 1.5G, errors are about half that amount (DeHart & Davis, 2002; Previc & Ercoline, 2004).

- One version of this is the moderate amount of excess G pulled in a turn followed by turning the head to look at or reach for something. Similar (or contributing) to the Coriolis Effect, the perception is of uncommanded or excess tilt in roll and/or pitch.
- In high G turns by fighter aircraft (2 to 5.5 G) a condition of overbanking has been observed while the pilot was looking out the cockpit for an adversary, wingman or other object, and descended into terrain. The theory is that G-excess in this condition creates an under-banked illusion if the pilot's head is facing inside the turn and elevated, or outside the turn and depressed.

Vertical Motion Misperception

This variation results in false sensations of pitch and vertical velocity based on changes in +Gz. An upward acceleration causing a net Gz increase yields a sensation of climbing and tilting to occur. Leveling off from a sustained descent results in a temporary increase in +Gz making the pilot feel pitched up and climbing. Compensating often results in the pilot putting the aircraft back into a descent. In one in-flight study, blind-folded pilots were told to maintain level flight following a quick level off from a 10 m/sec descent. The mean response was to initiate a 6.6 m/sec descent (Fulgham & Gillingham, 1989).

The G-excess illusion may be a factor during Shuttle entries and approaches to landing, but we have not developed an illusion assessment sequence for SDAT for this category of illusions in Year 1; we will do so in Year 2.