Human Spatial Orientation Perceptions during Simulated Lunar Landing

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ABSTRACT

During crewed lunar landings, astronauts are expected to guide a stable and controlled descent to a landing zone that is level and free of hazards by either making landing point (LP) redesignations or taking direct manual control. However, vestibular and visual sensorimotor limitations unique to lunar landing may interfere with landing performance and safety.

Vehicle motion profiles of candidate lunar descent trajectories were used as inputs to a mathematical model for orientation system function, to predict human perception of orientation and identify disorientating illusions. Simulations were conducted using the vestibular-only portion of the model as well as incorporating the activation of visual cues. Dust blowback from the descent engine was modeled as well. The NASA Ames Vertical Motion Simulator was used to experimentally investigate human orientation perception during manually controlled landing trajectories. Subjects were tasked with reporting perceptions of vehicle tilt angle and horizontal velocity. There were three treatment conditions studied: eyes closed (blindfolded), eyes out the window on simulated lunar terrain, or eyes on display instruments.

It was seen in the vestibular-only orientation perception model that the acceleration profile of the descent engine throughout candidate trajectories is likely to create a somatogravic illusion. This illusion creates the perception of being upright even when the actual vehicle orientation is significantly tilted.
The model predicts the underestimation of tilt angle for the candidate automated trajectories as well during maneuvers resulting from LP redesignation and manual control maneuvers. The activation of visual pathways in the model improved orientation perceptions, however misperceptions persisted when visual cues were limited such as prior to the pitch-over maneuver and during dust blowback.

Results from the motion base simulator experiment are in agreement with the likelihood of the somatogravic illusion occurring without the astronauts' continued focus on instrument displays. Horizontal velocity was poorly perceived without reliable visual cues, both in magnitude and direction. Misperception of spatial orientation is likely to increase workload and may reduce performance and safety during landing. Countermeasures should be designed to minimize the risk of astronaut disorientation, including the design of advanced displays.

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LIST OF ACRONYMS

ACCEL	Acceleration Control Mode
ALHAT	Autonomous Landing and Hazard Avoidance Technology
ARC	Ames Research Center
CNS	Central Nervous System
CoM	Center of mass
COUHES	Committee on the Use of Humans as Experimental Subjects
FPA	Flight Path Angle Control Mode
GIF	Specific gravtio-inertial force
GNC	Guidance navigation and control
HRIRB	Human Research Institutional Review Board
HSD	Horizontal Situation Display
ICAB	Interchangeable cab
IPC	Incremental Position Control Mode
ISS	International Space Station
KS	Kolmogorov-Smirnov
LEO	Low earth orbit
LLRV	Lunar Landing Research Vehicle
LM	Lunar Module
LMP	Lunar Module Pilot
LP	Landing point
LPD	Landing Point Designator
MSE	Mean square error
NEO	Near-Earth Object
OTTR	Otolith tilt-translation reinterpretation
OTW	Out the Window
PIO	Pilot induced oscillation
S/C	Spacecraft
SCC	Semicircular canals
SD	Spatial disorientation
RCAH	Rate Control Attitude Hold Control Mode
ROTTR	Rotation Otolith Tilt-Translation Reinterpretation
TRCPH	Translational Rate Control Position Hold Control Mode
UFPA	Unified Flight Path Angle Control Mode
VINC	Incremental Velocity Control Mode
VMS	Vertical Motion Simulator
VSD	Vertical Situation Display

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1 INTRODUCTION

On July 20, 1969, the United States and the human race were on the verge of the monumental achievement of landing humans on the moon. Apollo 11 lunar astronauts Neil Armstrong and Buzz Aldrin were piloting the Lunar Module (LM) down to the surface of the moon. Armstrong had his hands on the controls and was looking out a forward-facing window at the lunar surface, while Aldrin was the co-pilot, reading out information from the instrument displays. Shortly before landing, at an altitude of approximately 2000 feet, Armstrong identified that the designated landing area was full of rocks and craters.

> *"We could see the landing area and the point at which the LPD (Landing Point Designator) was pointing, which was indicating we were landing short (slightly north) of a large rocky crater surrounded with the large boulder field with very large rocks covering a high percentage of the surface. I initially felt that that might be a good landing area if we could stop short of that crater, because it would have more scientific value to be close to a large crater. (However), continuing to monitor the LPD, it became obvious that I could not stop short enough to find a safe landing area."* – Neil Armstrong (Apollo 11 Technical Crew Debriefing 1969)

In response, Armstrong switched control modes so that he could operate the vehicle manually, and pitched over to fly past the rock field. Once the rock field was cleared, Armstrong quickly identified a suitable landing location. However, the maneuver to modify the landing point (LP) had cut into the allotted fuel. With time running out, the crew was faced with yet another challenge.

> *"I first noticed that we were, in fact, disturbing the dust on the surface when we were something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease. I don't think that the (visual) altitude determination was severely hurt by this blowing dust;* ***but the thing that was confusing to me was that it was hard to pick out what your lateral and downrange velocities were, because you were seeing a lot moving dust that you had to look through to pick up the stationary rocks and base your translational velocity decisions on that. I found that to be quite difficult.*** *I spent more time trying to arrest translational velocity than I thought would be necessary."* – Neil Armstrong (Apollo 11 Technical Crew Debriefing 1969)

With the increasing dust blow back, combined with being in the unique lunar environment that they had yet to previously experience, it became difficult for the crew to operate the vehicle. The lunar surface was being obscured by the dust blowback, making targeting a suitable LP more and more difficult. Still, the LM had a limited amount of fuel and was the crew was quickly running out of time.

> *"As we got below 30 feet or so, I had selected the final touchdown area. For some reason that I am not sure of, we started to pick up left translational velocity and backward velocity.*

That's the thing I certainly didn't want to do, because you don't like to be going backwards, unable to see where you're going. So I arrested the backward rate with some possibly spastic control motions, but I was unable to stop the left translational rate. As we approached the ground, I still had a left translational rate which made me reluctant to shut the engine off while I still had that rate. I was also reluctant to slow down my descent rate anymore than it was or stop (the descent) because we were close to running out of fuel. We were hitting our abort limit." – Neil Armstrong (Apollo 11 Technical Crew Debriefing 1969)

Fortunately, the Apollo 11 crew was able to pilot the vehicle to an adequate landing zone and safely bring the LM to the lunar surface. However, the combination of the dust blowback, the vehicle dynamics, the lunar terrain, limited fuel, and other influences made the safe operation of the LM during the landing remarkably difficult. In particular, Armstrong had difficulty in determining the orientation of the vehicle and where the vehicle was headed. These challenges limited his ability to effectively maneuver the lander safely.

"I think I was probably overcontrolling a little bit in lateral. I was confused somewhat in that I couldn't really determine what my lateral velocities were due to the dust obscuration of the surface. I could see rocks and craters through this blowing dust. ***I was surprised that I had as much trouble as I did in determining translational velocities****. I don't think I did a very good job flying the vehicle smoothly in that time period. I felt I was a little bit erratic."* – Neil Armstrong (Apollo 11 Technical Crew Debriefing 1969)

The Apollo 11 landing and Armstrong's comments show the importance of the astronaut's perceptions of vehicle orientation and motion on safe and effect piloting. The astronauts' ability to discern their own orientation and the orientation of the vehicle plagued the Apollo 11 crew, and will continue to remain a challenge for future lunar landing vehicles.

The first step to understanding these difficulties is to analyze the unique conditions experienced during lunar landing including vehicle motions, partial gravity, and dust blowback and determine the effects on the astronaut's perceptions of spatial orientation. Only with a thorough understanding of the potential for misperceptions of spatial orientation can we then develop suitable countermeasures to ensure effective and safe landings.

1.1 Motivation

The future of human spaceflight is now on a trajectory with an emphasis for exploration beyond low earth orbit (LEO). This renewed emphasis on exploration is likely to include human exploration of planetary bodies. Starting with the Constellation program, initiated in 2004 as part of President Bush's Vision for Space Exploration there has been development for a series of return missions to the moon (The Vision for Space Exploration 2004). More recently, President Obama's decision to engage in a more "Flexible Path" to human space exploration includes visits to other destinations including asteroids and Near-Earth Objects (NEOs), as well as an eventual return to the moon. The moon, in combination with the International Space Station (ISS), provides a suitable test bed for many of the technologies required for more lengthy explorations as well as is an opportunity to understand the effects of long term spaceflight on human physiology.

The return of human space exploration beyond LEO will bring with it a host of challenges resulting from asking the human astronaut to operate in conditions never before experienced. Conditions, such as lunar landing, provide the astronaut with a unique environment and set of responsibilities which will test the capabilities and limitations of the human. However, in order to ensure safe and effective operations, the effect of these unique environments on human capabilities must be well understood. Particularly, the ability of the astronauts to accurately perceive vehicle orientation and use this to operate the spacecraft is of concern. Since the Apollo era, there have been significant improvements in computer and sensor technologies, but no changes have taken place in the astronaut's sensory systems. Pilots are still likely to experience motion cues that are either conflicting or ambiguous. They are still likely to experience illusions or incorrectly perceive motion cues. If or when this misperception of spatial orientation occurs, it is still likely that the astronauts will be adversely affected and potentially make control inputs that are incorrect for the actual orientation of the vehicle resulting in ineffective or unsafe maneuvers. Furthermore, disorienting stimuli will likely increase with the astronauts workload which could indirectly affect performance and safety.

While all six of the attempted lunar landings were completed safely, the astronauts reported a variety of challenging experiences. These included dust blowback limiting visibility, difficulty recognizing objects on the factual lunar terrain, and unique lighting conditions due to the non-Lambertian properties of the lunar regolith and the lack of an atmosphere. The astronauts will be exposed to lunar gravity after three or more days in weightlessness. This has the potential to result in spatial disorientation (SD). None of the Apollo astronauts recognized and reported SD of the traditional types in any of the six landings. However, future plans include more extensive exploration and as a result, far more landings. SD is commonly experienced by pilots flying aircraft, and as the number of flights increase the number of cases of SD as well as the resulting accidents increase. It is reasonable to expect a similar effect for SD during an increased number of lunar landings, particularly considering the daunting environment.

Technologies have improved to allow detailed lunar mapping from orbit to identify craters and rocks as small as 7-20 m prior to the actual landing. Laser imaging technology is expected to be used during the descent to refine the details of terrain in the vicinity of the planned landing area with even greater accuracy as high as 50 cm resolution (Epp and Smith 2007)(S. Paschall, et al. 2008). Even intelligent planning algorithms, such as those that are part of the NASA Autonomous Landing and Hazard Avoidance Technology (ALHAT) program, can be used to identify suitable LP locations as well as identify potential alternatives (Forest, Kessler and Homer 2007). While these technologies will significantly assist the astronaut during lunar landings, the astronaut will still need to accurately perceive his/her own orientation. Upcoming lunar landings are expected to retain a manually controlled mode, requiring direct inputs from the astronaut. The Constellation program requirements (Requirement 3.4.1, NPR 8705.2B) ensured that for crewed missions, the crew shall be provided the capability "to manually control the flight path and attitude of their spacecraft" (Human-Rating Requirements for Space Systems

2009). Misperceptions in orientation are likely to influence control inputs, particularly when using this manual mode.

Recently, President Obama commissioned a report on the future options for human spaceflight (Review of Human Spaceflight Plans Committee 2009). In response to this report, the future plans of NASA remain uncertain, though it appears that return visits to the moon might be delayed. While this analysis is done specifically for lunar landings, it is very much so applicable to landing on other planetary bodies including asteroids, NEOs, Mars, and Martian moons. This analysis provides the framework to analyze the potential for SD in any number of gravitational fields and trajectories which might be encountered while landing on a specific planetary body. Many of the specific challenges facing lunar landing astronauts such as dust blowback, unique visual conditions, and the reappearance of a gravitational field after extended exposure to microgravity will be experienced landing at any location. Thus, even if a return mission to the moon is not part of the short-term plans, this analysis still holds practical implications as well as forms a framework for future analysis. Additionally, upon the eventual return to the moon, this analysis will have direction application. There was particular emphasis put on not making significant assumptions that would limit the analysis to a particular vehicle design. The trajectories analyzed are most directly apply to the Constellation program Altair lunar landing, but are similar to the Apollo trajectories and will likely be similar to trajectories flown by any upcoming lunar landing vehicle due to the physics of the landing on the moon. Thus, this analysis has applications for future lunar landings when NASA decides to return to the moon as well as for more near term missions to other destinations within the solar system.

1.2 Contribution

The study aims to improve the understanding of potential sensorimotor difficulties associated with manual or supervisory control of a lunar lander. In particular the potential for spatial orientation illusions, misperceptions, and SD will be studied. Previously, potentially disorienting stimuli have been identified, both in general aviation and specifically in the lunar landing scenario(Previc and Ercoline 2004). While these factors have been identified, specifically what their effects will be on the astronauts' ability to perceive the vehicle orientation has not been studied in detail. The contribution of this work includes the detailed analysis on individual factors to determine their particular effects as well as combining multiple factors to understand the interactions. For example, the influence of partial gravity will be combined with the lunar landing trajectory motion to study the vestibular limitations and misperceptions. Then visual cues, including dust blow back, will be added to study their contribution. This will be done in such a way that quantitative approximations for the magnitude and duration of misperceptions can be made.

The analysis will also consider a wide range of different factors which have an influence on vehicle design as well as human-machine responsibilities for upcoming lunar landing missions. Various automated trajectories will be studied from a trade space of possibilities (Paschall and Brady 2008). During landing the astronauts are expected to have the capability to redesignate the LP, thus redesignation trajectories were studied as well. Finally, in the case in which the astronauts take over in direct manual control, various simulated manually controlled trajectories were analyzed. Each of these cases included maneuvers that were primarily in the roll or left/right direction as well as the pitch or forward/backward direction in order to study the potential effects of the direction on orientation perceptions. Beyond the types of trajectories and types of motion cues the astronauts can use, analysis was also done on potential vehicle parameters. In particular the effect of the astronaut's head location within the vehicle was studied. Some vehicle designs include the astronauts being located high above and far in front of the vehicle center of mass (CoM). During rotations this results in accelerations experienced by the astronauts in addition to those due to the vehicle linear motion. The effect of the head location within the vehicle for various design points was studied to analyze the effect on astronauts' orientation perceptions.

Future analysis plans to include how orientation misperceptions influence vehicle control during lunar landing, but this was not explicitly studied here. Additionally, this analysis leads to recommendations on a series of countermeasures which could be implemented to prevent SD or minimize the effect on vehicle performance and safety. The recommendations of these countermeasures is included here, however the testing of these countermeasures remains a topic of future work.

1.3 Problem Statement

This study aims to quantitatively investigate the potential causes of spatial orientation misperceptions experienced by astronauts during lunar landing scenarios during a variety of conditions including automated landings, LP redesignation landings, and manually controlled landings. This analysis will allow for the prediction of potentially disorienting stimuli experienced during lunar landing as well as lead to determining suitable countermeasures to limit the effects of these stimuli. The analysis is exploratory in nature and thus is not particularly suitable for the development of hypotheses. The preliminary analysis provides motivation and hypotheses for future analysis. Prior to initiating this work there were not specific testable hypotheses. However, for the motion based simulator experiment there were two primary hypotheses. These are given below:

<u>Hypothesis 1:</u> The visual treatment (eyes closed, eyes out the window, or eyes on the display) will have an effect on the accuracy of orientation perceptions during landing trajectories

- Eyes out the window visual cues will have a positive effect on orientation perceptions in comparison to the eyes closed case
- Eyes on the display visual cues will have a positive effect on orientation perceptions in comparison to the eyes closed case
- Eyes on the display visual cues will have a positive effect on orientation perceptions in comparison to the eyes out the window case

<u>Hypothesis 2:</u> The visual treatment will have an effect on the accuracy horizontal velocity perceptions during landing trajectories

- Eyes out the window visual cues will have a positive effect on horizontal velocity perceptions in comparison to the eyes closed case

- Eyes on the display visual cues will have a positive effect on horizontal velocity perceptions in comparison to the eyes closed case
- Eyes on the display visual cues will have a positive effect on horizontal velocity perceptions in comparison to the eyes out the window case

1.4 Thesis Outline

The remainder of this thesis is divided into four chapters, followed by references and appendices. Chapter 2 is the Background section. It introduces the reader to the lunar landing task and challenges that the astronauts face with regard to orientation perception. Next it provides a review of knowledge and research on spatial disorientation during previous landing missions in space. A review of spatial orientation sensory systems is given along with an introduction to the spatial orientation model used in the analysis. Chapter 3 is the Methods section, which describes the techniques used for the numerical simulation conducted to predict orientation perceptions and the procedures used for the motion based simulator experiment. Chapter 4 is the Results section, which describes the findings of the simulation and experiment. Those results are expanded upon in Chapter 5 which is the Discussion section. This section also includes some of the limitations of the methodologies and results as well as their implications. The final section, Chapter 6, is the Conclusions and Recommendations. This section reviews the major results and implications of the study, proposes potential countermeasure concepts, and indentifies areas for future research.

2 BACKGROUND

2.1 The Lunar Landing Task

Landing a manned spacecraft on any planetary body requires the precise and fluid interaction of the astronauts and the automated systems. The process of lunar landing has two distinct steps. The first step is the selection and identification of an appropriate landing point (LP) that is level and free of hazards. Secondly, the vehicle must enact a stable and controlled descent to the surface. To confound the difficulty of the lunar landing task is the ever present fuel limitation. Any excess fuel provided for the lunar descent serves as payload mass for the launch from the Earth's surface. In addition, added fuel carried to the lunar surface requires a more robust, and thus heavier, structure for the landing vehicle. Thus the fuel margin for the lunar descent is kept to a minimum. Furthermore, any time which the astronauts or automated systems wish to use during descent requires the landing vehicle to burn descent fuel in maintaining a hover. Thus descent time is proportional to descent engine fuel, and that fuel is exceeding expensive since it must be launched from Earth. The time constraint during lunar landing will always be stringently tight. This was first seen during Apollo 11, when astronauts Neil Armstrong and Buzz Aldrin maneuvered the vehicle to avoid hazards and landed the vehicle with only enough fuel remaining for approximately 25 seconds worth of hover prior to a Go-No-Go decision on landing (Apollo 11 Mission Report 1969)(Brady and Paschall, The Challenge of Safe Lunar Landing 2010). Furthermore, as experience is gained and lunar landing becomes more routine it is likely that this time constraint becomes even more limited as designers try to make each lunar landing more fuel and mass efficient.

The complexity of a the full lunar landing task is beyond the scope of this work, however a brief description of the role of the astronaut during lunar landing is included here, specifically for the purpose of how it might be impacted by orientation perception influences. For a more extensive study of the role of the astronaut and the interaction between human and automation during Apollo lunar landings see (Mindell 2008). During the lunar orbit phase and transfer orbit coast prior to the descent initiation, the digital autopilot was responsible for controlling the vehicle. The astronauts were responsible for performing checklist preparation tasks and ensuring the automated procedures were being enacted correctly. The phases of the mission just prior to the beginning of the landing sequence are given in Figure 2.1.

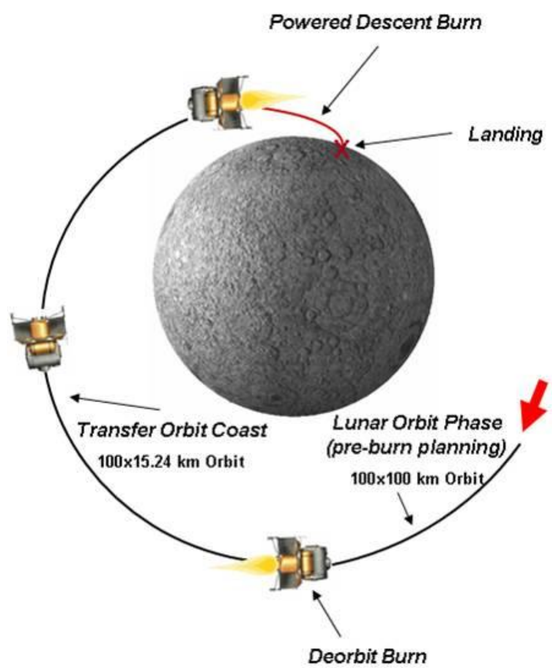

Figure 2.1: Pre-Descent Mission Phases (Sostaric and Paschall 2007)

Following the transfer orbit coast, the descent begins with the powered descent initiation (PDI). This is enacted at an altitude of approximately 15 km above the lunar surface. At this point during the trajectory the lunar landing vehicle is pitched back by approximately 90 degrees, such that the descent engine thruster is pointed forward. The astronauts during Apollo were standing “upright” within the vehicle such that they were coming in feet first, with their backs facing the lunar surface, and their eyes looking up at the stars. The exception to this is Apollo 11 where the astronauts were facing down at the lunar surface, though their feet were still leading in the direction of travel. This was done such that during PDI, the astronauts could make visual contact with the lunar surface and by identifying the times between seeing different landmarks they could provide an independent estimate of velocity. This was used to make sure the inertial guidance system was functioning properly and to check that the PDI burn was being carried out properly. This procedure actually allowed Neil Armstrong to note that the vehicle was travelling faster than expected and predict accurately that they would land downrange of their targeted landing area (Apollo 11 Mission Report 1969). Following this estimation, the vehicle would perform a 180 degree yaw maneuver to return it to the 90 degrees pitched back orientation with the astronauts' backs facing the lunar surface. After Apollo 11, this initial orientation and following yaw maneuver were removed, and the LM began PDI pitched 90 degrees back.

The PDI marks the beginning of the lunar landing descent and is the beginning of the analysis performed here. The lunar landing phases are seen in Figure 2.2.

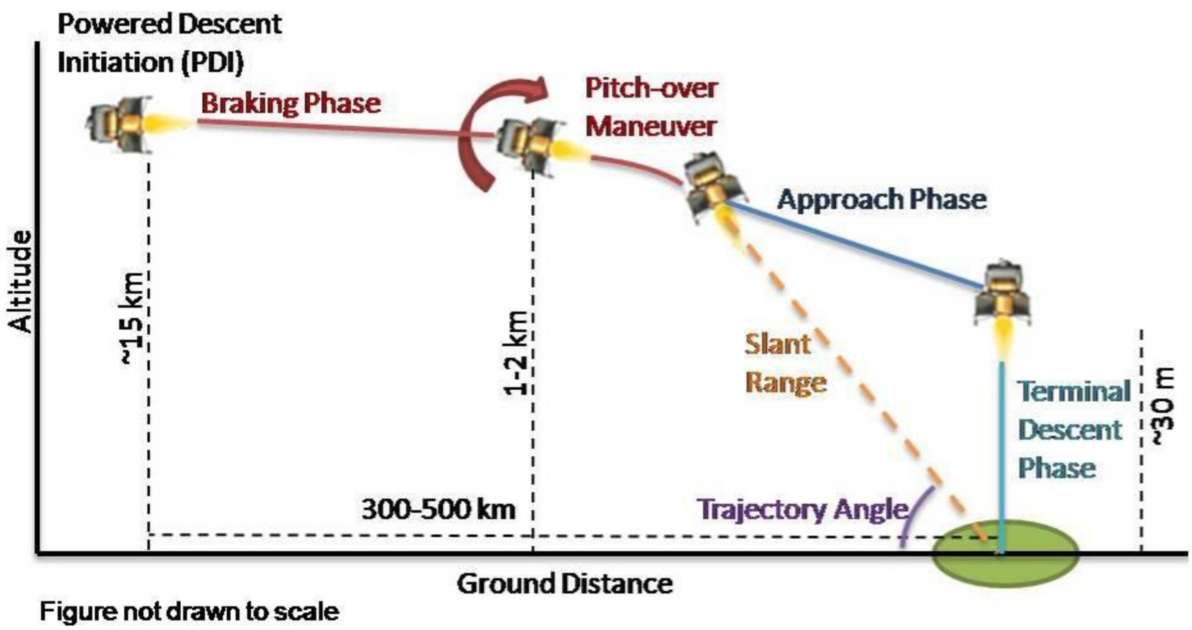

Figure 2.2: Lunar Landing Mission Phases (Sostaric and Paschall 2007)

This first phase of the descent trajectory is the braking phase, which beings at PDI at an altitude of approximately 15 km. The automated braking phase is the longest phase of the landing lasting between 400-600 seconds, and slows the vehicle from orbit and begins the descent to the surface. The vehicle then rotates in the pitch-over maneuver to a more upright orientation. During Apollo, this allowed the astronauts to make visual contact with the lunar surface and search for a LP that was free of hazards. This was followed by the vehicle coming entirely upright such that the astronauts were standing in a natural orientation within the vehicle for terminal descent and finally touchdown. While upcoming lunar landings are likely to have a different type of vehicle than the Apollo LM as well has have slightly different trajectory parameters, the series of mission phases are likely to remain constant.

During the Apollo era, there were two astronauts who took part in the lunar descent and landing, while the third astronaut for each mission remained in orbit about the moon in the command module. During the braking phase and pitch-over, the astronauts did not have an active role in vehicle control. They were responsible for reviewing checklists and monitoring systems, but the vehicle motion was controlled by the digital autopilot. However, beginning in the approach phase the astronauts obtained the capability to influence the vehicle's maneuvers during descent. The Commander's responsibility was to look out the window at the lunar surface and to fly the vehicle with his hands on the control sticks. The Lunar Module Pilot's (LMP) responsibility was to read the instruments within the vehicle and verbally report the system states and status to the Commander. The Apollo LM guidance computer had three different primary modes in which the vehicle motion could be controlled (Mindell 2008)(P. Parker 1974). Following the braking burn, the digital computer switched from the braking phase program (P63) to the approach phase program (P64) automatically. Within this mode a fully automated landing could be enacted using the vehicle's sensors to control a stable descent to the surface. There was no active searching for hazards in this control mode, thus if the pre-designated landing zone contained hazards this mode would not attempt to avoid them. In a fully automated landing, the digital computer automatically switches into another program, P65, during terminal descent. This program nulls the horizontal velocity of the vehicle prior to touchdown. A second control mode was also part of the P64 program and was effectively a supervisory control mode. Here the LMP would read aloud to the commander LP angles provided by the guidance computer. The Commander then used an inscription on his window known as the Landing Point Designator (LPD), which had angle markings on it. By looking through the LPD at the angle markings which were provided by the guidance computer, the Commander could see the designated LP on the lunar surface. The Commander could check the lunar surface for hazards and potentially adjust the designated LP in the guidance algorithms. This was done by nudging the right hand controller in the direction which he wanted to move the LP. Within the guidance algorithm this moved the designated LP by either two degrees if the input was left or right or half a degree if the input was fore or aft. Therefore, in this mode the astronauts were not specifically responsible for flying the vehicle, but were capable of influencing vehicle maneuvers and adjusting the LP in a supervisory control mode. The final control mode was part of the P66 program. In this mode, the Commander is able to fly the LM. Using a "rate of descent switch" near his left hand the Commander could increase or decrease the rate of descent by one foot per second for each click either down or up. Using the right hand controller, the Commander could control the attitude of the LM using a rate control attitude hold (RCAH) control mode in which stick deflections were proportional to the vehicle's rate of change of attitude. It should be noted that while this control mode was manual, it still involved significant use of the digital computer and guidance systems to close the inner loops of the control system and enact the descent rate and attitude rates which were commanded by the astronauts. Finally, there was a control mode in program P67 in which the Commander could directly control the descent engine thrust and attitude accelerations, however this mode was implemented only as a backup. It was nearly impossible to fly because the innermost loops were being controlled. This results in a high order manual control task requiring the pilot to provide significant lead to obtain stability (McRuer and Magdaleno 1966). This requires piloting skill and results in high workload.

Despite its availability none of the six lunar landings during the Apollo era were completed in the fully automated control mode. Instead, during the approach mode the astronauts switched into the supervisory mode in which they could make LP redesignations. Then, in all six landings the Commander switched into P66 to take manual control of the vehicle during the final landing stages prior to touchdown. Future lunar landings may have slightly different roles for the astronauts. For example, the

Constellation project proposed that four astronauts would journey to the lunar surface. Also future lunar landings will take advantage of technological advancements. NASA's ALHAT program has developed hazard detection and avoidance algorithms which could assist the astronauts in detecting hazards and finding a suitable LP during the approach phase. Using these technological advancements, future lunar landings could locate and avoid hazards automatically, while the astronauts could serve in a supervisory role making sure automated systems are operating appropriately. Nonetheless, the fact that the Apollo astronauts took manual control despite the presence of an automated landing system, in combination with the Constellation program requirement to allow for piloted manual control (Human-Rating Requirements for Space Systems 2009), make it unlikely that the astronauts will function in an entirely monitoring role. Thus it remains critical that the challenges of the lunar environment experienced during landing are well understood and their impact on the performance of the astronauts is taken into account.

2.2 Challenges of the Lunar Environment

The human orientation perceptual system has evolved in environmental settings of the Earth and for the purpose of perceiving motions which can be achieved within the human body dynamic limitations of everyday life. Thus, it should not be surprising that the orientation perceptual system may have difficulty performing in the lunar environment while experiencing motions unique to lunar landing. Prior to lunar landing, the astronauts will have experienced three or more days in weightlessness, which is likely to influence the interpretation of vestibular cues when head movement are made or when the vehicle maneuvers. Additionally the vehicle maneuvers are unique to lunar landing and may result in illusory perceptions of vehicle motion. Furthermore many of the visual cues which could limit orientation misperception due to vestibular signals are likely to be limited or disorienting. In particular, it has been seen that slope and distance estimation is inaccurate on the lunar surface (C. Oravetz 2009). There are many factors which limit visual perception in the lunar environment. The lack of an atmosphere on the moon makes judging the distance of objects more difficult. On Earth, we rely on the fact that objects which are far away to appear more blurry due to atmospheric effects. In the lunar environment, objects that are far away appear just as clearly as objects which are nearby. Additionally, on the lunar surface there are no familiar objects to use as size and distance references. While on Earth the size of a rock might be discernable due to a familiar sized object (for example a car or tree) being located nearby, these cues are not available on the moon. Furthermore the non-Lambertian reflectance properties of the lunar regolith make visual perception even more challenging. These factors combine to create the distance/size ambiguity that makes it very difficult to discern if an object is large and far away or small and nearby.

While these factors make orientation and motion perception on the lunar surface difficult, they are confounded by factors unique to the landing phase. Visual cues are likely to be difficult to discern on the moon and they are even more difficult given that the astronauts will have a limited field of view. To save mass, it is quite likely the upcoming lunar landings will provide the astronauts with only very small forward looking windows. These views will limit the astronauts' ability to see behind or below the vehicle. Recent vehicle designs as part of the Constellation program involve a larger landing vehicle.

This requires large fuel tanks below the astronauts' cabin and effectively creates a porch which the astronauts cannot see below. Thus the landing area will be obscured from the astronauts' view until the vehicle is nearly upright. Even the horizon will not be visible until the pitch-over maneuver brings the vehicle upright. Furthermore, since the terrain directly beneath the vehicle is not visible the astronauts must inspect the landing zone on approach and then fly over to it and perform final descent without visual contact with the LP. It is likely that even when the landing area is visible, the astronauts may have difficulty identifying landmarks on the fractal lunar terrain. Distant concave features such a lunar craters can sometimes be perceived as hills when they are viewed looking "down sun" (Ziedman 1972)(Ramachandran 1988). As the vehicle approaches the lunar surface the descent engine thruster will create dust blow back obscuring the astronaut's view. This is similar to helicopter pilots who experience "brown-out" when landing in sandy terrain. Thus the astronauts are likely to complete the most critical portion of the landing, the terminal descent phase, without visual reference to search for craters or hazards. In some cases, the dust blow back may limit the astronauts' view of the horizon.

During the Apollo era, great care was put into picking the time and location of each landing to provide the astronauts with the best visual cues and ensure the terrain was as benign as possible (Cappellari 1972). The goal was simply to land safely on the moon, with little concern as to when or at what geographical location. Future lunar landings are expected to be less limited with these requirements. While the Apollo landings were all near the equator, there is strong scientific desire to land near the lunar poles. Specifically, Shackelton crater near the lunar South Pole is a desirable location since there is likely ice water located there. However, landing on the lunar poles adds challenges to the lunar landing task. The terrain at the lunar poles is far more fractal with greater concentrations of crater and rock hazards. Additionally, the sun never comes far above the horizon resulting in low lighting angles. These low sun angles result in long shadows which make it impossible for the human eye to locate hazards or safe landing zones. The lack of an atmosphere exacerbates this problem since light is not diffused as much. As a result, the shadows become increasingly deep and dark. The presence of shadows can be seen in the following set of images obtained from the KAGUYA spacecraft.

Figure 2.3: Lighting Conditions near North Pole from KAGUYA Spacecraft (JAXA 2007) (Brady 2009)

Figure 2.3 contains a series of images taken from the KAGUYA spacecraft as it approaches the lunar North Pole from approximately 70 degrees latitude. At the initial latitude (1), the sun angle is relatively high and the lighting of the lunar terrain is sufficient for the identification of craters and rocks. As the vehicle approaches the North Pole (1 → 9), it can be seen that the shadows become longer and deeper as the sun angle continues to decrease. At the lunar North Pole, the visibility provided by the sun is nearly nonexistent. With an increased number of lunar landings in future missions and the desire to land at points of scientific interest, landings will be required to occur at times and at locations that are more challenging than even those experience during the Apollo era.

2.3 Spatial Disorientation in Previous Space Landings

In beginning an analysis of the likelihood, causes, and types of spatial disorientation that might occur during the unique stimuli experienced during lunar landing it is critical to look back at both previous studies as well as prior experiences that we can draw from. One challenge is that the past experiences with which can be drawn upon are very limited. This however should encourage, not hinder, research on this topic.

2.3.1 Apollo Lunar Landings

The Apollo lunar landings provide the best, although most scarce, resource to consider SD during lunar landings. It should be noted that during the Apollo era, none of the astronauts recognized and reported

SD of the traditional types in any of the six lunar landings. Many of the astronauts did, however, report that lunar dust obscured the final portion of their approach. For example, two landings were made without reliable visual cues (Apollo 12 Mission Report 1970) (Apollo 15 Mission Report 1971). In the case of Apollo 15 the landing resulted in damaging the descent engine bell when touching down with two legs in a five foot deep crater. There is reason to believe that the dust blow back from the descent engine affects not only the astronauts' ability to locate hazards, but also to determine horizontal velocities. The following is a quote from Neil Armstrong, the Commander from Apollo 11:

> *"The exhaust dust was kicked up by the engine and this caused some concern in that it degraded our ability to determine not only our altitude and altitude-grade in the final phases,* ***but also, and probably more importantly, our translational velocities over the ground****."* – Neil Armstrong (Apollo 11 Technical Crew Debriefing 1969)

Alternatively, the Commander of Apollo 12, Pete Conrad, reported that the dust indeed obscured his visual contact with the ground, but that did not limit his velocity perceptions:

> *"…we picked up a tremendous amount of dust much more so than I expected. I could see the boulders through the dust, but the dust went as far as I could see in any direction and completely obliterated craters and anything else. All I knew was there was ground underneath that dust.* ***I had no problems with the dust determining horizontal and lateral velocities****, but I couldn't tell what was underneath me."* – Charles "Pete" Conrad (Apollo 12 Technical Crew Debriefing 1969)

Thus from the Apollo lunar landings it can be seen that particularly the dust might impact the orientation perceptions made by astronauts. Additionally the limitations of applying the experiences of the astronauts during Apollo directly to future landing missions should be mentioned. First, only twelve astronauts experienced the lunar landing stimuli. In aircraft scenarios, thousands of pilots might fly very similar motions in similar conditions and only a handful might experience SD. Thus, while SD has yet to be reported in the six lunar landings to date, it does not eliminate the possibility of a SD episode occurring in future landings. Second, there are three types of SD: 1) unrecognized, 2) recognized, and 3) incapacitating (Gillingham and Wolfe 1986). Thus it is possible that astronauts experienced cases of SD, however it was not recognized. Third, in some cases it has been seen that in the early years of the United States space program afflictions experienced by the astronauts were not accurately reported. For example, space motion sickness was not acknowledged to occur commonly for astronauts until later in the space program development. It is possible that SD in some form may have occurred and either was not identified or not reported. Lastly, the trajectories flown and vehicle dynamics of upcoming lunar landings are likely not to be identical to Apollo and thus may include stimuli which could induce SD.

2.3.2 Shuttle Landings

Experiences from shuttle landings provide a unique opportunity to study SD that may occur during lunar landings. Similar to astronauts on a mission to land on the moon, Shuttle astronauts have experienced an extended period of time in weightlessness, and thus may have experienced some adaptation in orientation mechanisms. The actual landing then places the astronauts in a gravity rich environment where there is no time for orientation mechanisms to readapt. Furthermore, in both cases the landing is a mission critical point, in which the astronauts must be active, alert, and in top condition to respond. Thus SD could potentially impact mission success. During Shuttle landings it has been seen that the reappearance of the gravitational force during re-entry may result in vertigo, oscillopsia or illusory motion of the external visual field, and reduced visual acuity when astronauts make any head movements. Some crewmembers train themselves to avoid making any significant head movements to prevent these illusory sensations, while others intentionally make small head movements in an effort to help readaptation. These illusions usually persist for several hours after landing. After landing, many shuttle crewmembers have reported that when they tilt their heads they experience a strong tumbling sensation. This has been described as if the "gain" of their head tilt estimator has been significantly increased and is known as the "Tilt-Gain" illusion (Young, et al. 1984)(Parker, et al. 1985). Other astronauts, upon returning, report a transient sensation of linear motion either horizontally or slightly upwards when head tilts are made. These illusory motions are usually in the direction opposite to the head tilt, but sometimes in the same direction (Parker, et al. 1985)(Reschke, et al. 1994)(Harm, Reschke and Parker 1999). The theoretical underpinnings of these "Tilt-Translation" illusions is attributed to the orientation system reinterpreting all otolith cues as being due to translational accelerations such as they would be when in weightlessness. When returning to Earth, otolith signals respond to tilts, but are incorrectly attributed to translational accelerations. This is known as the otolith tilt-translation reinterpretation (OTTR). The OTTR hypothesis assumes that the utricular otolith mediates all tilt sensation, and thus if all otolith cues were simply reinterpreted to be translational acceleration then a sustained head tilt should be perceived as a sustained acceleration, which is not what is usually observed. Instead it was proposed that both Tilt-Gain and Tilt-Translation illusions are due to a change in the effect of semicircular canal cues to transiently estimate the rotation of the direction of "down" relative to the head (Merfeld 2003). This hypothesis is known as the Rotation Otolith Tilt-Translation Reinterpretation (ROTTR). In this hypothesis, overestimation of passive tilt results in rotation dominating the sensation (Tilt-Gain) while underestimation results in the sensation of linear translation (Tilt-Translation). An implication of the ROTTR hypothesis is that whether Tilt-Gain or Tilt-Translation illusions occur upon return to Earth may be astronaut dependent. To date there has not been a systematic clinical study on the characteristics of head tilt illusions of Shuttle astronauts post-landing. Tilt-Gain or Tilt-Translation illusions can potentially occur even without any head movements being made relative to the vehicle if the vehicle is executing roll and pitch maneuvers. Just as in lunar landing, illusory motions are likely to lead to incorrect manual control responses. A dangerous pilot induced oscillation (PIO) on the STS-3 landing as well as other outlier landing performances were seen to be correlated with astronauts having strong neurovestibular symptoms post-landing (McCluskey, Clark and Stepaniak 2001).

Thus it appears likely that neurovestibular adaptation to weightlessness results in illusory perceptions during the reappearance of a gravitational field that occurs during landing. Furthermore, it has been seen that these illusory motion perceptions may have an impact on the astronauts' ability to operate the vehicle particularly during manual control tasks. There are, however, some significant differences between Shuttle landings and future lunar landings. Although lengths of stays have varied between missions, Shuttle astronauts usually spend a week or two in weightlessness whereas astronauts on their way to the moon will likely only experience approximately three days of weightlessness. It is believed that most neurovestibular adaptation to weightlessness will likely have occurred within this time frame. Secondly, the Shuttle landings return the astronauts to a gravitational environment (1G) in which they have spent their entire lives and were previously well adapted. Lunar landings will expose the astronauts to a gravitational environment that they will likely have only experienced briefly during parabolic flight training, if at all. Also whether entering the 1/6 G environment of the moon following neurovestibular weightlessness adaptation will have the same effect as returning to the Earth is still a topic for study. Finally, the Shuttle is a different vehicle than any type of lunar landing vehicle and the trajectories experienced will be drastically different. Nonetheless, the illusory orientation perceptions experienced by astronauts during Shuttle missions provide a useful starting point for the study of SD during lunar landings.

2.3.3 Future Lunar Landings

There has been limited study on the potential for SD during lunar landing to date. Recent research has shown that humans poorly estimate lunar slopes and distance as discussed in Section 2.2 (Oravetz, Young and Liu 2009). While this research was focused on how astronauts orient themselves and navigate on the lunar surface, it is also quite likely to influence perceptions during landing. Future lunar landings will be more challenging perceptually than those completed during the Apollo era. Landing near the lunar poles means that landings will occur at very low sun angles (0-2 degrees). This will result in very long shadows which will limit the astronauts' ability to interpret the lunar surface. Also, it has been seen during Shuttle landings that the reappearance of a gravitational field after adaptation to weightlessness is likely to result in the misinterpretation of motion when head movements are made either within the vehicle or by the vehicle. This is likely to occur during lunar landings as well. The lack of quantitative research thus far on the likelihood of SD during lunar landing warrants this study.

2.4 Spatial Orientation Sensory Systems

Humans can accurately perceive their orientation and inertial motion in everyday life through the integration and processing of signals from multiple sensory sources. The central nervous system (CNS) receives signals used for orientation perception from a variety of sources including the visual system, the vestibular system, and proprioceptive sensors. Proprioceptive sensors play an important role in determining the relative orientation of different portions of the body as well as the judgment of perceived postural verticality. However as will be discussed, this analysis focuses on SD due to vehicle motion and rotation and thus the astronauts' head movements relative to the trunk within the vehicle are not critical. This combined with the fact that proprioception is virtually uninvolved in the separate judgment of the subjective vertical (Bronstein 1999)(Mittelstaedt 1999), allows for these cues to be neglected in this study of SD. The visual system, when activated (when the eyes are open and the surrounding environment is appropriately lit), provides strong cues regarding orientation information, particularly verticality information, position, and linear and angular velocity. Visual information about spatial orientation is generally obtained from optic flow. Optic flow can be defined as the pattern of visual motion experience during self-motion relative to a stationary global environment (Gibson 1950). For a more detailed explanation of the visual system see (Cornsweet 1970). The vestibular system is a key organ for sensing body motion as well as for postural control. Physically it is a small, fluid-filled system located in the inner ear. In each ear is located a set of three roughly orthogonal semicircular canals (SCCs), and a pair of otolith organs. Over the range of frequencies normally experienced in everyday life, the SCCs serve as angular velocity transducers (Goldberg and Fernandez 1971). The otolith organs function as an accelerometer, signaling acceleration and gravity (Fernandez and Goldberg 1976). More precisely the otolith organs transmit proportional to specific gravito-inertial force (GIF) as defined in Equation 1.

$$\vec{f} = \vec{g} - \vec{a} \tag{1}$$

Where $\vec{f}$ is the specific gravito-inertial force vector, $\vec{g}$ is the gravity vector, and $\vec{a}$ is the head acceleration vector. For a more extensive review of the vestibular system, see (Goldberg and Fernandez 1984).

One obvious result of Equation 1 is that if the otolith organs measure GIF, then gravity and acceleration are not measured independently. This is a property of accelerometers of all kinds and is due to Einstein's equivalence principle (Einstein 1908). Thus the otolith organs can be stimulated equivalently by linear inertial acceleration (translation) or head reorientation with respect to gravity (tilt). This can be seen in Figure 2.4.

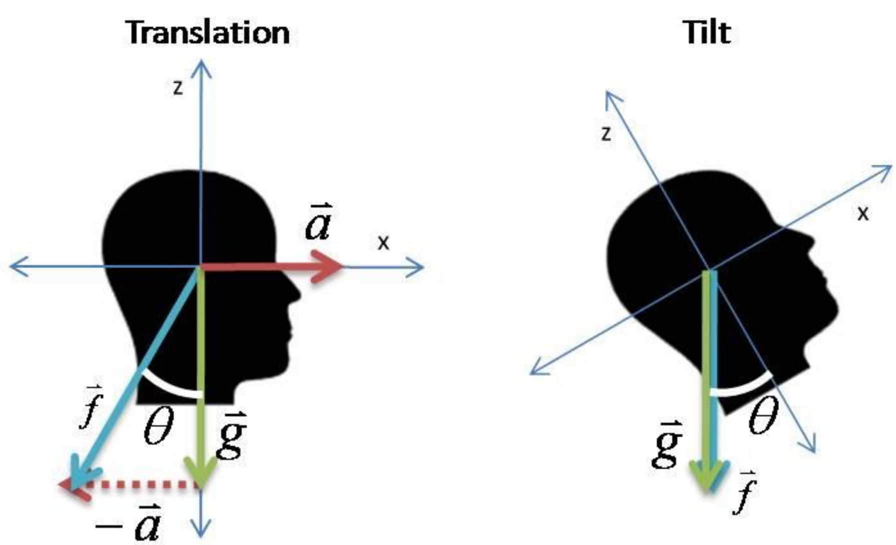

Figure 2.4: Tilt Translation Ambiguity

As seen in Figure 2.4 the same rotation in the GIF relative to the head axes can be produced by either a translation or tilt. Thus it is the CNS's responsibility for disambiguating the otolith signals. It is understood that the CNS uses cues from other sensory sources to help disambiguate the otolith cues into gravity and acceleration. In particular, angular velocity information from the SCCs and visual information play a role. In the absence of visual information, when the system must rely upon SCC information to combine with otolith signals to perceived gravity, the frequency of the signals becomes critical in the disambiguation. At medium to high frequencies experienced in everyday life, the SCCs provide accurate angular velocity information. This can be integrated and combined with otolith cues to help disambiguate the GIF into the perceptions of gravity and accelerations. However at low frequencies, the mechanics of the SCCs fail to accurately signal angular velocities and the CNS attributes the perception of gravity to be in line with the GIF direction. In normal everyday life, this function is appropriate since generally long duration (low frequency) changes in the GIF direction are due to head tilt (ie. lying down in bed), since long duration accelerations are not seen in regular motion. However, low frequency or constant accelerations are routinely experienced in aircraft or spacecraft motion. This leads to an illusion where sustained acceleration is misperceived as head or body tilt, known as the somatogravic illusion.

2.5 The Observer Model

A variety of mathematical models have been proposed for how the CNS combines and processes orientation information from various sensory signals to yield perceptions of orientation. For a more complete review see (Newman 2009). A family of these models is known as “observer” models (Oman 1982)(Oman 1991)(Merfeld, Young, et al. 1993)(Merfled and Zupan 2002)(Haslwanter, et al. 2000)(Vingerhoets, Medendorp and Van Ginsbergen 2006)(Newman 2009). These models assume that the CNS employs internal models for sensory organ dynamics and body dynamics to estimate “down”, head angular velocity and linear acceleration. The outputs from the internal models are “expected” sensory afferents which are then compared to the actual sensory afferents results in a “sensory conflict”. These sensory conflicts are used to drive the models. Thus the CNS function is similar to a state observer in engineering systems (Luenburger 1971). Within these models a relatively small number of free parameters are used to capture the primary features of experimental data for a very wide variety of different stimuli motions. Furthermore, these models are nonlinear and through the use of quaternions can be applied to complex motions in three dimensional space.

This study uses a version of the “observer” model family seen Figure 2.5 to study the vestibular only (SCCs and otolith organs) case.

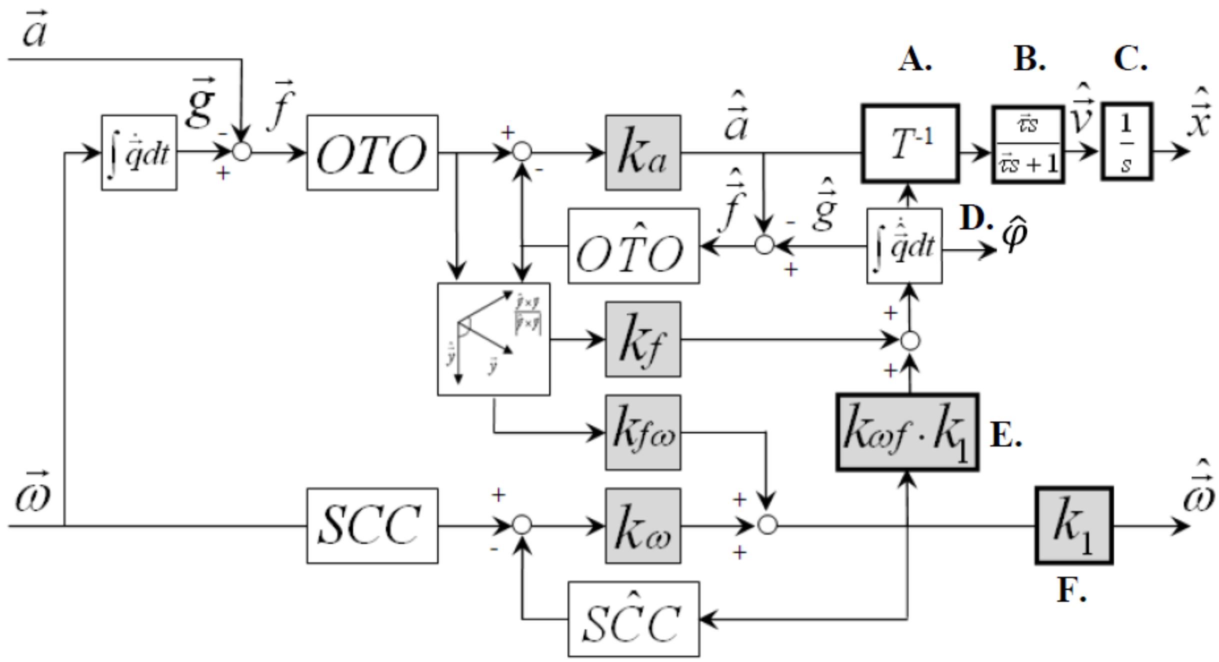

Figure 2.5: Vestibular-only version of the Observer Model (Newman 2009)

The model seen in Figure 2.5 is from (Newman 2009), however was originally developed in (Merfeld, Young, et al. 1993) and refined in (Merfled and Zupan 2002). The implementation used for this study is courtesy of (Newman 2009). The model essentially consists of two inputs: linear acceleration which combined with gravity is the input to the otolith organs (OTO), and angular velocity which is the input to the semicircular canals (SCC). Internal processing yields predicted perceptions of gravity, head angular velocity, linear acceleration, velocity, and position. For a more detailed explanation of model techniques and dynamics see Merfeld (1993). In addition to the vestibular-only version of the model seen in Figure 2.5 a version that includes vision was also used (Newman 2009).

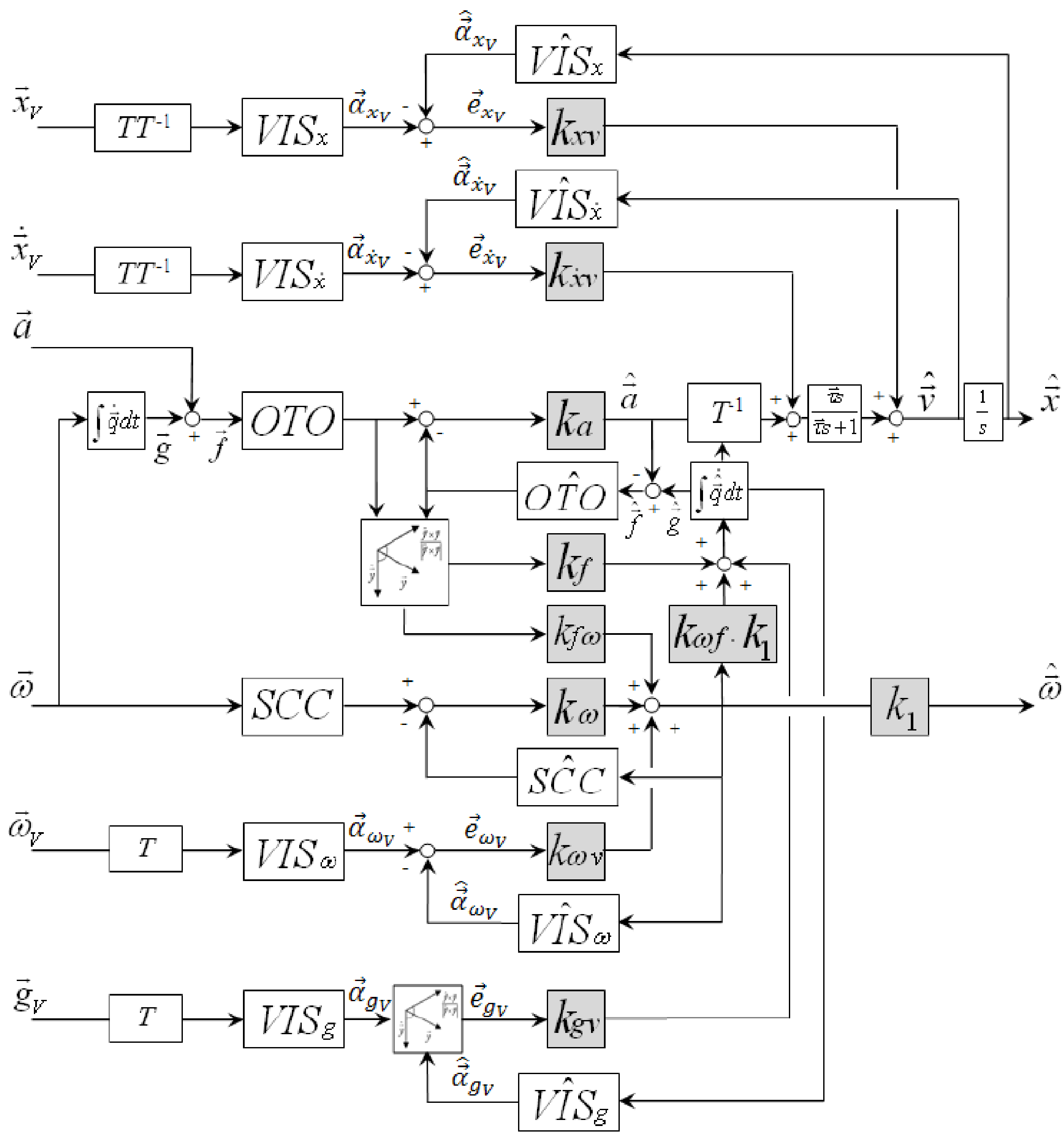

Figure 2.6: Visual Version of the Observer Model (Newman 2009)

In the version of the model that includes vision shown in Figure 2.6, pathways for visual position, visual velocity, visual angular velocity, and visual direction of down have been added to the vestibular core of the model (Newman 2009). This visual version of the model as well as the vestibular-only version will collectively be referred to as the Observer model. It should be noted that in all cases, the simulations run are done using the complete visual model, however in the case which vestibular-only stimulation is desired, the gated visual pathways are left deactivated. In order to use the model, a series of free parameters must be specified. These were set in accordance with (Newman 2009) and are given Table

2.1. The vestibular parameters were set in accordance with (Vingerhoets, Van Ginsbergen and Medendorp 2007), while the visual parameters were set to match a previous model's simulations (Borah, Young and Curry 1978).

Table 2.1: Residual Weighting Parameters of Observer Model

	Vestibular Parameters					Visual Parameters				Leaky Time Constants		
Parameter	K_a	K_f	$K_{f\omega}$	K_ω	$K_{\omega f}$	K_{x_v}	$K_{\dot{x}_v}$	K_{g_v}	K_{ω_v}	τ_x	τ_y	τ_z
Value	-4	4	8	8	1	0.1	0.75	10	10	16.67	16.67	1

The inputs of the model include the time series of the following parameters: visual linear position and velocity, visual angular velocity, visual direction of down, vestibular linear acceleration and angular velocity. More details on the model's inputs can be found in Section 3.1.2.

A few minor changes were made to the model to allow for its application to lunar landing trajectories. In particular, the magnitude of gravity was transformed from a constant to a time varying value since during a lunar landing the magnitude of gravity varies by approximately 2.5% from PDI to touchdown. More details of this variation and implementation can be found in Section 3.1.2. Additionally, the original model allows for the initial orientation of the simulated subject to be input through specifying the direction of the gravitational vector in head fixed coordinates (see Section 2.6). This is limited in that it does not allow for the specification of initial azimuth angle. To allow for this, the model was modified such that the initial quaternion could be directly specified. This can be useful for motions where the subject starts facing backwards and rotates about but ends facing forwards, and the final orientation is of interest. The specification of the quaternion is done in the MATLAB m file, while the initial direction of gravity is done on the GUI. For more details on the initial orientation inputs see Section 3.1.2.

2.6 Coordinate Frame

There are two coordinate frames used in this analysis. The first is the world coordinate frame, which is right-handed and has +x in the downrange direction, +y in the cross-range direction (to the left), and +z in the "up" direction away from the lunar surface. This coordinate frame is inertial and does not rotate with the vehicle or with the vehicle's direction of travel. Thus if the vehicle begins to travel in a cross-range direction, the x and y directions of the world coordinate system remain fixed in inertial space. The second coordinate frame is termed the head fixed coordinate frame and is seen in Figure 2.7.

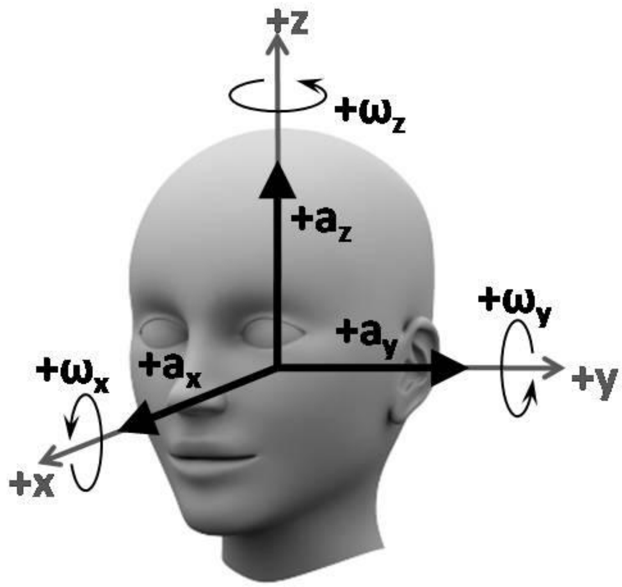

Figure 2.7: Head Fixed Coordinate Frame Definition

The frame is right-handed and is fixed to the center of the astronaut's head. The respective components of linear acceleration and angular velocity are also shown. It should be noted that this study assumes the astronaut's head to be fixed within the vehicle, such that as the vehicle rotates the astronaut's head rotates with the vehicle. While the astronauts presumably could be make head movements within the vehicle, this was not studied for two reasons. First, what head movements the astronauts might make is highly variable and impossible to predict. Second, by studying the SD that might occur simply from vehicle motions, it can be identified what causes of SD cannot be avoided simply by the astronauts being instructed not to make head movements. Finally, it is not expected that the astronauts will make large head movements since most of the display instrumentation and window views are likely to be within or near their peripheral vision. Thus, for this analysis the head fixed coordinate frame is equivalent to the vehicle fixed coordinate frame except for the potential offset in the origins if the astronaut's head is not located the vehicle CoM.

2.7 Head Location Background

With the assumption that the astronauts are not making large head movements within the vehicle, the motions experienced by the astronaut will be identical to the vehicle motion, unless the astronaut's head is not located at the vehicle CoM. In this case, there are additional centripetal and tangential accelerations experienced at the astronaut's head location due to vehicle rotations. Most vehicle designs, the Apollo LM and the Constellation program's Altair vehicle, have the astronauts' positions above and in front of the vehicle CoM as seen in Figure 2.8.

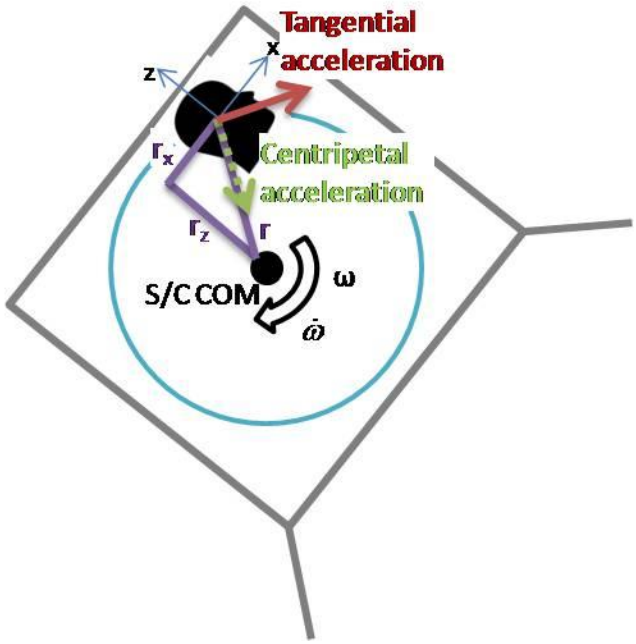

Figure 2.8: Head Location Offset from Vehicle Center of Mass

Figure 2.8 shows the simplified two dimensional case where the y component of the head fixed coordinate frame is ignored and the angular motion is purely about an axis that is perpendicular with the plane of the paper. The astronaut's head location is above and in front of the spacecraft (S/C) CoM by distances of r_z and r_x, respectively, resulting in an offset distance, r. Vehicle rotations produce angular velocities, ω, and angular accelerations, $\dot{\omega}$ about the S/C CoM. The result is the tangential and centripetal accelerations as defined in Equations 2 and 3.

$$\vec{a}_{tan} = \dot{\vec{\omega}} \times \vec{r} \tag{2}$$

$$\vec{a}_{cent} = \vec{\omega}^T \vec{\omega} \vec{r} \tag{3}$$

These accelerations will be present at the head location in addition to the vehicle accelerations. Due to the somatogravic illusion discussed in Section 2.4, head accelerations can be misinterpreted as tilt motions, so the offset between the vehicle CoM and the head location can be responsible for misperceptions of orientation. The head locations studied are listed in Section 3.1.3.

3 METHODS

The potential effect of different stimuli on spatial orientation perceptions was analyzed in two different ways. First, a numerical model and simulation were used to predict astronauts' perceptions of vehicle motion and orientation and to compare those to the simulated vehicle motions. Secondly, an experiment was performed in a moving base simulator where human subjects reported their perceptions of vehicle motions and orientation and those were compared to the actual simulator motions. When possible the predictions and results from these two methodologies were used in comparison with each other to confirm the result. Certain aspects were different between the model and simulation versus the experiment and this allowed for additional findings to be made using the two methodologies.

3.1 Numerical Observer Model and Simulation

One of the two methodologies used to study astronauts' spatial orientation perceptions during lunar landing is the simulation of a numerical orientation perception model, known as Observer (Newman 2009), using landing trajectories. This methodology has two parts. First, trajectory information, particularly angular velocities and linear accelerations of the vehicle are obtained from lunar landing guidance simulations. These trajectory parameters are then used as inputs in the Observer model. The model takes actual vehicle motions and provides predictions of what the astronaut's perceptions of those motions would be. This allows for the comparison between perceived motions and actual vehicle motions and the identification of orientation misperceptions and SD. The mechanisms and structure of the Observer model are described in Section 2.5.

3.1.1 Lunar Landing Trajectories

The first step of the Observer model and simulation methodology is the lunar landing trajectories. Guidance, navigation, and control (GNC) equations have been developed for precision lunar landing (Epp, Robertson and Brady 2008)(Sostaric and Paschall 2007). Using the GNC combined with the assumed vehicle dynamics from the Constellation Program Altair LDAC-2 design, trajectory parameters can be found over the time course of the descent and landing. Studies have been conducted analyzing the trade space of potential lunar landing trajectories (Epp and Smith 2007)(Paschall and Brady 2008). Of particular importance in the trajectory trade space is the magnitude of the deceleration during the braking phase, the trajectory angle, and the slant range. Slant range and trajectory angle are defined in Figure 2.2 at the particular point in time after the pitch-over maneuver occurs. Each trajectory within the trade space consists of a time history of important vehicle parameters such as linear acceleration, angular velocity, and orientation relative to the lunar surface. The trade space is shown below in Figure 3.1 along with the numbers of particular trajectories of interest in their respective blocks.

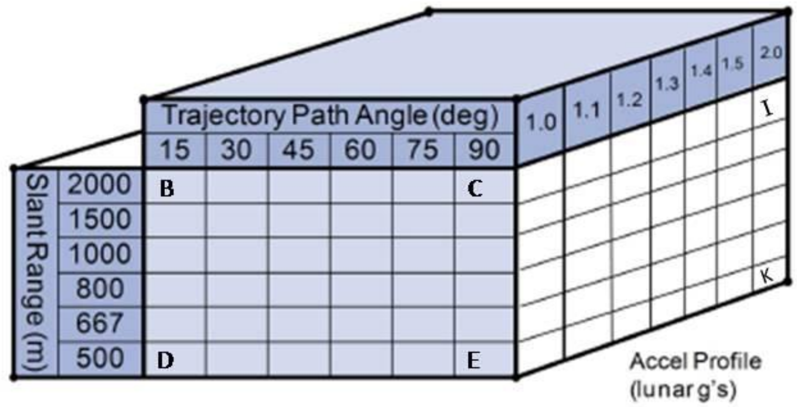

Figure 3.1: Lunar Landing Trajectory Trade Space (Paschall and Brady 2008)

Within the lunar landing trajectory trade space depicted in Figure 3.1, various different trajectories of interest were analyzed. In particular, trajectories near the corners of the trade space were analyzed to put some bounds on how different parameters resulted in trajectories that affected the predictions of orientation perceptions. In addition, trajectory A is analyzed extensively because it is considered the baseline trajectory. It is also important to note that some of the trajectories within the trade space resemble those used during the Apollo era. In particular, trajectories F and G closely resemble Apollo trajectories in the trade space parameters of slant range, trajectory angle, and acceleration profile. These are shown in Table 3.1 along with the parameters of the baseline trajectory A. There a total of 252 trajectories within the trade space.

Table 3.1: Lunar Landing Trade Space Trajectories of Interest

Letter	Significance	Braking Profile	Slant Range	Trajectory Angle
A	Baseline	1.1 lunar G's	1000 m	30°
F	Apollo-like #1	1.1 lunar G's	2000 m	15°
G	Apollo-like #2	1.05 lunar G's	2000 m	30°

3.1.2 Model Inputs

The model inputs include the motion of the vehicle and the astronauts in time series of linear accelerations and angular velocities, the magnitude of the gravitational field in time series, and the initial orientation and initial perceived orientation of the simulated subject. If visual components of the model are activated then additional inputs are required such as time series linear positions and linear velocities as well as time series of when these sensory cues are on or off. It should be noted that the linear accelerations for the vestibular system can be determined from linear positions by numerically taking two derivatives. Also the vestibular and visual inputs that are redundant, such as angular velocities, can be uniquely specified in each case. This allows for the simulation of scenarios where the visual inputs are different from the vestibular inputs, such as vection illusions. A list of Observer model inputs as well as the correct units and coordinate frame for each is given in Table 3.2.

Table 3.2: Observer Model Input Parameters

Visual/Vestib	Input	Units	Coord Frame	Time Series/Initial
	Time	seconds	N/A	Time Series
	Initial Orientation wrt Gravity	Unit vector	Head fixed	Initial
	Magnitude of Gravity	Earth G's	N/A	Time Series
Vestibular	Linear Accelerations	Earth G's	Head fixed	Time Series
	Angular Velocities	degrees/sec	Head fixed	Time Series
Visual	Linear Positions	meters	World	Time Series
	Linear Velocities	meters/sec	World	Time Series
	Angular Velocities	meters/sec^2	Head fixed	Time Series
	Direction of Down	Unit vector	Head fixed	Time Series
	Visual Position ON/OFF	Binary	N/A	Time Series
	Visual Velocity ON/OFF	Binary	N/A	Time Series
	Visual Angular Velocity ON/OFF	Binary	N/A	Time Series
	Visual Gravity ON/OFF	Binary	N/A	Time Series

For each simulation, the model requires the magnitude of the gravitational field in which the simulation occurs, in fractions of an Earth G. If the simulation occurred on the Earth's surface this value would be 1 G. If the simulation occurs on the lunar surface this value would be approximately 0.1654 G (1.623m/s^2). In the case of lunar landing, the magnitude of the gravitational field varies by approximately 2.5% from PDI to touchdown. Since the guidance equation accelerations account for this small variation, it was included in the simulation. Thus instead of the magnitude of gravity being specified by a single number throughout the trajectory, it is defined by a time series of values. These values as a function of time can be seen below in Figure 3.2.

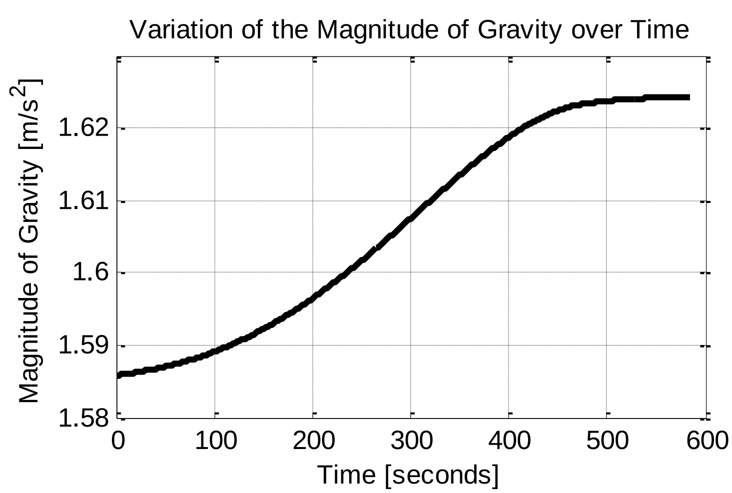

Figure 3.2: Variation of the Magnitude of Gravity over Time During Descent

This variation was included as a column input alongside the velocities and accelerations in the Excel input file for Observer. It should be noted that not including the small 2.5% change in the gravitational field experienced by the vehicle during the descent does not have a qualitative effect on the prediction of orientation perceptions. However, as this capability had been added to Observer, it was included in the following simulations. In other scenarios, for example landing on an asteroid, the magnitude of gravity would vary by nearly 100% during a short period having this capability would be important. It should be noted that there is limited understanding of how the human sensory channel would perceive and adapt to small, steady changes in gravitational force. It is assumed that the human understands the gravitational field in which he/she is placed, though we have not specified the mechanism by which this occurs.

Another input that must be specified is the initial orientation of the simulated subject. As described in Section 2.5, this can be done either by specifying the initial direction of gravity (ex. upright would be X:0, Y:0, Z:-1) or the subject's initial quaternion (ex. upright would be q = [1;0;0;0];). Generally in this analysis, specifying the direction of gravity was sufficient. The initial orientation of the simulated subject tilted pitch back at -88 degrees corresponded to the initial direction of gravity given in

Table 3.3.

Table 3.3: Initial Direction of Gravity Input for Tilt Pitch Back of -88 Degrees

Component	X	Y	Z
Initial Direction of Gravity	-0.9994	0.0	-0.0349

For the simulations completed, it was assumed that the simulated subject correctly perceived this initial orientation, then once the simulation began perceived orientation was based upon sensory cues. This was done just for simplicity, and this assumption did not play a significant role beyond the first 20 seconds of the simulation. After this, the orientation perception is dependent nearly entirely on sensory inputs. Thus the simulated subject could be assumed to have an initial perception of upright, or of any other orientation, and it would not have impacted perceptions beyond the first several seconds.

A lunar landing trajectory includes a time course during the landing descent and touchdown of important parameters, such as linear acceleration, angular velocities, and Euler orientation angles. The baseline automated trajectory, Trajectory A, is used here as an example trajectory. The 3-2-1 roll-pitch-yaw Euler angles are shown for the vehicle during the time course of the descent and landing for Trajectory A in Figure 3.3.

Vehicle Orientation Euler Angles for Automated Trajectory A

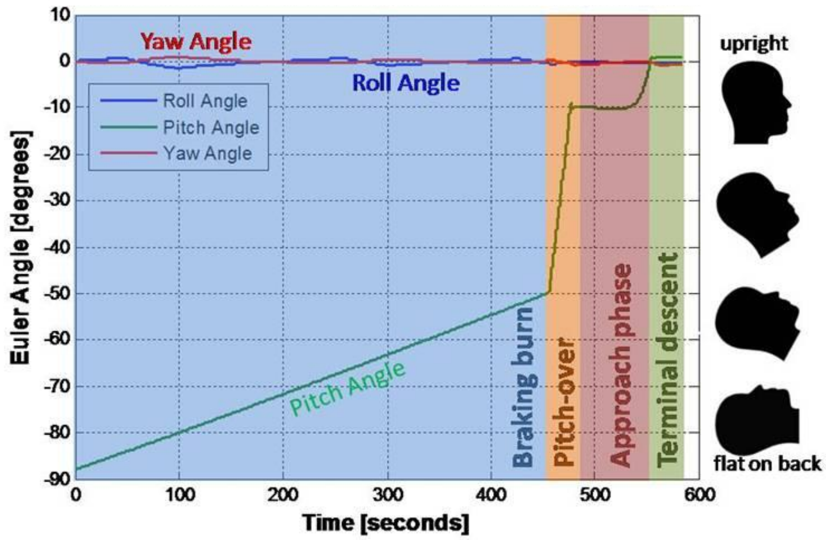

Figure 3.3: Vehicle Orientation Euler Angles for Automated Trajectory A

The vehicle motion is primarily a pitch maneuver, and therefore the yaw and roll angles are very small throughout the trajectory. The pitch angle, however, starts tilted significantly back at PDI. At PDI, the astronauts and the vehicle are tilted back slightly past -90 degrees. However, to avoid the singularity that occurs in the pitch Euler angle of -90 degrees, approximately the first 100 seconds of the trajectory following PDI has been truncated, such that each trajectory starts at a pitch angle of -88 degrees. From here, the vehicle slowly pitches upright over the lengthy braking burn. Following the braking burn, the vehicle quickly uprights itself during the pitch-over maneuver. The approach angle maintains a small pitched back orientation of approximately -10 degrees, and then the vehicle comes completely upright during terminal descent. This can be seen with the head figurines on the right portion of Figure 3.3 which represent the orientation of the astronaut's head at the different pitch angles. The Euler angles are not direct inputs into the Observer model, however are useful to see, because this is the actual vehicle orientation which is compared to the perceived orientation. The actual inputs, at least to the vestibular portion of the model, are vehicle angular velocities and linear accelerations. The guidance equations and simulation provide the vehicle angular velocities seen in Figure 3.4 and linear accelerations seen in Figure 3.5 in the coordinate frame described in Figure 2.7.

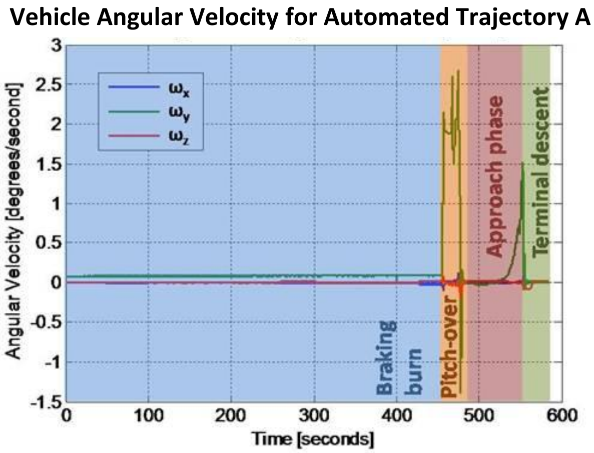

Figure 3.4: Vehicle Angular Velocity for Automated Trajectory A

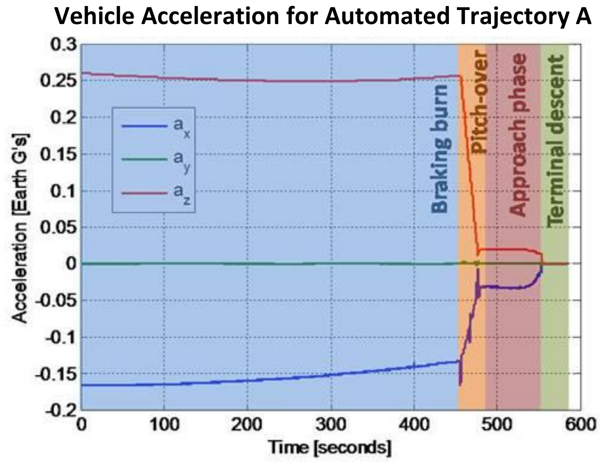

Figure 3.5: Vehicle Linear Acceleration for Automated Trajectory A

The angular velocity is primarily about the head fixed y-axis coordinate, which corresponds with the primarily pitching maneuver. There is a small and steady angular velocity causing the vehicle to pitch upright during the braking burn of approximately 0.1 degrees/second. The angular velocity is much larger during the pitch-over maneuver reaching values of approximately 2.5 degrees/second. Notice that at the end of the pitch-over maneuver, there is actually a brief negative rotation caused by the gimbal motion of the descent engine (Duda, Johnson and Fill 2009). Finally there is a smaller, but still sizable, angular velocity spike at the end of the approach phase as the vehicle comes completely upright. As mentioned previously these angular velocities will serve as the primary inputs into the vestibular system's semicircular canals. The linear accelerations are seen in Figure 3.5. At the beginning of the trajectory, the astronauts are on their backs, so the +x coordinate is pointing up away from the lunar surface. The negative x acceleration is due to the vehicle slowing and falling out of orbit toward the moon, and is nearly equal to the acceleration due to gravity on the moon. The positive z acceleration is due to the acceleration from the descent engine thrusting and slowing the vehicle. During the course of the braking burn the vehicle slowly pitches over, causing a larger portion of the acceleration due to gravity to shift from the x direction to the z direction. During pitch-over the vehicle changes orientation quickly. As the thruster becomes pointed nearly opposite the direction of gravity, the forces partially cancel, and the accelerations become smaller. Also, note that during pitch-over there are some acceleration spikes due to the rapid change of vehicle orientation and the gimbal motion of the decent engine. As discussed previously, these accelerations along with the gravity vector combine to create the gravio-inertial vector which is the stimulus for the vestibular system's otolith organs. The angular velocities seen in Figure 3.4 and linear accelerations seen in Figure 3.5 serve as the primary inputs into the model. The time series of these two parameters, in head fixed coordinates, serve as the two vector quantities which Observer uses as inputs to the vestibular system.

If any part of the visual portion of Observer is activated, additional input parameters are necessary. The inputs to the visual system are linear position, linear velocity, angular velocity, and direction of down. The direction of down is not explicitly specified as an input as the model obtains this from integrating angular velocity. Along with each of the visual sensory cue inputs, there is a time series column that specifies when each of these cues is active. The visual inputs of linear position and velocity, in world coordinates, are described in Section 2.6. These can be seen in Appendix A for the trajectories studied.

Each of the model inputs have been shown here for the example trajectory, automated Trajectory A. Other trajectories were analyzed as well. These include various trajectories within the automated trajectory trade space as well as some LP redesignation and direct manual control trajectories. Model inputs and Euler angles for alternate automated trajectories can be found in Appendix A, and are qualitatively very similar to Trajectory A previously shown. Euler angles of example trajectories for LP redesignation and manual control maneuvers are included here for demonstration. The complete model input plots can be found in Appendix A. The Euler angle plots for LP redesignation and manual control trajectories have been truncated such that the initial portion of the braking burn is removed. This portion of the trajectory does not include any additional maneuvers and is very similar to the braking burn seen in Figure 3.3 for Trajectory A. The unique maneuvers primarily take place during the approach phase and are explicitly identified in the figures. Two LP redesignation trajectories are included. One includes a redesignation to the cross range to the left which results primarily in roll maneuvers. The second redesignation trajectory is a redesignation down range or forward of the vehicle, which results primarily pitch maneuvers. Similarly, two manual control trajectories were simulated. The first is primarily a roll maneuver while the second is primarily a pitch maneuver.

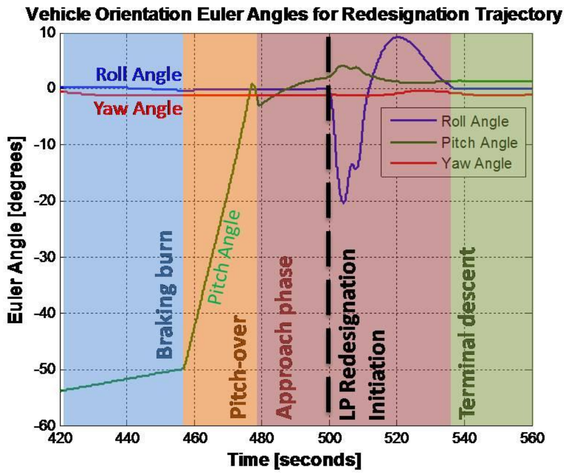

Figure 3.6: Vehicle Orientation Euler Angles for Cross Range Redesignation Trajectory

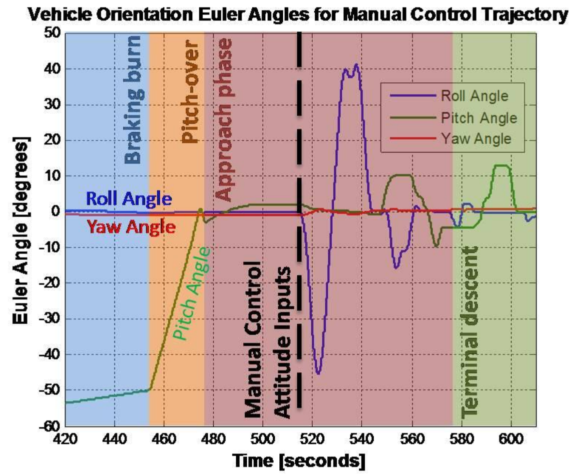

Figure 3.7: Vehicle Orientation Euler Angles for Cross Range Manual Control Trajectory

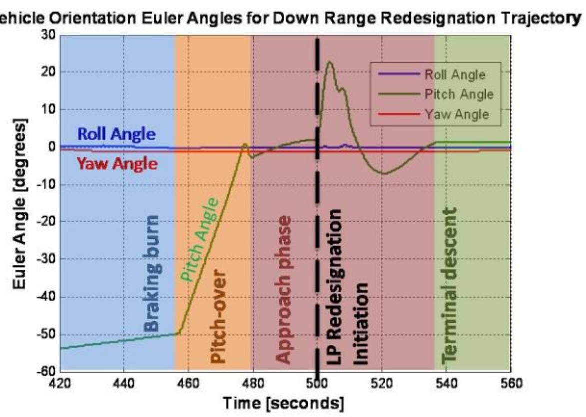

Figure 3.8: Vehicle Orientation Euler Angles for Down Range Redesignation Trajectory

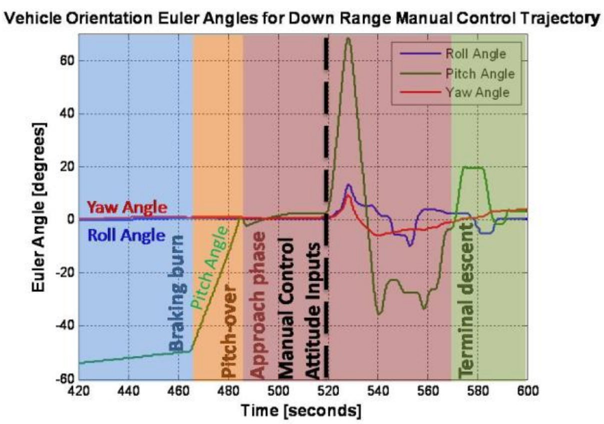

Figure 3.9: Vehicle Orientation Euler Angles for Down Range Manual Control Trajectory

The cross range LP redesignation trajectory seen in Figure 3.6 was the result of the vehicle following the traditional lunar landing automated maneuvers up until an altitude of 460 meters. At this point the vehicle is in a steady hover, but then a simulated astronaut LP redesignation is made. This relocates the LP from nearly directly beneath the vehicle to approximately 85 meters away in a direction nearly directly left of the vehicle or in the +y direction. The result is the simulated vehicle guidance first enacts a strong roll to the left to build up horizontal velocity, and then a strong roll to the right to null out this velocity, as seen in Figure 3.6. There is also a small pitch maneuver resulting from the LP redesignation. This is due to the vehicle not being in a perfect hover at the initiation of the LP redesignation as well as the redesignation being slightly offset from directly left of the vehicle. For the LP redesignation trajectory, the exact vehicle motion is determined by the guidance algorithms, while the final LP is selected by the astronaut. A similar trajectory, but with a downrange LP redesignation is seen in Figure 3.8.

The manually controlled trajectory seen in Figure 3.7 results from an actual pilot taking control of the simulation at an altitude of at approximately 460 meters. The pilot inputs an extreme roll maneuver, and then attempts to correct, null the velocity, and land the vehicle successfully. It can be seen that while the initial pilot input is primarily in the roll direction, the following corrective maneuvers are in both the roll and pitch directions. Another manual control trajectory is simulated with the corresponding maneuvers executed in the pitch direction. This can be seen in Figure 3.9.

3.1.3 Head Location Analysis

Another area of study for this analysis was the influence that the astronauts' head location within the vehicle for various designs impact orientation perceptions. For each head locations analyzed were defined by a distance that head was assumed to be forward of the vehicle CoM (r_x) and a distance that the head was assumed to be above the vehicle CoM (r_z) as defined in Figure 2.8. Different locations were approximated for the Constellation program Altair LDAC-2 design, as well as for the Apollo LM, and Lunar Landing Research Vehicle (LLRV) as given in Table 3.4.

Table 3.4: Head Location Assumptions for Vehicles

	r_x [meters]	r_y [meters]	r_z [meters]	r [meters]
Altair LDAC-2	3.2	0.0	0.9	3.3
LLRV	0.9	0.0	1.2	1.5
Apollo LM	1.8	0.0	2.4	3.0

At each head location, the angular velocities of the trajectory were used to determine the added centripetal and tangential accelerations. These were then added to the motion of the vehicle CoM to determine the accelerations experienced at the head location of the astronauts. The Observer model was then run in two different cases, one in which the head location was assumed to be located at the CoM while the other one had the specific head location of the vehicle being considered. Each run of the Observer model results in a time series of perceived orientation. To determine the effect of the astronaut's head location, the difference between the two sets of perceived orientations is taken. To reduce each trajectory to a single quantity representing the magnitude of the effect of head location, the maximum difference between the two perceptions was taken. This analysis is seen in Figure 3.10.

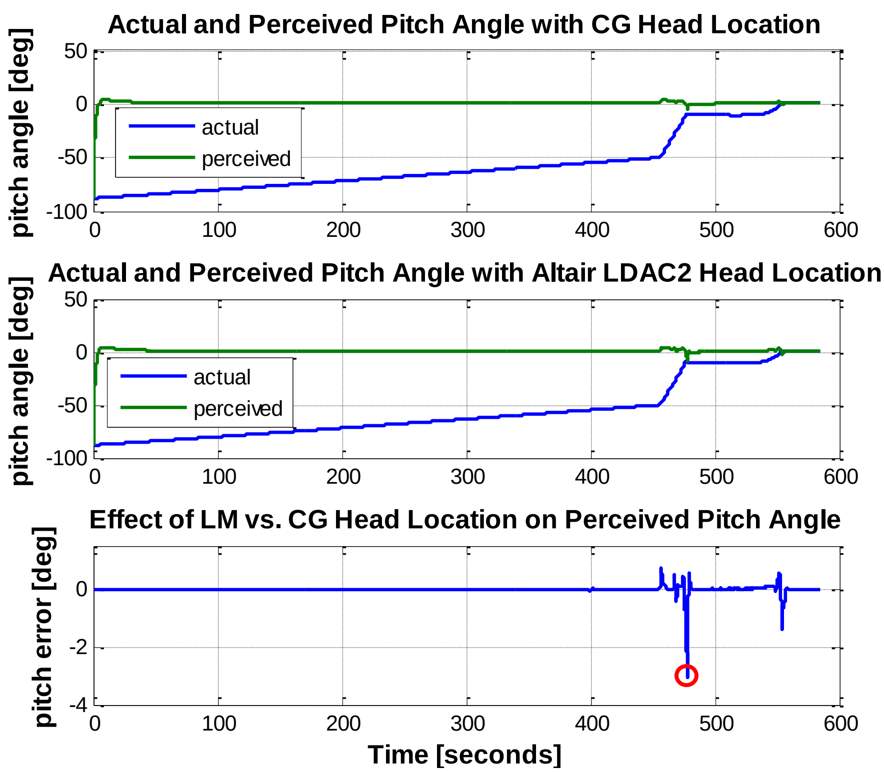

Figure 3.10: Example Head Location Analysis

The top plot depicts the actual and perceived pitch angle assuming the head is located at the vehicle CoM, the second plot depicts the actual and perceived pitch angle assuming the head is located at the Altair LDAC-2 head location defined in Table 3.4, and the bottom plot shows the difference between the two perceptions due to the head location. In this case the absolute maximum effect of the head location on perceived pitch angle was approximately 3.1 degrees. This analysis was done for a variety of head locations across different automated trajectories, LP redesignation trajectories, and manual control trajectories.

3.2 Ames Vertical Motion Simulator Experiment

3.2.1 Experiment Limitations

The NASA Ames VMS is a 6-DOF motion based simulator that has been used to study handling qualities and control mode characteristics of a lunar landing type vehicle in a realistic setting. The Constellation program Altair vehicle has design requirements to ensure Cooper-Harper rating (Cooper and Harper 1969) handling qualities of within Level 1 (Human-Rating Requirements for Space Systems 2009). This requirement sparked a series of handling qualities experiments conducted in the VMS (Bilimoria 2008). For these experiments, pilot astronauts serve as evaluation pilots operating the simulation in various different control modes. As a result, there are numerous manually controlled motion-based simulations run in the VMS flying lunar landing motion trajectories. While the pilot occupies the left seat in the VMS, the right hand seat remained unoccupied. This allowed for the opportunity to insert another subject into the right hand seat, whose only responsibility was to experience the lunar landing motions and report perceptions of that motion.

The experiment focuses on the final approach, terminal descent, and touchdown portions of the landing trajectory. Hence, none of the braking burn and pitch-over maneuver was included in the simulations, as it is unlikely that the astronauts will exercise any direct manual control during these portions of the landing. However, this is a bit of a limitation, since orientation misperceptions are likely to occur during the unique orientation and acceleration profiles experienced during the braking burn and during the quick rotation of the pitch-over maneuver. The initial orientation and state of the vehicle in the VMS experiment is given below in Table 3.5.

Table 3.5: Initial Conditions of VMS Simulation

Initial conditions	
Down range distance	1,350 feet
Cross range distance	250 feet
Down range speed	60 feet/second
Cross range speed	0 feet/second
Vertical descent speed	-16 feet/second
Pitch angle	16 degrees back
Roll angle	0 degrees

The initial conditions of the vehicle in the VMS simulation correspond to the vehicle state during the final approach, after the pitch-over maneuver has occurred. Thus there was the limitation that orientation misperceptions occurring prior to this point during the landing could not be studied in the VMS experiment. Another limitation is that while the Observer simulations could at least attempt to incorporate the influence of lunar partial gravity, the VMS experiment was conducted in Earth gravity. This potentially has two areas of concern. To more accurately model lunar missions, ideally subjects would have at least three days of adaptation to weightlessness prior to experiencing the lunar landing motions. This adaptation period might result in different interpretation of motion cues and different perceptions than are normally seen in Earth gravity. Unfortunately it is unlikely that it will be feasible to experiment on subjects that have been adapted to microgravity for at least three days. Thus this limitation must be noted and considered in the analysis, but will not be a reasonable area for improved study.

Additionally, in lunar gravity the gravio-inertial force influencing otolith cues will rotate far more than on Earth given the same horizontal acceleration as seen in Figure 3.11.

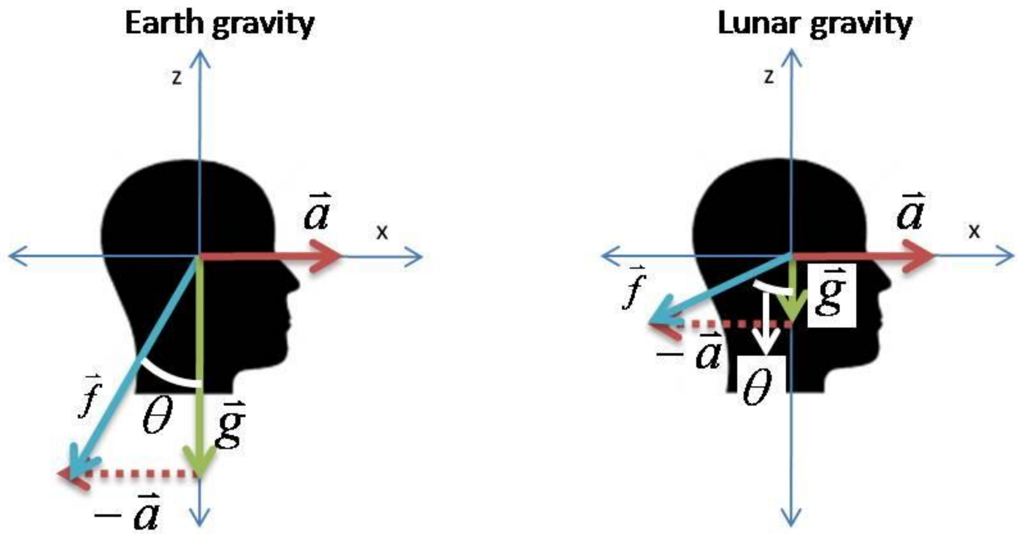

Figure 3.11: GIF Rotation due to Acceleration in Earth (left) and Lunar Gravity (right)

Figure 3.11 shows the rotation of the gravio-inertial force vector (f) by an angle θ due to an acceleration (a) in Earth gravity. In lunar gravity, if the same acceleration is experienced, the shorter gravity vector causes the gravio-inertial vector to rotate by a much larger angle. The VMS motion algorithm for this experiment was modified to create motions that caused the perception of the proper rotation in the gravio-inertial force. However, this requires rotating the cab to orientations that would not actually be experienced in a lunar gravity landing. Thus there are still issues with the VMS motion drive algorithm in the simulation of lunar gravity maneuvers. Furthermore, the motion capabilities of the VMS, while some of the best in the world, are not limitless. Certain maneuvers cannot be enacted as quickly as they actually occur, and certain orientations simply are beyond the range capabilities of the simulator. In particular, the limits of linear distance constrain the simulators ability to reenact trajectories that include thousands of feet of motion. The VMS is required to use other techniques in order to simulate sustained deceleration or high velocity maneuvers. This limitation must be considered when analyzing a subject's perception of this motion. Nonetheless, simulator motions which are very similar to the motions experienced during lunar landing provide a unique opportunity to study spatial orientation perceptions.

The design of the handling qualities study had a significant impact on the design of this orientation perception experiment. Since the handling qualities experiment was studying piloting capabilities and control modes, every run was operated by a human pilot. As a result while the trajectories are all fairly similar, the motions experienced on each trial are entirely unique. For the orientation perception subjects there was no repetition of the same run more than once. It was not possible to determine the variation in a subject's perception of a particular motion because it was only experienced one time. Ideally a small number of representative landing trajectories would be selected and a subject would experience each of these many times. Instead a large number of similar, but different, trajectories were used with each being determined by the pilot's stick inputs on that particular run and a subject could only experience each unique run once.

The pilot's inputs, and thus the motion of the vehicle, should be fairly similar when flying the VMS in a certain control mode and guidance combination along with the same initial vehicle conditions. There will indeed be some variation which will make each run unique, but approximate motion of the vehicle should be similar, especially if the pilot is provided with guidance cues. Thus, there is some opportunity for repetition within each control mode and guidance combination. Unfortunately, due to the limited amount of pilot time, the control mode experiment may only repeat each control mode and guidance combination three times. As will be discussed in the next section, the orientation perception experiment has three different treatments and two different tasks that are not done simultaneously so there are total of six different combinations that ideally need to be tested within each control mode and guidance combination. To attempt to understand some of the variation within a control mode and guidance combination, multiple trials of the six combinations would be needed. Since there are as few as three runs in which to complete these combinations, this was not possible. This will influence the experimental design as discussed in Section 3.2.2.

3.2.2 Experimental Design

The VMS orientation perception experiment aims to study the influence of different motion cues on orientation perception during simulated lunar landing motions. There are three different motion cues sources which are of interest:

1) C: The eyes Closed case, in which subjects rely only on their vestibular cues without any vision.
2) W: The eyes out the Window case, in which vision was allowed and subjects were instructed to look out a window at a simulated view of the lunar surface.
3) D: The eyes on the Displays cases, in which vision was allowed and subjects were instructed to look down at instrument displays.

Beyond the three treatments, the subjects were also asked to report two different components of orientation. There are many different parts of orientation for humans to perceive, including positions, velocities, accelerations, orientation, angular velocities, etc. For the lunar landing, it was determined that there were two components of orientation that would particularly important for the piloting task, each given below.

1) Tilt estimation (pitch and roll angles)
2) Horizontal velocity estimation (magnitude and direction)

First, it is important for the astronauts to estimate tilt angle. Due to the helicopter-like design of the lunar landing vehicle, tilt angle is essentially linearly proportional to the horizontal acceleration. For example, pitching the vehicle forward or nose down will result in a forward acceleration. This is important for safe and efficient operation of the lunar landing vehicle. Also for touchdown, the vehicle should be oriented upright to ensure a safe landing so the perception of tilt can be important here as well. During final descent and touchdown, the pilot's task is to position the vehicle approximately above the desired landing point and then to null the horizontal velocity. Landing with significant horizontal velocity will likely damage the vehicle's landing gear and may cause the vehicle to topple over. Thus it is critical, especially during terminal descent, for the astronaut to accurately perceived horizontal velocity as he/she works to null it out.

Early testing and prior experience made it clear that the tilt estimation and horizontal velocity estimation tasks could not be completed simultaneously on a single run. Assuming that the two orientation components of interest must be reported separately, in combination with the three treatments, a total of six runs would be required to test each of the treatment/component combinations. The test matrix of treatment and component combinations is given in Figure 3.12.

		Treatments		
		Eyes Closed (C)	Eyes out the Window (W)	Eyes on the Displays (D)
Orientation Component Measured	Horizontal Velocity (V)			
	Tilt (T)			

Figure 3.12: Experimental Test Matrix of Treatments and Orientation Components

Ideally each of these combinations would be repeated multiple times without changing other piloting variables such as control mode or guidance cues. As discussed below this is simply not possible to do.

The handling qualities experiment tested one pilot each day, testing a series of control modes and guidance cue combinations. For each run a certain control mode was used during the approach portion of the trajectory and then the pilot could potentially switch to a second mode for the terminal descent. The two primary approach modes were Rate Control Attitude Hold (RCAH) and Incremental Velocity (VINC). To go along with these approach modes, there were also a series of terminal descent modes. These included each of the modes used for approach as well as Translational Rate Control Position Hold (TRCPH), Incremental Position Control (IPC), or Acceleration mode (ACCEL). It should be noted that the Ames experimenters settled into this test matrix after a few days of testing. During this initial testing other control modes were used. These included using the Acceleration mode (ACCEL) during the approach phase as well as using other modes such as Flight Path Approach (FPA) and Unified Flight Path Approach (UFPA). Complete test matrix information for each subject can be found in Appendix B. For each control mode, the pilot was either provided with guidance cues on the display which he could follow or not provided with these cues. There were two different types of guidance as well, matching with the respective approach mode, either Acceleration guidance or Velocity guidance. The final test matrix for this experiment is given Figure 3.13.

Display Guidance Type	Control Modes						
	RCAH	RCAH/ TRCPH	RCAH/ IPC	RCAH/ ACCEL	VINC	VINC/ TRCPH	VINC/ IPC
No Guid	$W_tC_vD_t$ $[W_vC_tD_v]$	$W_vC_tD_v$ $[W_tD_tC_v]$	$C_vW_vD_t$ $[C_tD_vW_t]$	$C_tD_vW_t$ $[C_vW_vD_t]$	$D_vW_tC_t$ $[W_vD_tC_v]$	$W_tD_tC_v$ $[D_vW_vC_t]$	$D_tW_vC_v$ $[W_tC_tD_v]$
Vel Guid					$C_vD_tW_v$ $[C_tW_tD_v]$	$D_vC_tW_v$ $[D_tC_vW_t]$	$C_tW_tD_v$ $[C_vD_tW_v]$
Acc Guid	$W_vD_vC_t$ $[D_tW_tC_v]$	$D_tC_vW_t$ $[C_tD_vW_v]$	$D_vC_tW_t$ $[W_vC_vD_t]$	$W_vC_vD_t$ $[D_vW_tC_t]$			

Key
W = eyes out the Window
D = eyes on the Displays
C = eyes Closed

t = estimating tilt
v = estimating velocity

No [ ] = primary trials
[ ] = backup trials

Figure 3.13: Handling Qualities Experiment Test Matrix

As seen in Figure 3.13, there were seven combinations of control modes and three different guidance types. However, only the blue boxes were actually tested, so each control mode was only done with two of the guidance types. Within each of the combinations of control modes and guidance types, there were only at least three trials run. The first was a practice run to familiarize the pilot with the mode, and then the next two were done to assess the pilot's performance on the control mode and guidance combination. In some cases, the pilot would request additional practice runs or additional assessment runs, which case more than three runs might be flown, however this was not guaranteed. The treatment and component combination tested for each of the runs is given Figure 3.13. For example the first run for control mode RCAH and no guidance type (No Guid) would be eyes out the window estimating tilt (W_t). The second would be eyes closed estimating velocity (C_v). After the three guaranteed runs, there are additional combinations given in the brackets [ ]. These refer to the combinations to be used if more than three runs are completed within a specific control mode and guidance type. If more than six runs are done, the series of combinations repeats starting with the first combination tested.

As previously mentioned, there are six combinations of treatment and component that ideally would be tested multiple times within each of the control mode and guidance type blocks. Unfortunately, this simply cannot be done given the limit of three runs per block. Thus the experiment was designed in a counterbalanced fashion, similar to the concepts of Graeco-Latin squares. There were a variety of considerations taken into account when counterbalancing. Each of the six combinations was seen at least once within a given control mode across both guidance types. Within a single guidance type, across control modes each combination was seen a nearly even amount. For example, if the acceleration guidance type across RCAH, RCAH/TRCPH, RCAH/IPC, RCAH/ACCEL there are twelve guaranteed trials. Within these twelve runs, each of the six combinations is seen exactly twice. Within the no guidance type across each of the four RCAH modes, each of the six combinations is seen exactly twice. This can be seen in Figure 3.14. Within the no guidance type for the three VINC approach modes there are only nine guarantee runs. Thus each of the six combinations is seen either once or twice. The combinations that were only seen once in the no guidance type with VINC were seen twice with the velocity guidance type with VINC as well as seen twice if more than three trials are allowed. This can be seen in Figure 3.15.

Display Guidance Type		Control Modes				
		RCAH	RCAH/ TRCPH	RCAH/ IPC	RCAH/ ACCEL	Totals
	No Guid	$W_tC_vD_t$ [$W_vC_tD_v$]	$W_vC_tD_v$ [$W_tD_tC_v$]	$C_vW_vD_t$ [$C_tD_vW_t$]	$C_tD_vW_t$ [$C_vW_vD_t$]	C_v=2 [2] C_t=2 [2] W_v=2 [2] W_T=2 [2] D_v=2 [2] D_t=2 [2]
	Acc Guid	$W_vD_vC_t$ [$D_tW_tC_v$]	$D_tC_vW_t$ [$C_tD_vW_v$]	$D_vC_tW_t$ [$W_vC_vD_t$]	$W_vC_vD_t$ [$D_vW_tC_t$]	C_v=2 [2] C_t=2 [2] W_v=2 [2] W_T=2 [2] D_v=2 [2] D_t=2 [2]
	Totals	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_T=1 [1] D_v=1 [1] D_t=1 [1]	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_T=1 [1] D_v=1 [1] D_t=1 [1]	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_T=1 [1] D_v=1 [1] D_t=1 [1]	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_T=1 [1] D_v=1 [1] D_t=1 [1]	

Figure 3.14: Treatment Counterbalance for RCAH Portion of Test Matrix

Display Guidance Type		Control Modes			
		VINC	VINC/ TRCPH	VINC/ IPC	Totals
	No Guid	$D_vW_tC_t$ [$W_vD_tC_v$]	$W_tD_tC_v$ [$D_vW_vC_t$]	$D_tW_vC_v$ [$W_tC_tD_v$]	C_v=2 [1] C_t=1 [2] W_v=1 [2] W_t=2 [1] D_v=1 [2] D_t=2 [1]
	Vel Guid	$C_vD_tW_v$ [$C_tW_tD_v$]	$D_vC_tW_v$ [$D_tC_vW_t$]	$C_tW_tD_v$ [$C_vD_tW_v$]	C_v=1 [2] C_t=2 [1] W_v=2 [1] W_t=1 [2] D_v=2 [1] D_t=1 [2]
	Totals	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_t=1 [1] D_v=1 [1] D_t=1 [1]	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_t=1 [1] D_v=1 [1] D_t=1 [1]	C_v=1 [1] C_t=1 [1] W_v=1 [1] W_t=1 [1] D_v=1 [1] D_t=1 [1]	

Figure 3.15: Treatment Counterbalance for VINC Portion of Test Matrix

Figure 3.14 and Figure 3.15 show the counterbalance of treatment and component combinations within the framework of the control mode and guidance type test matrix. The number of times a combination was seen in a given row or column was totaled at the end of that row or column. This was first done for the three guaranteed runs and then done in brackets for the three runs to be done if extra trials are performed. Each of the combinations is seen as evenly as possible across the design. Beyond having an even number of trials of each treatment combination, counterbalancing was also done on the ordering of each of the treatments. For example, the combination of eyes out the window estimating tilt (W_t) was seen a total of seven times in the first three trials per block of the experimental matrix. Of those trials it appeared first within a block twice, second within a block twice, and third three times. This was as evenly distributed as possible. This methodology was maintained for each of the different combinations when creating the test matrix. This counterbalancing methodology will allow for analysis of the six treatment combinations even though there are might be as few as three runs per block within the handling qualities test matrix.

3.2.3 Subjects

Eight subjects (6M/2F) took part in the experiment and were ages 26-32. One of the subjects has piloting experience (Subject 2). All of the subjects were NASA Ames employees recruited on a volunteer basis. The subjects reported to have adequate vision and did not wear glasses. Each of the subjects filled out a motion sickness questionnaire and reported to not be particularly susceptible to becoming motion sick. All participants gave informed consent in accordance with the MIT Committee on the Use of Humans as Experimental Subjects (COUHES) as well as the NASA Ames Research Center (ARC) Human Research Institutional Review Board (HRIRB). See Appendix B for consent forms, motion sickness questionnaires and more details on the subjects.

3.2.3.1 HRIRB and COUHES Approval

The orientation perception experiment was reviewed and received approval from the NASA ARC Human HRIRB as well as from the MIT COUHES (Appendix B). Subjects signed a consent form that was approved by the ARC HRIRB and MIT COUHES and can be found in Appendix B. Subject's identities and information have remained anonymous.

3.2.4 Equipment

3.2.4.1 Vertical Motion Simulator Motion Base

The NASA Ames Vertical Motion Simulator (VMS) is a moving based simulator used for the study of aircraft and spacecraft simulations where vehicle motion is critical to the evaluation. The simulator can be seen in Figure 3.16.

Figure 3.16: NASA Ames VMS (Aponso, Beard and Schroeder 2009)

The simulator consists of an Interchangeable Cab (ICAB) and a motion base upon which the ICAB sits. Each ICAB is constructed and modified for simulation of a particular vehicle of interest and then when prepared can be placed on the motion based for experimentation. The motion base has six degrees-of-freedom (vertical, lateral, longitudinal, pitch, roll, yaw) with the largest range of motion of any simulator in the world. The specifications are given in Table 3.6 as system limits which are the maximum obtainable capabilities of the hardware and the operational limits which represent attainable levels for normal piloted operations.

Table 3.6: VMS Motion Capabilities(Danek 1993)

Degree of Freedom	Displacement		Velocity		Accelerations	
	System Limits	Operational Limits	System Limits	Operational Limits	System Limits	Operational Limits
Longitudinal	± 4 ft	± 4 ft	± 5 ft/s	± 4 ft/s	± 16 ft/s^2	± 10 ft/s^2
Lateral	± 20 ft	± 15 ft	± 8 ft/s	± 8 ft/s	± 13 ft/s^2	± 13 ft/s^2
Vertical	± 30 ft	± 22 ft	± 16 ft/s	± 15 ft/s	± 22 ft/s^2	± 22 ft/s^2
Roll	± 17.8 deg	± 13.8 deg	± 52 ft/s	± 40 ft/s	± 230 deg/s^2	± 115 deg/s^2
Pitch	± 17.8 deg	± 13.8 deg	± 52 ft/s	± 40 ft/s	± 230 deg/s^2	± 115 deg/s^2
Yaw	± 24.1 deg	± 13.8 deg	± 52 ft/s	± 46 ft/s	± 230 deg/s^2	± 115 deg/s^2

Table 3.6 shows that while the motion capabilities of the VMS are very impressive, they still limit the simulators ability to reenact the motions experienced during a real lunar landing. For example the limited pitch angle capabilities prevent the study from considering portions of the landing trajectory prior to the pitch-over maneuver, since these vehicle attitudes are too extreme to replicate. However, the simulator is particularly capable in the vertical motion direction, which is a suitable for the landing task studied here. The critical components the of the VMS motion drive system can be seen in Figure 3.17.

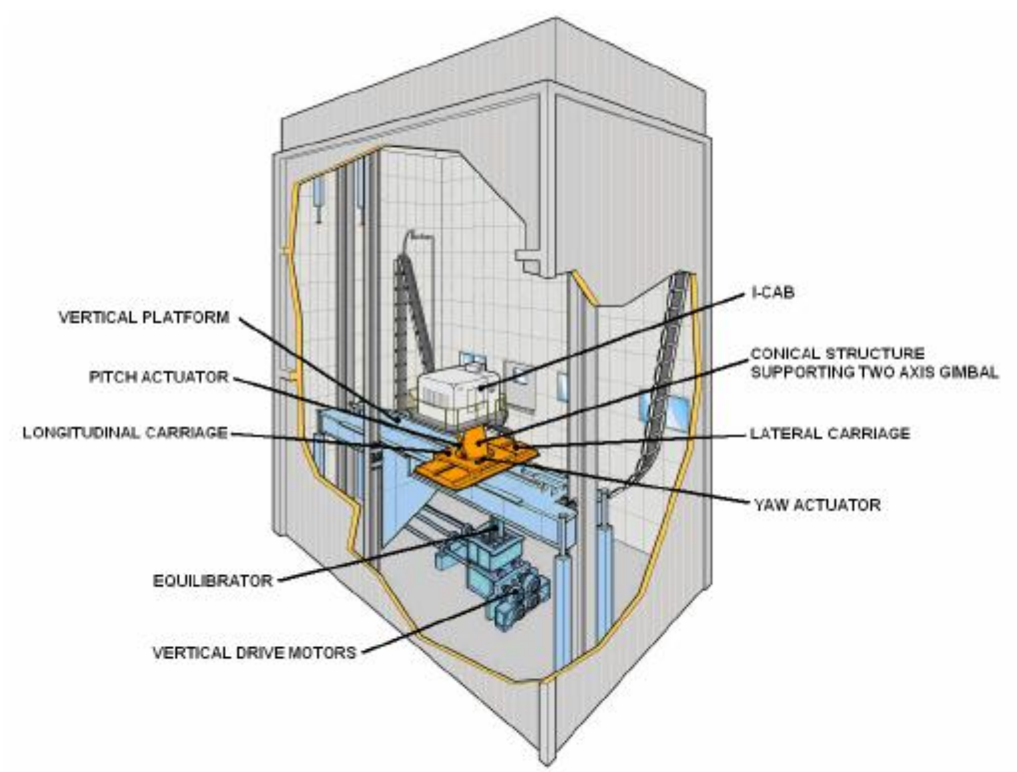

Figure 3.17: VMS Motion Drivers (Aponso, Beard and Schroeder 2009)

3.2.4.2 Vertical Motion Simulator ICAB Interior

The interior of the ICAB is modified for the lunar landing task (Bilimoria 2008). The Apollo lunar lander pilot stations had a standing configuration to reduce vehicle mass by eliminating seats, and a similar configuration was adopted here. In the Apollo LM, the left hand station was occupied by the Commander who was responsible for flying the vehicle, while the right hand station was occupied by the Lunar Module Pilot, who served as co-pilot. In the experiment within the ICAB the flying pilot occupied the left hand station, while a second subject occupied the right hand station. This second subject had no flying responsibilities, and instead was tasked with reporting their own orientation perceptions. The layout of the right hand station is shown in Figure 3.18 and Figure 3.19.

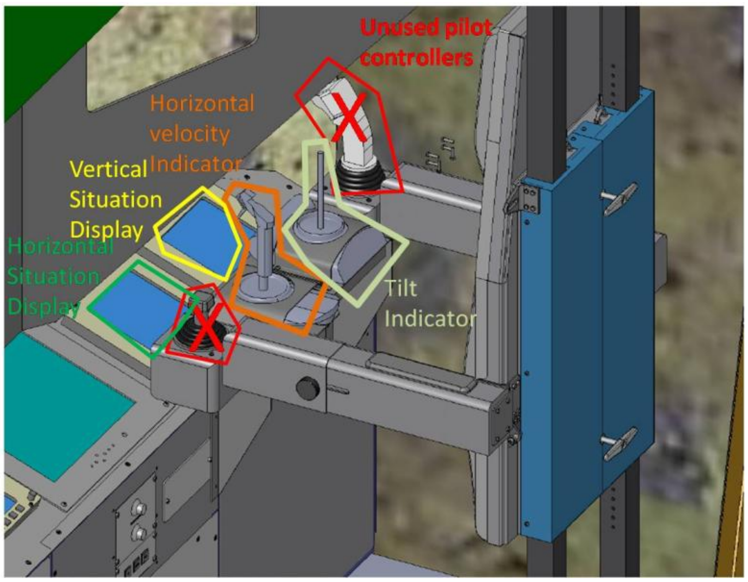

Figure 3.18: Layout Depiction of VMS Right Hand Seat


Figure 3.19: Layout Picture of VMS Right Hand Seat

The subject stood upright in the co-pilot station and was strapped to the back board following the VMS standard safety procedures. In front of the subject were a series of hand manipulators. On the armrests were the standard piloting hand controllers, identical to those used by the pilot subject in the left hand station. The right hand station subjects were instructed to not use or touch the controllers. There was some consideration to using these controllers for the subject's indication of perceived orientation as the communication channels were already set up. However, these hand controllers had different characteristics than those that were desired for the indicators used. Instead, two indicators were added to the ICAB directly in front of the subject. The left hand indicator was for horizontal velocity perceptions while the right hand indicator was for tilt perceptions. The indicators were positioned so they matched the displays being used for each perception task. For example, for tilt perceptions when using the displays the vertical situation display (VSD) was primarily used and it was on the right, thus the tilt indicator was positioned on the right. The same was done for the horizontal velocity indicator and the horizontal situation display (HSD).

3.2.4.3 Vertical Motion Simulator Displays

Along with these indicators, the subject was presented a series of displays. The right most display was VSD while the left hand display was the HSD. There was also a landing zone camera display positioned to the far left between the two subjects, however the right hand station subjects were instructed to not use this display. The VSD and HSD were identical replicas of the displays presented to the flying pilot. These displays are shown Figure 3.20 and Figure 3.21.

Figure 3.20: Horizontal Situation Display Layout

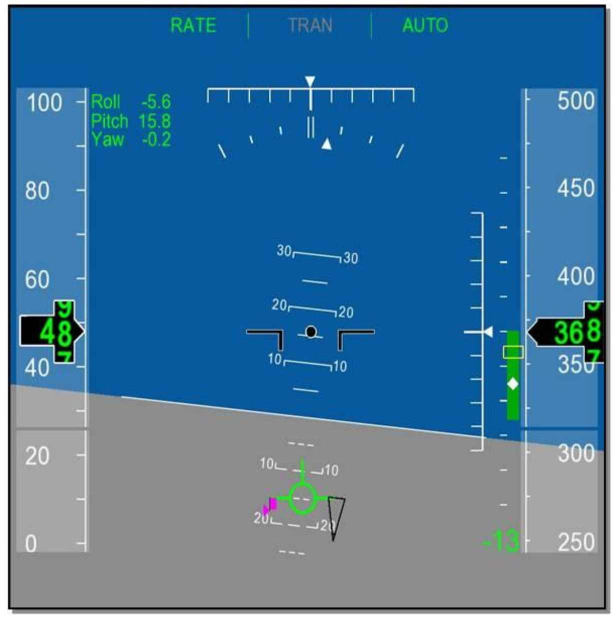

Figure 3.21: Vertical Situation Display Layout

There is an excess of information provided on these displays for the right hand station subject. For a complete explanation of these displays see (Frost, Mueller and Bilimoria 2009). The right hand subjects, when given the treatment of 'Eyes on the Displays' used a limited portion of this information. For horizontal velocity perception, the green line in the HSD is a velocity vector pointing in the direction of vehicle motion. The magnitude of the velocity could be estimated from the length of this vector; however there are two rescalings that occur during a typical trajectory, so this was not recommended. Instead subjects were instructed to obtain horizontal velocity magnitude from the tape display on the far left of the VSD. These readings are in feet per second, so no conversion is necessary. For tilt angle perception only the VSD is used. The digital read out of roll and pitch are provided in the upper left portion of the display in degrees. Also, the pitch ladder in the center of the display shows the vehicle orientation. Subjects were instructed to primarily use the pitch ladder, similar to how a pilot would obtain attitude information while in flight. The location of the orientation perception indicators did to some extent obscure the subjects' view of the VSD and HSD as can been in Figure 3.19. The subjects were capable of moving their heads and leaning forward to see the displays over the indicators and no subjects reported being unable to accurately read the displays due to the indicator location.

In addition to the instrument displays the VMS ICAB provided out-the-window (OTW) graphics of the lunar surface. These graphics were computer generated and would move in accordance with the vehicle motions. An example view is seen in Figure 3.22.

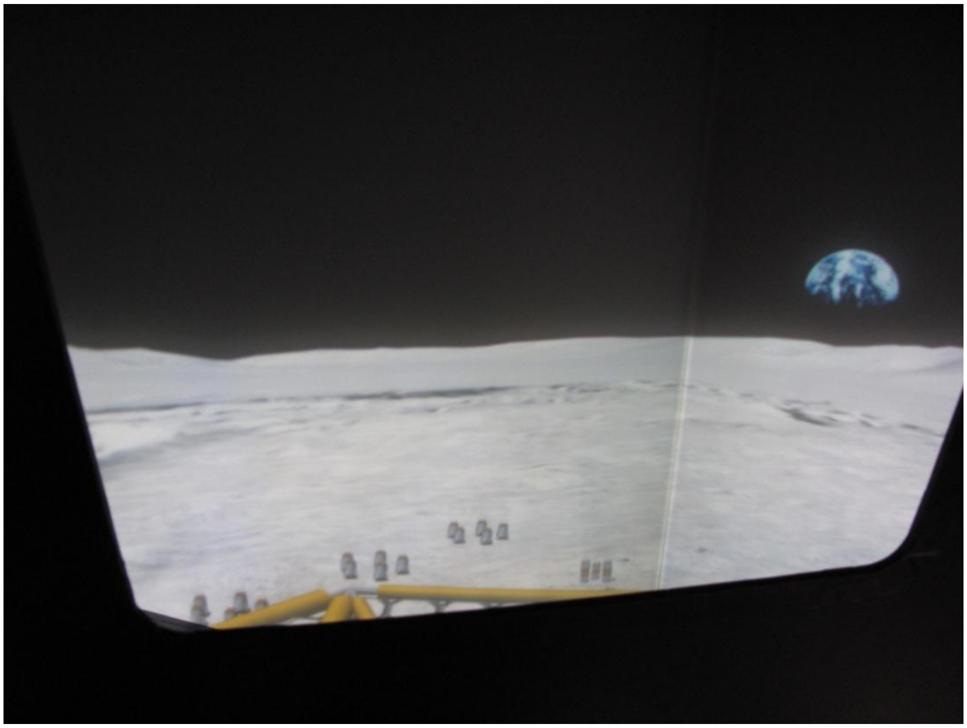

Figure 3.22: OTW view inside the ICAB

The OTW view seen in Figure 3.22 shows the lunar surface with a few objects from a lunar base for size reference as well as the lunar horizon. The yellow structure in the bottom of the screen is part of the lander. Large portions of the OTW display is obscured by an added cardboard structure that reduces the window size down to a more realistic size similar to that of the Apollo LM and Altair vehicle design. This structure just obscures of the screen behind it, so the subject can make head movements to see different parts of the OTW view, similar in function to that of a real window. It should be noted, that there was no physical window obstructing the subjects view of the OTW view. While the OTW was high detail and fairly well done, there were some limitations to be mentioned. First, the viewpoint of the display was set for the left hand station pilot position, and thus the viewpoint was likely slightly off for the right hand station subject. Secondly, there were a few important limitations of the visual field. The scene included objects from a lunar base which the subject could have used in judging relative distances. On at least initial landings, these objects would not be present and thus the astronauts will not have this added visual cue for orientation perception. Also the landing area was modeled as being essentially perfectly flat with mountains and a horizon in the far distance. This is fairly unrealistic for the planned landing zones on the lunar poles where large mountains and slope will be common that could make orientation perception more challenging. Lastly, this simulation did not have any capabilities to model any of the dust blowback expected during terminal descent in the OTW view.

3.2.4.4 Horizontal Velocity Indicator

The horizontal velocity indicator can be seen in Figure 3.23.

Figure 3.23: Horizontal Velocity Indicator

This device was an off-the-shelf wired Saitek® Cyborg Evo joystick. The joystick power and data were transmitted over a 6 foot standard USB cord. The joystick could be easily modified for left or right hand use and was converted to left hand use. The spring at the bottom will return the stick to the neutral upright position if no force is applied. When force is applied, the spring provides greater feedback the farther the stick is tilted in any direction. Subjects would point the indicator in the direction that they perceived the horizontal velocity of the vehicle to be over the time course of a landing. The amount of stick deflection was not critical, just the direction of the deflection. Subjects were encouraged to deflect the stick is significant amount, but not all the way to the limit. The subjects reported their perceptions of the magnitude of horizontal velocity using the thumb 8-way ‘point-of-view’ hat switch at the top of the stick. Vertically the thumb hat switch had three positions: up, neutral, and down. The subject’s discrete perception of horizontal speed was indicated using this switch, as seen in Table 3.7.

Table 3.7: Thumb Hat Position on Horizontal Velocity Indicator for Speed Ranges

Thumb hat position	Horizontal speed perception
Up	speed > 25 ft/s
Neutral	25 ft/s > speed > 5 ft/s
Down	5 ft/s > speed

It is possible to deflect the thumb hat position up and to the left or right instead of straight up. These inputs were interpreted as perception in the thumb hat position up range. Similar assumptions were made for the neutral and down positions. A custom support mount was constructed to hold the horizontal velocity indicator stationary and can be seen in Figure 3.19. The raw outputs from the Saitek® Cyborg Evo joystick were pitch and roll angle measures as well as button positions.

3.2.4.5 Tilt Angle Indicator

The final tilt angle indicator used can be seen in Figure 3.24.

Figure 3.24: Tilt Angle Indicator

The tilt angle indicator is a modified Saitek® Aviator joystick. The purpose of this indicator is to allow subject to report their perceived tilt angle. Thus the indicator provides the user with a distinct axis going through the base portion which can be aligned with the subject's perceived direction of down. Additionally, the indicator must allow for the subject to report a large range of tilt angles. To accomplish this, the Saitek® Aviator joystick was modified because it provided convenient USB interface with a 6 foot cord and a sturdy gimbal mechanism. The hand grip, top buttons, and spring were removed from and replaced with a long wooden dowel to create the straight axis. To keep the axis continuously through the base, a 2.5 inch hole was drilled in the bottom plastic casing and another shorter wooden dowel was attached to the gimbal mechanism. The Saitek Aviator joystick only had a range of motion of ± 15 degrees, so additional modifications were necessary. Both the outer casing and the inner gimbal mechanism were hollowed out to increase the range of motion of the stick. This was done until the range of motion was maximized without the gimbal becoming less sturdy. The final range of motion was approximately ± 25 degrees. This was not seen to interfere with the subjects' ability to report perceptions. The standard Saitek® Aviator joystick functions using two interlocking gimbal mechanisms, one for pitch and one for roll, each connected to a fixed rotational potentiometer. The potentiometers would vary their resistance between near 0 Ohms and 50 KOhms linearly proportional to the tilt of the stick. The stock potentiometers varied their entire resistance range over the original ± 15 degrees. While the potentiometers could physically rotate beyond this range, they were unable to measure rotations past these limits. The stock potentiometers were replaced by Panasonic ECG – EVJ-C51F02B54 potentiometers. The new potentiometers had very similar mechanical characteristics and were also 50 KOhm resistors, but had a measurement range of 270 degrees. These potentiometers were soldered to the connectors previously used and placed in the structure in place of the stock potentiometers. The data output from the stick was calibrated using the data acquisition software since the potentiometers were not aligned perfectly. The red knob on the stick was used by the subjects to indicate in the recorded data which treatment they were receiving. A label was put above the knob and prior to each run the subject was tasked with putting the knob in the correct position for the treatment they were about to attempt. This allowed for the treatment to be coded into the data as a backup. A custom support mount was constructed to hold the tilt angle indicator stationary and can be seen in Figure 3.19. While subjects were permitted to move the stick in whichever way they felt most comfortable, they were recommended to hold it near the base where the wooden dowel meets the plastic holder.

3.2.5 Data Acquisition Software

The NASA Ames VMS has a highly developed data acquisition and recording system in place, so the orientation perception data acquisition was modified to fit within its frame work. The VMS system uses UDP datagrams running on a Linux system. The USB output of the joysticks were put into a USB hub securely fastened to the back of the right hand station inside the ICAB since the USB cords were only 6 feet long. The USB hub was then connected to a laptop running Linux. A program was written in 'C' to read the joystick output using the 'joystick.h' header file and convert it to UDP datagrams which could then be incorporated into the VMS data recording system. The tilt joystick output had to be calibrated to notify the firmware on the joystick electronics card of the expected range of motions for the stick. This was done using the basic Linux joystick calibration program. The program went through a series of calibration steps requesting the stick be put in different orientations and then it took a reading. This was done for pitch and roll independently. The vertical neutral orientation was determined using levels to account for any small tilts between the tilt angle indicator and the ICAB. The outputs of the data acquisition software for the joysticks pitch and roll angles were values between ± 32767. These were then converted to actual angles in post-processing using a linear conversion. The position of the buttons and the thumb hat were recorded as 0, 1, 2, etc. depending on how many positions the button could be in. The sampling rate was determined by the VMS data recording system and was either nominally 100 Hz, though was set at 10 Hz for the first three subjects.

3.2.6 Pre-Experimental Procedures

Prior to the commencement of test, each subject was introduced to the experiment, provided some instructions, training, given practice both fixed based out of the ICAB and in the ICAB, and tested on a baseline pre-experiment tracking task.

3.2.6.1 Safety, Consent Forms, Questionnaire

Subjects were first introduced to the VMS and the lunar landing experiment. Subjects then read information about the VMS and the operating and safety procedures. This was followed by the subjects reading and signing the consent form which describes the experiment and the subject's rights. Each subject was given a tour of the VMS and a briefing on safety and hazard procedures by a member of the VMS staff as well as signed a safety card. Each subject was given a questionnaire providing information about themselves, particularly focusing on motion sickness susceptibility (See Appendix B).

3.2.6.2 Training

An experimenter guided each subject through a set of training slides. These slides introduce the subject to VMS and the orientation perception response task. In particular, some guidance is given to the subjects on how to report their orientation perception. For tilt perception, subjects were instructed to "keep the rod aligned vertically and point it directly down at the surface of the moon." Subjects were shown how to best hold the indicator as well as were given advice on how to most effectively perceive orientation in each treatment case. The subjects were encouraged to report what their orientation "felt like" even if it was an orientation they "knew" was not likely. For the "Eyes on the Display" treatment case, subjects were asked to report their best perception of orientation based upon the instrument displays even if their other senses were telling them they were in an alternate orientation.

Subjects were also shown how to put on and use the blindfold as well as instructed where to look during each of the treatments. Along with the training slides, each subject had the opportunity to experience at least one automated landing run in the VMS ICAB without any motion. This familiarized the subject on the procedures, where to look for each treatment, and how to operate the indicators. Finally, each subject was given some fixed base practice outside of the VMS ICAB.

3.2.6.3 Practice

The fixed base practice was done using displays similar to those used during the experiment, except these were simplified to just show the information of interest. These displays were created in Simulink and MATLAB using the Virtual Reality Toolbox and seen in Figure 3.25 and Figure 3.26.

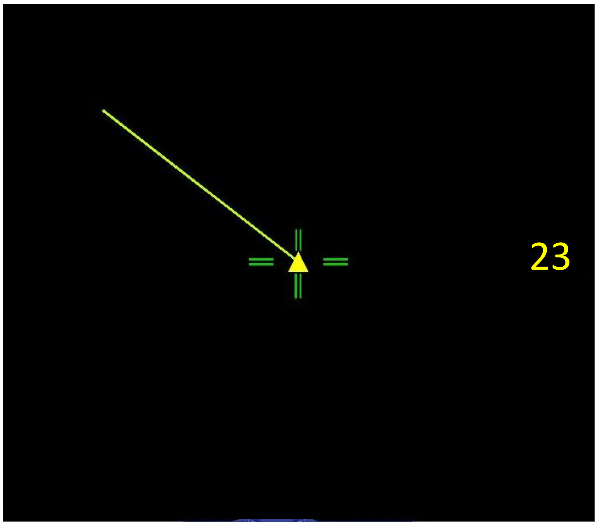

Figure 3.25: Practice HSD

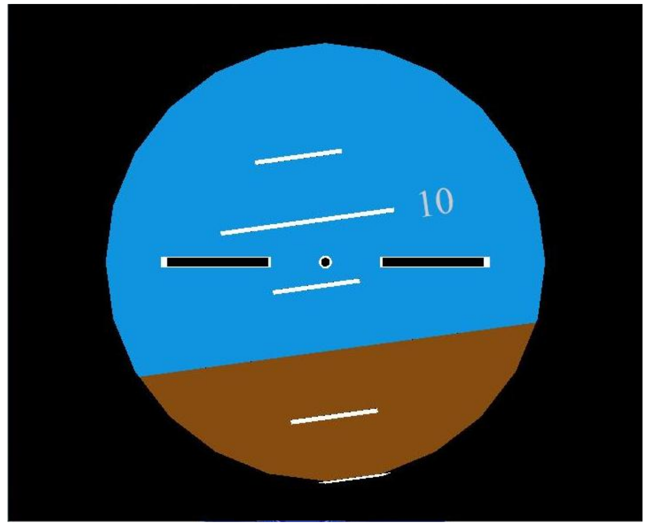

Figure 3.26: Practice VSD

During horizontal velocity perception training, the display in Figure 3.25 was used and the velocity vector would move about in pseudo-random motion and the subject would be tasked with using a replica of the horizontal velocity indicator to report the motion the velocity vector. Similarly, for tilt angle perception training the display in Figure 3.26 would move about in pitch and roll and the subject would track the motion using a replica tilt angle indicator. In both cases, there was no information feedback during a particular run which the subjects could use to judge their performance and correct. However, after each practice run which lasted 50 seconds, plots were provided which showed the actual motion over time along with their reported perceived motions as well as a metric of the magnitude of error during a run. This allowed the subject to determine qualitatively what types of errors were being made, such as a gain error, lag error, or bias as well as how large these errors were. Corrections then could be made to improve tracking performance for the next run. Subjects were given as many practice runs as needed to become comfortable with the task and become proficient in operating the indicators.

3.2.6.4 Baseline Pre-Experiment Tracking Test

Once the subject had become proficient in the tracking task during practice, additional runs were done as a pre-experiment tracking test. The purpose of this test was to quantify how effectively each subject could use the experimental indicators to track a display instrument without any motion cues. At least three trials were taken for each indicator per subject. The last trial was always taken shortly before entering the VMS for actual experimentation.

3.2.7 Experimental Procedures

Each subject was tested on one day with one flying pilot. First the subject went through the pre-experimental procedure described above. During this time the flying pilot was doing training and practicing flying in the VMS with motion active. Once this training was complete, the right hand station subject would enter the VMS and occupy his/her station along with the pilot. The subject would wear a headset which allowed communication between the interior of the VMS and the control station. The subject was provided with a blindfold which would be worn on the forehead then placed over the eyes on runs designated as eyes closed. For a given run, the experimenter would communicate with the subject over the headset which treatment would be performed (either eyes closed, eyes out the window, and eyes on the display) and whether to report perceptions of tilt angle or horizontal velocity. The subject would then turn the red knob to the corresponding position and prepare for the trial. The VMS then would prepare the simulator and the trial would begin. During a given trial the subject would operate one of the two indicators using one of the three sets of treatment cues (for example looking down at the display instruments to perceive and report tilt angle). The trial would conclude either due to the pilot landing the VMS on the simulated lunar surface or the pilot "punching-out" and resetting the simulation. This was occasionally done if the pilot was unable to control the vehicle and wanted to try again. At the end of a trial the VMS motion base would reset, a new treatment and perception combination would be communicated in and another trial would begin. Between trials, the subject was able to communicate if they were feeling any motion sickness and the testing would stop and allow for the subject to leave the cab. This did not occur during any of the testing. Each trial took approximately 90 seconds with 30 seconds between trials. Trials were completed one after another until a break time was reached. Breaks were given approximately every hour or more frequently if requested by the subjects. The series of tests for a single subject were all completed within a single day in three one hour testing periods.

3.2.8 Data Analysis and Statistics

The pre-experimental data was analyzed to quantify the ability of subjects to use the indicators for a simple tracking task. The roll and pitch angle tracking was quantified using mean square error (MSE) for each trial. Particular tracking errors were diagnosed by calculating the gain, bias, and delay of the response relative to the target. The gain was defined as the average relative magnitude of the response compared to the target at each point during a trial. Since the targets motion was sinusoidal about zero, the bias was defined as the average value of the response over each trial. Finally the delay was calculated as the average difference of the times when the minimum and maximum of each sinusoid occurred for target and the response. The velocity direction tracking was quantified using maximum instantaneous errors for each trial as well as MSE. For analysis of the velocity magnitude, since subjects tracked specified ranges of velocities, the time over each trial in which the actual velocity was not accurately bound by the perceptual range was calculated. While the pre-experimental testing trials were each the same length, the landing trajectories were not. To allow for comparison, the total time of bounded tracking error was normalized by the trial time to yield a fraction of the trial which was not accurately bounded by the response range. For both tilt and velocity trials, the first 5 seconds of each trial were ignored in the analysis since the data showed the subject would often still be reacting to the start of the simulation during this time period.

Post-processing of the data files was done to covert the raw joystick output into physically meaningful variables. The tilt angle was converted into pitch and roll angles in degrees. The horizontal velocity data was synthesized into velocity magnitude in ft/second and velocity direction in degrees from straight forward. The primary metric used for assessment of a subject's perception of tilt angle was running

MSE. The MSE was calculated at each point in time for a window that spanned ± 3 seconds from the time point of interest. For each trial, the maximum running MSE was taken as the primary metric for roll and pitch. The purpose of the window was to minimize the effect of large instantaneous errors of short duration while capturing perceptual errors that could influence vehicle control and thus performance and safety. Shorter misperceptions might not be acted upon by the pilot or might be obscured by the slow vehicle dynamics. The ± 3 seconds window size was determined through initial analysis of the data, finding the approximate duration of perceptual errors, and trying to capture this information in a single metric. In the running MSE analysis the maximum value was only taken after the first five seconds of each simulation. The subject's perceptions were compared to both the motion for the mathematical model of the vehicle that the VMS motion base is trying to simulate and the actual VMS motion.

For analysis of the horizontal velocity, the trajectory was divided into approach and terminal descent portions. The dividing point was defined as the first point in time in which the vehicle reached a horizontal velocity slower than 5 ft/s. This was selected because it was the point in which the pilot was advised to transition into the terminal descent control mode if that option was available. Even on trajectories when no mode transition occurred the trial was divided into these portions for analysis. For analysis of velocity direction, a similar metric as used for the tilt analysis of running MSE with a window of ± 3 seconds, was attempted. In addition, the MSE over the entire trajectory was computed. For analysis of the velocity magnitude, similar to the pre-experimental testing data, the time over each trial in which the actual velocity was not accurately bound by the perceptual range was calculated. Since trials varied in duration, the fraction of the trial in which the actual velocity was not accurately bound by the perceptual range was used as the primary metric for velocity magnitude perception.

Analysis was done to determine the effect and significance of treatment (eyes closed, eyes out the window, or eyes on the display). This was done using a within-subjects one-sample t-test on the differences between the various treatment cases. The significance limit was set at $p<0.05$. Additionally, one-sample Kolmogorov-Smirnov (KS) tests were performed to ensure the data were normal prior to performing t-tests.

4 Results

The results are divided into three sections: Observer model simulation with vestibular only, Observer model simulation with vision, and the Ames VMS experiment. These results are presented in this section.

4.1 Numerical Observer Model and Simulation – Vestibular

A variety of lunar landing trajectories were input into the Observer model simulation, first considering the vestibular only case. A summary of these results is given here. The Observer model simulation predicts the astronauts will experience a strong somatogravic illusion, perceiving themselves as upright throughout the trajectory. This illusion is predicted to persist even during the braking burn when the astronauts are tilted back by as much as 90 degrees with respect to vertically upright. The Observer model predicts the astronauts will highly underestimate the roll and pitch maneuvers during automated trajectories, LP redesignation trajectories, and manually controlled trajectories. The somatogravic illusion arises due to the thrust from the descent engine thruster aligning the GIF with the body axis (-z head fixed coordinate) of the astronauts. The GIF vector is accurately perceived, but incorrectly portioned between gravity and acceleration. Head location analysis reveals that for the cases considered here, the head location has a small, but measurable (0.3-4.1 degrees) effect.

4.1.1 Baseline Automated Trajectory A

The first trajectory analyzed is the baseline Trajectory A. The parameters for this trajectory are given in Table 3.1 and the vehicle orientation over time is given in Figure 3.3. Since this automated trajectory is primarily a pitch maneuver, the perceived and actual roll and yaw Euler angles are omitted.

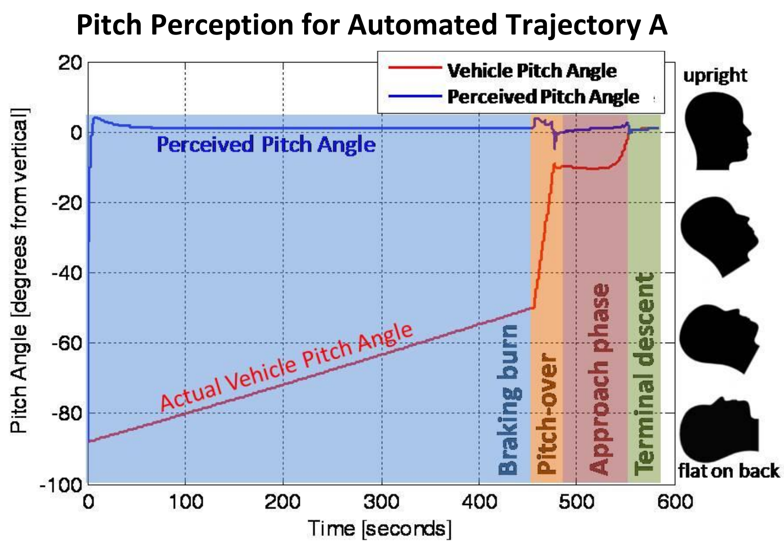

Figure 4.1: Pitch Perception for Automated Trajectory A

Figure 4.1 shows the vehicle pitch angle and the predicted astronaut's perception of pitch angle as functions of time throughout the trajectory. The primary results shown in Figure 4.1 is that, while the vehicle pitches upright by about 90 degrees, the astronaut's perceived pitch angle remains approximately 0 degrees throughout the trajectory. This corresponds to the astronauts feeling as if they are upright with respect to the local lunar surface. The cause of this dramatic misperception is due to a somatogravic illusion being created by the descent engine thrust. The thruster force results in aligning the GIF vector with the body axis of the astronaut. This can be best shown in Figure 4.2.

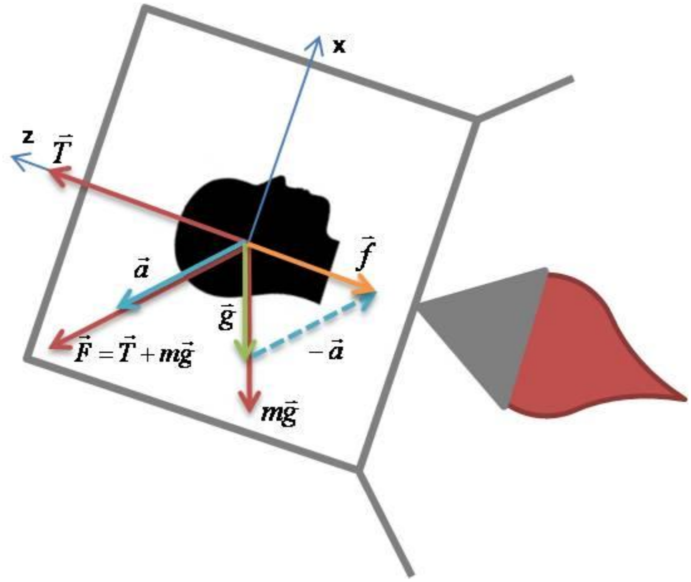

Figure 4.2: Somatogravic Illusion during Descent

The vehicle is seen from the side at an arbitrary pitched back orientation experienced during the braking burn. The head fixed axes from Figure 2.7 are included. The astronauts head is aligned with the body axis of the vehicle. To determine the direction of the GIF vector, the forces must be considered. There are two external forces acting on the vehicle and the astronaut. The first is the lunar gravitation force, mg. The second is the thrust force, T, from the descent engine thruster. This is generally very closely aligned with the body axis of the vehicle. Summing these forces yields the net force, F. Dividing this by the vehicle mass, m, results in the acceleration experienced by the astronaut, a. The gravitational acceleration, g, can be found by dividing that gravitational force, mg, by the vehicle mass, m. Using Equation 1, the GIF vector, f, can be found by taking the difference between the gravity vector and the acceleration vector. As seen in Figure 4.2, the GIF vector aligns with the astronaut's body axis or the –z direction. The CNS misinterprets the direction of the GIF vector as the direction of gravity. Thus the astronaut perceives the direction of gravity to be aligned with his/her body axis and feels upright. While this example shown in Figure 4.2 is for an arbitrary pitched back orientation, the same calculations can be done at any point during the trajectory to see that the descent engine thruster will cause the GIF to align with the –z axis. During the pitch-over maneuver, the descent engine thruster gimbals slightly to rotate the vehicle upright. This small misalignment with the body axis of the vehicle, will rotate the GIF vector away from directly in line with the –z axis. The result can be seen in Figure 4.1, where during pitch-over the predicted astronaut perception of pitch varies slightly about 0 degrees.

The astronaut's perception of GIF can be explicitly seen in Figure 4.3.

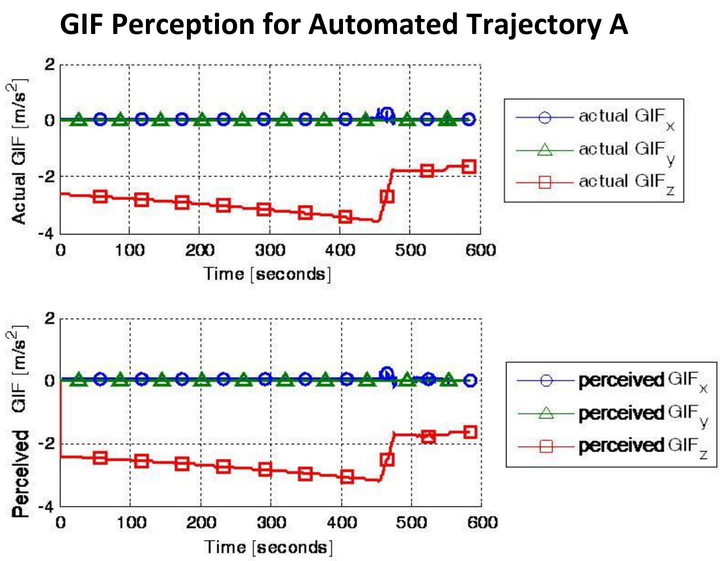

Figure 4.3: Gravio-Inertial Force Perception for Automated Trajectory A

As demonstrated in Figure 4.2, the top plot of Figure 4.3 shows the GIF vector is aligned with the –z axis throughout the trajectory. The x and y components are nearly zero throughout the descent, and while the magnitude of the GIF changes, its direction is consistently aligned with the –z axis. The Observer model prediction of the astronaut's perception of the GIF is seen in the bottom plot of Figure 4.3. The perception of GIF is quite accurate as seen by comparing the top and bottom plots of Figure 4.3. The direction is correctly perceived as being in the –z axis, and there are only small misperceptions underestimating GIF magnitude. Despite the accurate perception of GIF, the direction of gravity is poorly perceived as seen in Figure 4.4.

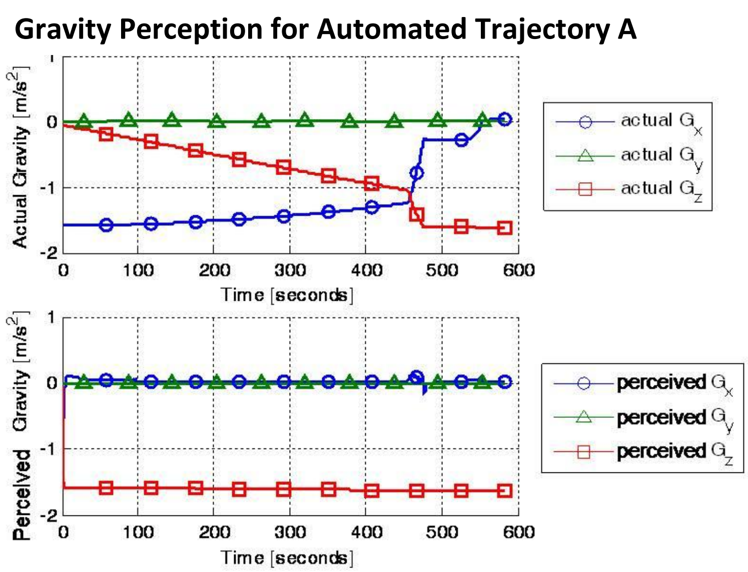

Figure 4.4: Gravity Perception for Automated Trajectory A

The actual direction of gravity rotates from being entirely in the –x head fixed component as the astronauts are on their back at the beginning of the braking burn to being entirely in the –z direction as the vehicle pitches upright during the course of the descent. The bottom plot of Figure 4.4 shows the astronaut's perception of gravity is entirely in the –z head fixed component. This corresponds to the somatogravic illusion seen in Figure 4.1, where the astronaut perceives the direction of gravity to be down through his feet. The perception of gravity being in line with the body axis results in the astronaut's misperception of being upright. The CNS misperception of gravity is accompanied by a misperception of acceleration seen in Figure 4.5.

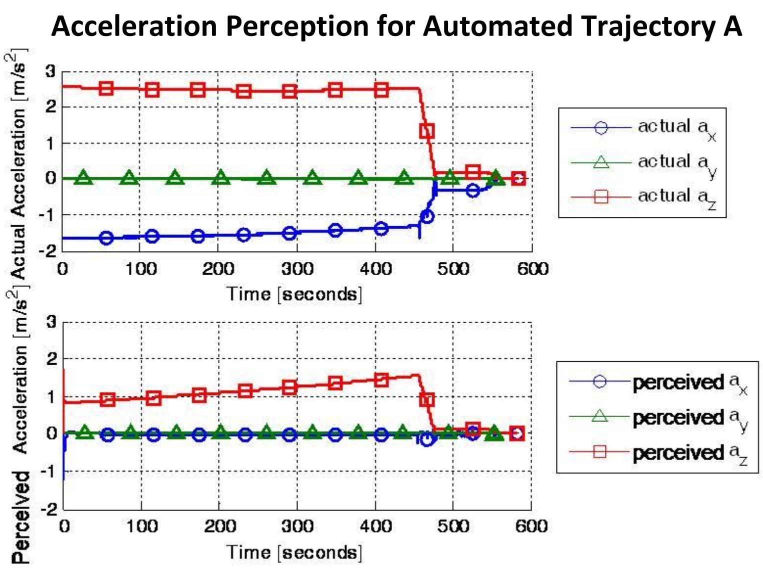

Figure 4.5: Acceleration Perception for Automated Trajectory A

The top plot of Figure 4.5 is the acceleration profile of the vehicle previously seen in Figure 3.5. The predicted perceptions of these accelerations are seen in the bottom plot of Figure 4.5. The accelerations are misperceived as being entirely in the z axis and much smaller in magnitude than the actual vehicle accelerations. The perceived acceleration is the remaining portion of the perceived GIF that as not attributed to the perception of gravity. Thus while the GIF is accurately perceived, the division of the GIF into gravity and acceleration portions is not done accurately, resulting in misperceptions of both gravity and acceleration. The vehicle angular velocities and the astronaut's perceptions of these are seen in Figure 4.6.

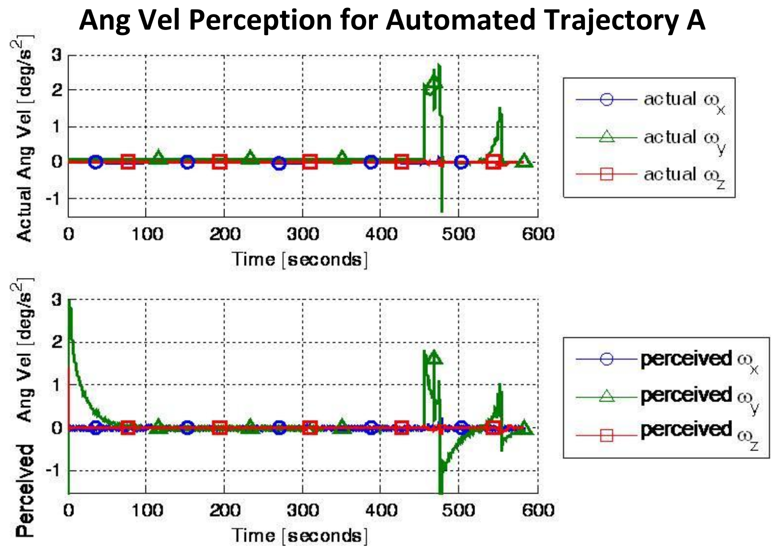

Figure 4.6: Angular Velocity Perception for Automated Trajectory A

The top plot of Figure 4.6 is the vehicle angular velocity profile previously seen in Figure 3.4, while the bottom plot depicts the perceptions of these angular velocities. Both the actual vehicle angular velocity and the perceptions are nearly entirely about the y axis due to the vehicle's pitch rotation upright during the course of the trajectory. The large perceived angular velocity spike and following decay seen at the beginning of the trajectory is an artifact of the simulation and would not be experienced by the astronauts. The remaining perception of angular velocity is fairly accurate. During pitch-over there is a fairly accurate, though slightly underestimated, perception of the angular velocity. Immediately following pitch-over there is a misperception of reverse angular velocity. This is due to the semicircular canal dynamics adapting to the steady rotation experienced during pitch-over and then when that rotation stops, incorrectly perceiving a counter rotation.

The automated baseline trajectory A contains acceleration and rotation rate profiles that the vestibular only Observer model predicts will produce attitude perceptions that differ substantially from the actual vehicle orientation. In particular, the somatogravic illusion is predicted such that the astronauts perceive themselves approximately upright throughout the trajectory despite starting pitched back by nearly 90 degrees. This illusion is created by the descent engine thruster creating an acceleration profile that yields the GIF vector direction to be in line with the astronaut's body axis or in the –z direction. The GIF vector, while accurately perceived, is incorrectly decomposed into acceleration and gravity portions. The incorrect perception of the direction of gravity results in the continuous misperception of orientation and the somatogravic illusion described above. The angular velocity profile is fairly accurately perceived.

4.1.2 Alternate Automated Trajectories

The baseline Trajectory A is generally representative of the other trajectories within the trade space. There are, however, variations in the descent and approach parameters amongst the various trajectories. These have a minor influence on the astronaut's perceptions of vehicle orientation. The primary orientation perception finding of the somatogravic illusion seen for the automated baseline Trajectory A also occurs for the other trajectories within the trade space. The first alternate trade space trajectory analyzed was Trajectory I. As seen in Figure 3.1, this trajectory has a braking burn acceleration profile of 2.0 lunar G's, a slant range of 2000 m, and a trajectory path angle of 90 degrees.

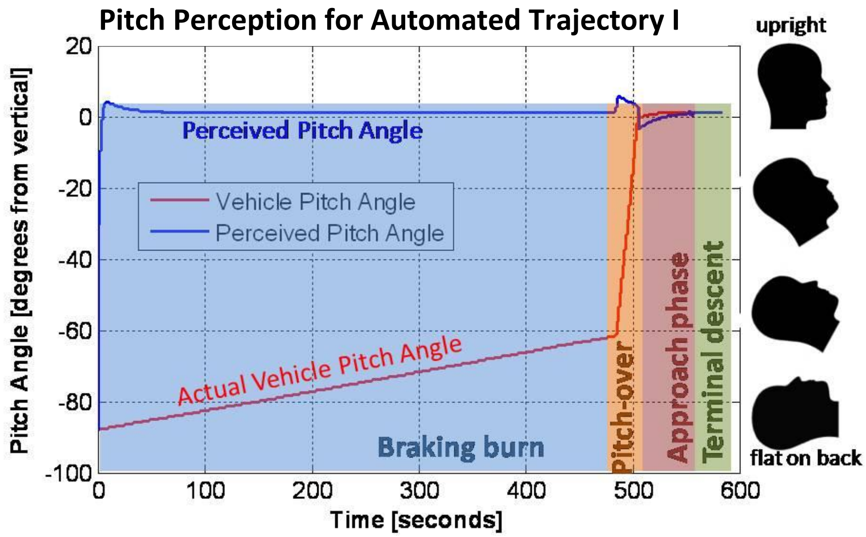

Figure 4.7: Pitch Perception for Automated Trajectory I

Figure 4.7 shows a similar somatogravic illusion predicted here for Trajectory I as was seen for Trajectory A. The Observer model predicts the astronaut to perceive an orientation of upright even when the vehicle is significantly pitched back. One difference between Trajectory I and Trajectory A is the final angle after the pitch-over maneuver. In the automated baseline trajectory A, the pitch-over maneuver rights the vehicle to approximately -10 degrees pitched back from vertical. The approach phase is carried out at this slightly pitched back attitude. Since the perceived orientation is upright, there was a small (~10 degrees) misperception in orientation during this phase. For Trajectory I, since the trajectory path angle is 90 degrees, the pitch-over maneuver completely rights the vehicle prior to the approach phase. As a result there is not a substantial misperception of orientation that occurs during the approach phase. The misperception that does occur during the braking burn is of the same origin as that seen for Trajectory A. The descent engine thruster yields a GIF vector aligned with the body axis of the astronauts. This is perceived as the direction of down resulting in a feeling of being upright. Another trade space automated trajectory analyzed was Trajectory D. This trajectory has a braking burn acceleration profile of 1.0 lunar G's, a slant range of 500 m, and a trajectory path angle of 15 degrees.

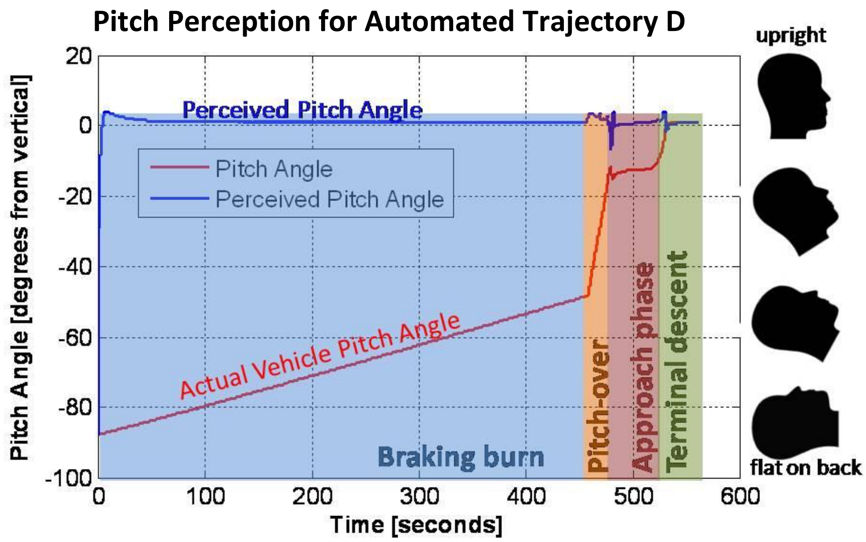

Figure 4.8: Pitch Perception for Automated Trajectory D

As seen in Figure 4.8, the astronaut is predicted to experience the same somatogravic illusion seen for the other automated trajectories studied. Due to the low trajectory path angle of 15 degrees, the approach phase is completed at a larger pitched back angle then previous trajectories studied of approximately 13 degrees. Also since the slant range is short at only 500 m, the approach phase is much shorter than for trajectory 050. In all cases, whatever orientation the vehicle is at the Observer model predicts the perception to be an upright orientation. Other automated trade space trajectories were studied beyond this, and while each trajectory is unique, the primary misperception associated with the somatogravic illusion was seen for all trajectories. Only small deviations depending upon the trajectory parameters were seen for the range of trade space trajectories.

4.1.3 Landing Point Redesignation Trajectories

Along with the automated trade space automated trajectories, two LP redesignation trajectories were also studied. As previously mentioned, since the LP redesignation trajectories have similar motions prior to pitch-over as the automated trajectory only the later portions of interested are included in Figure 4.9 and Figure 4.10. The first trajectory studied is given in Figure 3.6 and is the cross range LP designation to the left of the vehicle.

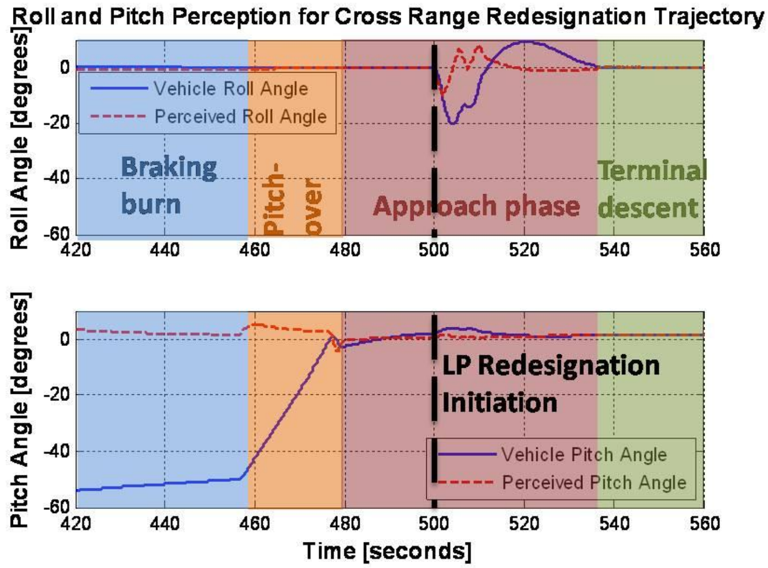

Figure 4.9: Roll and Pitch Perceptions for Cross Range Landing Point Redesignation Trajectory

While the LP redesignation was made essentially directly to the left of the vehicle, both the roll and pitch angle of the vehicle as well as perceptions are given in Figure 4.9. The vehicle's roll motions, first to the left and then back to the right, are poorly tracked by the astronaut's perceptions. In particular the roll angle is substantially underestimated. This is due to the descent engine thruster yielding a GIF vector that is nearly aligned with the body axis of the vehicle and the –z coordinate direction. Thus even as the vehicle rolls 20 degrees to the left, the astronaut perceives his/her orientation as nearly upright. At one point during the redesignation, the perception is actually of opposite sign to the roll angle. In this case the astronaut perceives a roll to the right despite the vehicle actually being rolled the left. The largest roll angle misperception seen for the cross range LP redesignation trajectory is approximately 23 degrees.

Another LP redesignation trajectory was analyzed for a redesignation made to a LP downrange. This results in primarily pitch maneuvers. The complete Euler angle motions of the vehicle for this redesignation are given in Figure 3.8. Figure 4.10 shows the astronaut's orientation perceptions during the downrange LP redesignation maneuver.

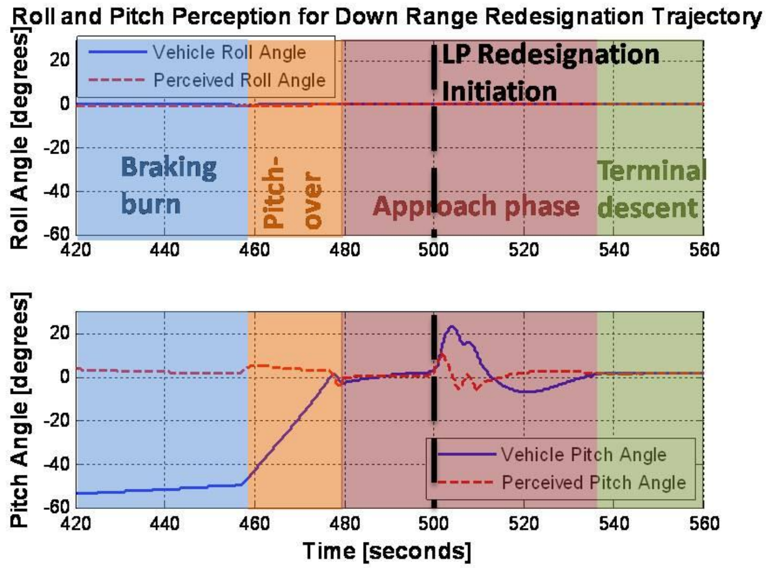

Figure 4.10: Roll and Pitch Perception for Down Range Landing Point Redesignation Trajectory

The roll angle is well perceived during the down range LP redesignation trajectory seen in Figure 4.10 since the LP redesignation does not result in any roll maneuvers. However, the pitch angle during the redesignation maneuvers is poorly perceived. It is underestimated in an equivalent fashion as the roll angle was underestimated for the cross range redesignation. Similarly, the largest pitch angle misperception seen for this trajectory was approximately 23 degrees. While only essentially directly cross range to the left and directly down range LP redesignations were studied here, equivalent misperceptions and underestimations of tilt angle occur for redesignations to the right, back up range, or in any other direction.

4.1.4 Manual Control Trajectories

The final set of trajectories studied was the manually controlled trajectories. Details of the vehicle motions during the two manually controlled trajectories, one cross range and one downrange, can be found in Figure 3.7 and Figure 3.9. The Observer model prediction of astronaut orientation perceptions for the primarily roll or cross range manual control maneuver can see in Figure 4.11.

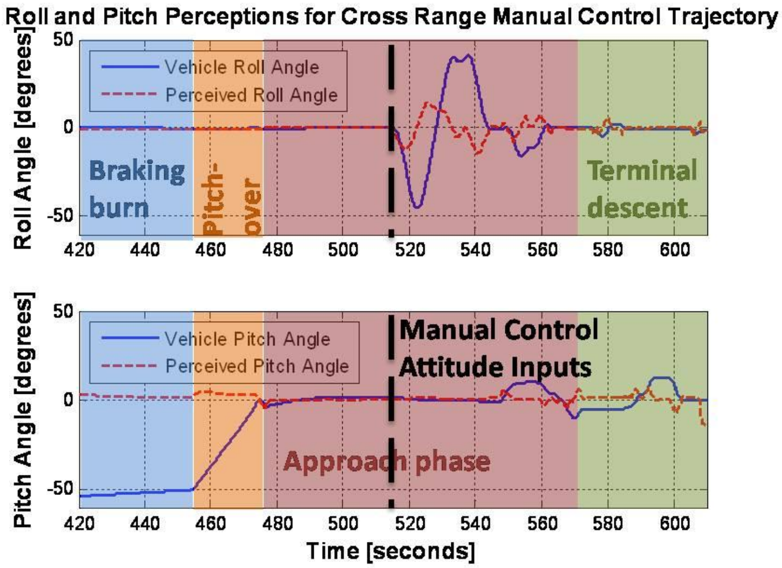

Figure 4.11: Roll and Pitch Perceptions for Cross Range Manual Control Trajectory

Figure 4.11 shows that the very large roll maneuvers experienced during this manual control trajectory were substantially misperceived and underestimated. In this maneuver, the vehicle first is commanded to roll to the left by approximately 45 degrees, however the largest perception of roll to the left was only approximately 12 degrees. Similar to the LP designation trajectories, the misperceptions are not only large in magnitude, but are often incorrect in direction as well. The first large roll to the left is at one point perceived as a roll to the right. The following recovery roll maneuver to the left is also substantially underestimated. In the manually controlled recovery period following the large control input, there are small pitch maneuvers which are also misperceived and underestimated. A manually controlled pitch maneuver is also studied here as seen in Figure 4.12.

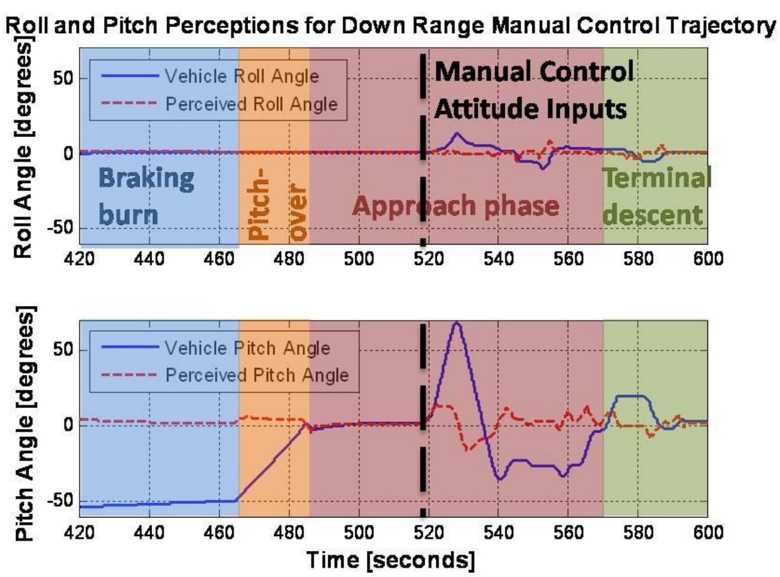

Figure 4.12: Roll and Pitch Perceptions of Down Range Manual Control Trajectory

The down range manual control trajectory seen in Figure 4.12 includes an extreme pitch forward control input by the pilot of nearly 70 degrees; however the predicted perception of this maneuver only approaches 13 degrees. This substantial misperception and underestimation of pitch angle can be seen for the remainder of the trajectory as the pilot enacts control inputs to re-stabilize the vehicle and bring it to the surface in an upright orientation. Similar, though less severe, misperceptions can be seen in the roll angle. Thus misperception and underestimation of tilt angle is seen for manual control trajectories with both down range and cross range pilot inputs. It should be noted that equivalent misperceptions occur for manual control trajectories with maneuvers pitching back, rolling right, or any other direction commanded by the pilot. The misperception seen here is similar in cause as the LP redesignation trajectories. The descent engine thruster yields a GIF vector that aligns with the –z axis, providing otolith cues that correspond to the astronaut being upright. This results in the underestimation of significant tilt angles applied by the pilots control inputs.

4.1.5 Head Location Analysis

For a given head location and trajectory, the calculations for each head location analysis are shown in Figure 3.10. The head locations considered are given in Table 3.4. The maximum effects that the head location had on the pitch angle are given below in the grey portion of Table 4.1.

Table 4.1: Magnitude of Effect of Head Location on Perceived Pitch Angle for Various Automated Trajectories

Trajectory Parameters				Head Location		
Trajectory	Braking burn [Lunar G's]	Slant range [m]	Trajectory angle	Altair LDAC-2	LLRV	LM
B	1.05	2000	15 °	3.4 °	0.8 °	1.6 °
C	1.05	2000	90 °	3.2 °	0.8 °	1.6 °
D	1.05	500	15 °	3.6 °	0.9 °	2.0 °
E	1.05	500	90 °	3.9 °	1.0 °	1.9 °
F (Apollo #1)	1.1	2000	15 °	3.2 °	0.8 °	1.4 °
G (Apollo #2)	1.05	2000	30 °	3.2 °	0.8 °	1.5 °
A (baseline)	1.1	1000	30 °	3.1 °	0.8 °	1.4 °
H	2.0	2000	15 °	3.5 °	0.9 °	1.7 °
I	2.0	2000	90 °	2.1 °	0.5 °	1.0 °
J	2.0	500	15 °	3.9 °	1.0 °	1.9 °
K	2.0	500	90 °	1.1 °	0.3 °	0.6 °

The effect of head location in Table 4.1 is seen to be small, but measurable (0.3 ° to 3.9 °). The Altair LDAC-2 head location resulted in the largest effect of head location for each of the trajectories studied. This is expected since this head location is farthest from the vehicle CG resulting in the largest centripetal and tangential accelerations experienced at the head location. The various automated trajectories tested had small effects on the effect of head location with the Apollo-like trajectories and the baseline Trajectory A being fairly representative of the trajectories tested.

Along with the automated trajectories, head location analysis was extended to the LP redesignation trajectories and the manual control trajectories. These results are seen in grey highlighted portion of

Table 4.2. This analysis was completed using tilt angle instead of pitch angle for the cases where the primary maneuver was in the roll direction instead of pitch direction.

Table 4.2: Magnitude of Effect of Head Location on Perceived Tilt Angle for Simulated Landing Point Redesignation and Manual Control Trajectories

Trajectory Parameters			Head Location		
Trajectory	Direction	Maneuver	Altair LDAC-2	LLRV	LM
LP Redesignation	Cross range	280 ft @ 1500 ft altitude	1.3 °	0.7 °	3.6 °
LP Redesignation	Down range	280 ft @ 1500 ft altitude	2.5 °	0.5 °	4.0 °
Manual Control	Cross range	45 ° roll left	2.0 °	1.3 °	4.1 °
Manual Control	Down range	70 ° pitch forward	3.6 °	0.9 °	4.1 °

The LP redesignation and manual control trajectories yielded comparable effects of head location as seen for the automated trajectories. The cross range maneuvers for both LP redesignation and manual control actually created fairly small effects for the Altair LDAC-2 head location compared to those previously seen. This is due to the head location assumption for the Altair LDAC-2 design being very far forward from the CG (large r_x), but not very high above the CG (small r_z). As a result, the tangential accelerations created from the head location offset are fairly small for maneuvers that were primarily about the roll axis. Maneuvers that were primarily pitch maneuvers resulted in much larger effects for the Altair LDAC-2 head location. Conversely, maneuvers that were primarily roll maneuvers had a comparable effect to pitch maneuvers for the LM head location since this location was high above the CG (large r_z). Overall the effect of head location was small, but measureable for automated, LP redesignation, and manual control trajectories for the head locations studied.

4.2 Numerical Observer Model and Simulation – Visual

Next a variety of lunar landing trajectories were analyzed in the Observer model simulation incorporating visual cues. It was seen that when visual cues are activated in the model, particularly the visual gravity cue which is provided by being able to see the horizon, the perceptions are far more accurate than in the vestibular only case. However, it is assumed that when the vehicle is pitched back sufficiently such that the astronauts cannot see the horizon, the visual gravity cue is deactivated. This results in the misperceptions previously seen persist prior to pitch-over. After pitch-over when the astronauts can see the horizon and the visual gravity cue is activated perceptions greatly improve. This was seen for the automated baseline Trajectory A as well as for the simulated LP redesignation and manual control trajectories. For extreme manual control trajectories if the vehicle pitches too far forward or backward, it is assumed the horizon cannot be seen and the visual gravity cue is deactivated. This creates misperceptions, specifically large underestimations of tilt angles. This is due to a lack of visual cues requiring reliance on vestibular cues which lead to the somatogravic illusion seen previously. Finally, dust blowback was simulated for a variety of cases by deactivating visual cues for this portion of the descent and landing. This was seen to have a minimal effect if the dust occurs at 100 feet since generally the vehicle is nearly upright by this altitude. However, if the dust begins earlier at 200 feet, it can result in misperceptions of orientation for automated, LP redesignation, and manual control trajectories.

4.2.1 Baseline Automated Trajectory A

The baseline trajectory (A) was analyzed assuming all of the visual orientation cues (linear velocity and position, angular velocity, and visual horizon) were available throughout. This serves as the best possible case for orientation perception. The analysis was limited to the final portion of the trajectory (final ~150 seconds) since this is of the greatest interest. Also since this automated trajectory is primarily a pitch maneuver, the roll and yaw orientation perceptions are omitted. The parameters for this trajectory are given in Table 3.1 and the vehicle orientation over time is given in Figure 3.3. Comparison to the case when it is assumed vision does to make a contribution can be made with Figure 4.1.

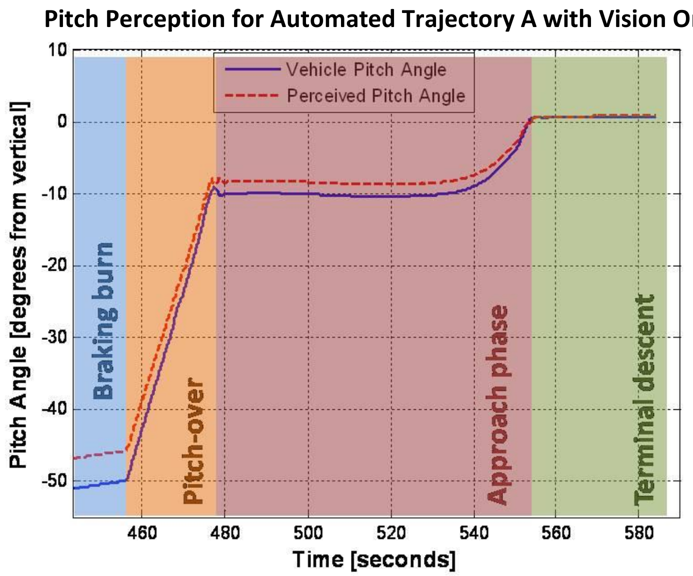

Figure 4.13: Pitch Perception for Automated Trajectory A with Vision On

As seen in Figure 4.13, including visual cues in the model predicts much improved perception of pitch angle. The perceived pitch angle is still slightly less than the actual pitch perception for most of the trajectory, however this is much more accurate than the perception in the vestibular only case which was nearly upright (see Figure 4.1). The visual perception of the horizon provides a useful cue for accurately estimating the direction of down or gravity. The slight underestimation of the pitch angle is due to the weighted averaging inherent in the Observer model between the visual (nearly equal to vehicle pitch angle) and vestibular (nearly zero or upright) orientation cues. The greater weighting on the visual cues results in the net perception being more closely correlated with the actual vehicle orientation, however slight underestimation persists. While the case where all of the visual cues are actived predicts an accurate perception of orientation, it is not necessarily a reasonable assumption. Prior to pitch-over the only visual scene provided to the astronauts out the window will be a view of the stars. Most likely from the stars only a visual angular velocity cue would be provided. Without a view of the horizon there would be no visual direction of down cue, and without a view of the lunar surface it is unlikely visual linear position or velocity would be available. Thus the following simulation assumes only visual angular velocity is activated at the beginning of the trajectory. During pitch-over it is assumed that at -25 degrees the lunar horizon comes into the window view and provides the astronauts with a visual direction of down cue. Thus the visual gravity cue is activated at this point in time.

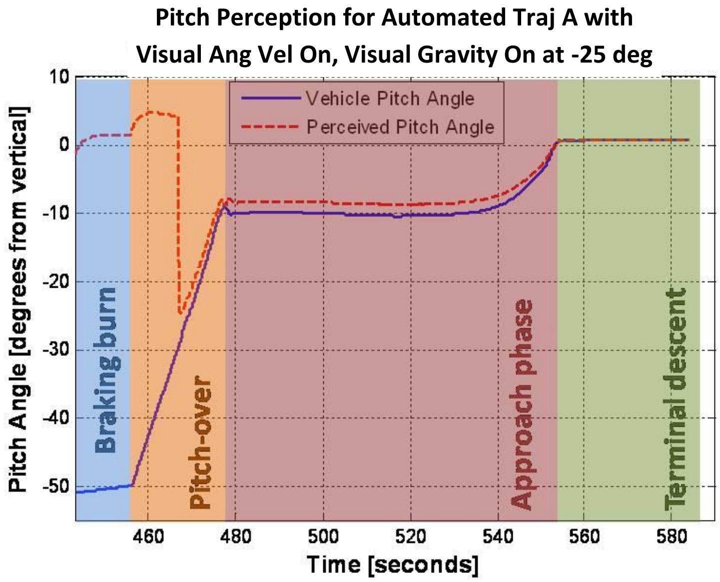

Figure 4.14: Pitch Perception for Automated Trajectory A with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees

With the visual gravity cue not active at the beginning of the trajectory, the large misperceptions seen in the vision off case (see Figure 4.1) are seen for the initial portion of the trajectory in Figure 4.14. The perception is being upright even though prior to pitch-over, the vehicle is significantly pitched back. Halfway through pitch-over, it has been simulated that the horizon comes into the window view and thus in the model the visual gravity cue is activated. At this point in time, the pitch perception quickly responds to far more accurately track the actual vehicle pitch angle. For the remainder of the trajectory, with the visual gravity cue activated and the horizon in view, the perceptions are quite accurate. The scenario simulated here with the visual gravity cue not activated until the horizon comes into view during pitch-over is a more reasonable scenario than assuming all of the visual cues are constantly active. It should be noted that the selection of the horizon appearing in the window view to provide a visual gravity cue occurring at -25 degrees was fairly arbitrary. The exact orientation and time which the horizon will appear in the window view will depend on the vehicle design and trajectory selected. However, it is likely to occur during the pitch-over maneuver, and from Figure 4.14 it can be seen that the horizon's appearance will greatly improve the perception of pitch angle.

4.2.2 Landing Point Redesignation Trajectories

The same cross range and downrange LP redesignation trajectory case studies first analyzed in Figure 4.9 and Figure 4.10 are studied here, but now incorporating visual cues. The complete Euler angle vehicle motions for these two case study trajectories can be found in Figure 3.6 and Figure 3.8.

The LP redesignation case studies are simulated with angular velocity visual cues activated in the model throughout, but the visual gravity cue only being activated after pitch-over at an angle of -25 degrees.

This is again done to simulate the horizon coming into the astronaut's window view at this point, just as was done for the automated Trajectory A seen in Figure 4.14. The perception of roll and pitch angles is seen for the cross range LP redesignation trajectory in Figure 4.15, now also incorporating visual cues.

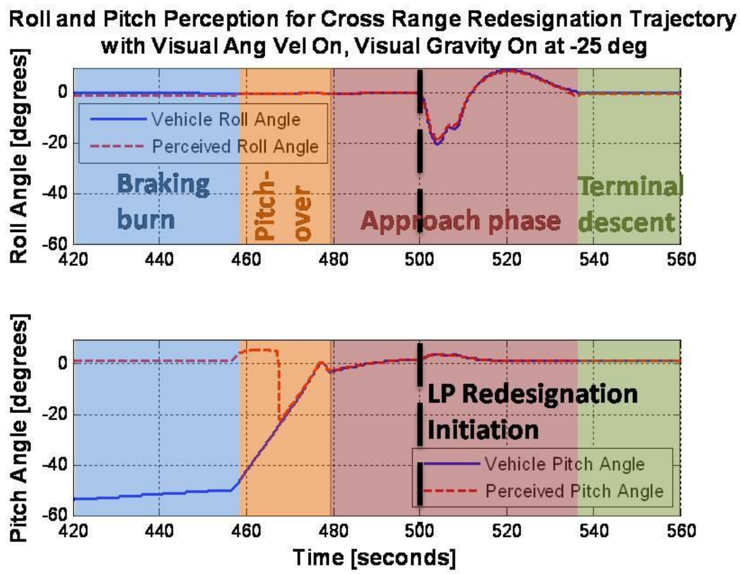

Figure 4.15: Roll and Pitch Perception for Cross Range Landing Point Redesignation Trajectory with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees

As seen in Figure 4.15, prior to pitch-over when the simulation assumes the horizon is not in view there are still very large misperceptions of pitch angle corresponding to being upright. Once the horizon comes into view and the visual gravity cue is activated in the model, the perception of pitch becomes very accurate. This is similar to the predictions for the automated Trajectory A seen in Figure 4.14. During the approach phase, in this simulated trajectory a LP redesignation is made nearly directly left of the vehicle which results in a significant roll maneuver first to the left and then back to the right. In comparison to the case were visual cues are not activated as seen in Figure 4.9, in this case the roll maneuvers are accurately perceived during the automated LP redesignation. Thus in this simulation, despite the LP redesignation the presence of the visual horizon allow for accurate perceptions of orientation. The only misperceptions that occur are during the braking burn and initial portion of the pitch-over maneuver when the horizon is not yet in view. The down range LP redesignation trajectory is also analyzed using the same assumptions for the presence of visual cues. This is seen in Figure 4.16.

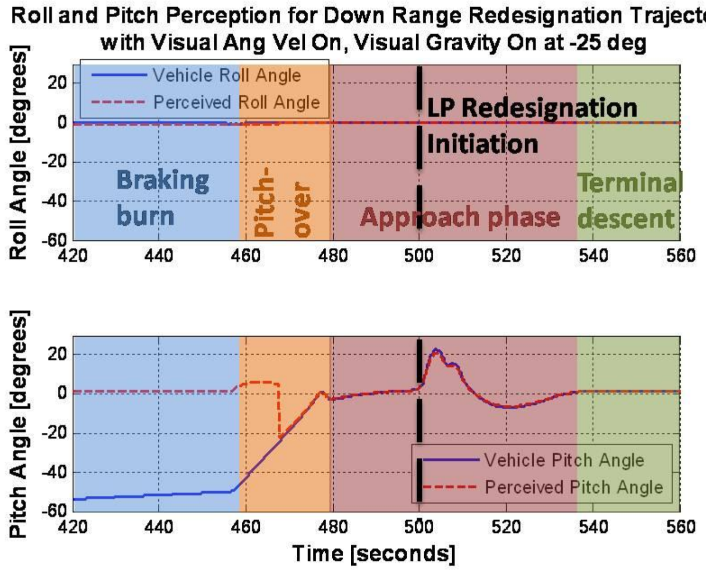

Figure 4.16: Roll and Pitch Perception for Down Range Landing Point Redesignation Trajectory with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees

Figure 4.16 shows many of the previously seen effects, but now for the down range LP redesignation trajectory case study. Prior to the horizon being in the astronaut's window view the model predicts large misperceptions of pitch. However, once the horizon comes into view during pitch-over the orientation is very well perceived even during pitch maneuvers resulting from a down range LP redesignation.

4.2.3 Manual Control Trajectories

The manual control trajectory case studies first shown in Figure 3.7 and Figure 3.9 and studied with visual cues deactivated in Figure 4.11 and Figure 4.12, are now analyzed by incorporating reasonable visual cues. This includes activating the visual angular velocity cue throughout the trajectory and activating the visual gravity cue during pitch-over at a vehicle pitch angle of -25 degrees to simulate the horizon coming into the astronaut's window view. The model's prediction of this simulation for the manually controlled cross range trajectory case study is seen in Figure 4.17.

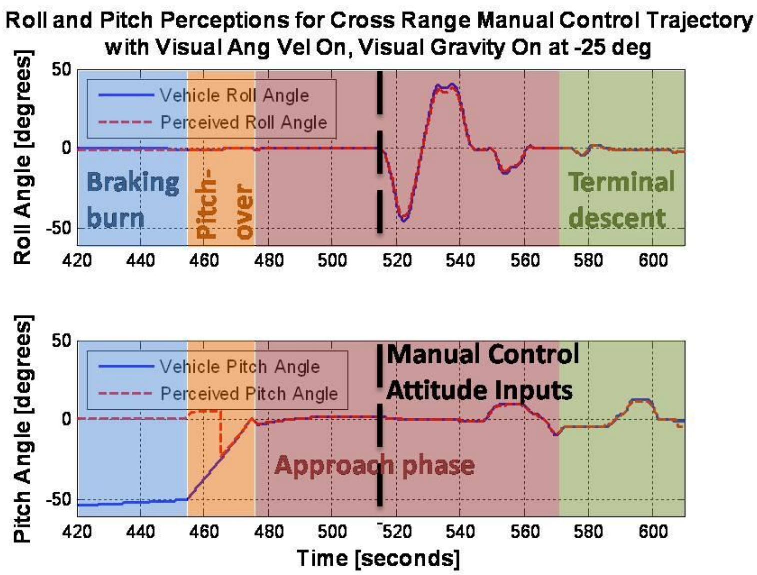

Figure 4.17: Roll and Pitch Perception for Cross Range Manual Control Trajectory with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees

In contrast to Figure 4.11 where the visual cues are deactivated, the simulation in Figure 4.17 with reasonable visual cues activated shows accurate perceptions of roll and pitch angles resulting from the large cross range manual control inputs in the trajectory. Once the horizon appears in the astronaut's window view, the model predicts accurate orientation perception. In this simulation it is assumed that as long as the vehicle retains a pitch angle between ±25 degrees, the horizon will remain within the astronaut's forward looking window, thus the visual gravity cue remains activated. In the cross range manual control trajectory, while the vehicle's roll angle reaches approximately ±45 degrees during the simulated piloting maneuver, the pitch angle does not exceed ±15 degrees. Therefore the horizon should remain within the forward window view and it is reasonable to keep the visual gravity cue activated. In the down range (pitch) manual control trajectory seen in Figure 3.9, the pitch angle exceeds the bounds of ±25 degrees causing the horizon to go out of the astronaut's window view. To simulate this, the visual gravity cue is deactivated for the time periods when this occurs. The down range manual control trajectory with the visual cue activation series discussed above can be seen in Figure 4.18.

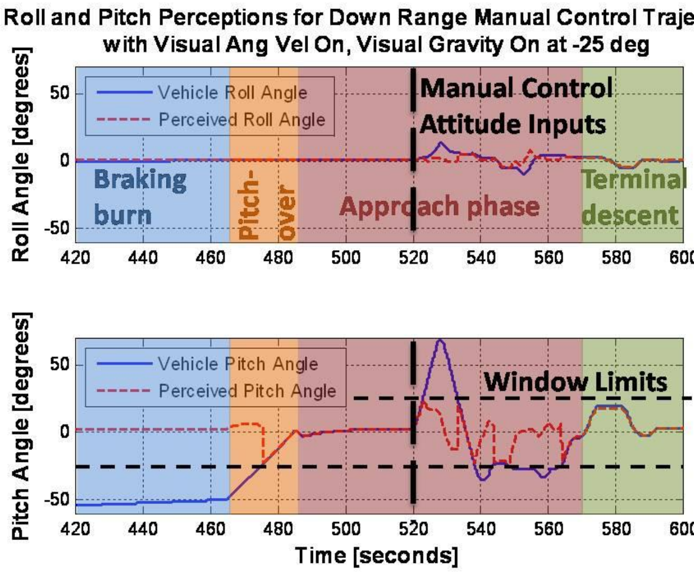

Figure 4.18: Roll and Pitch Perception for Down Range Manual Control Trajectory with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees

As seen previously, during the braking burn and pitch-over maneuver when the lunar horizon is not within the astronaut's view out the forward window the model predicts significant misperceptions of pitch. Once the horizon comes into view at a vehicle pitch angle of -25 degrees, the visual gravity cue is activated and the perceptions become far more accurate. While this is similar to the results seen for previous trajectories, after the beginning of the manual control attitude inputs this trajectory becomes unique. The down range manual control trajectory has large pitch maneuvers which exceed the assumed ±25 degrees bound on the view out the window. As seen in Figure 4.18, during the smaller pitch maneuvers the orientation perception becomes remains quite accurate. However, when the simulated manual control inputs yield a vehicle pitch angle greater in magnitude than 25 degrees, misperceptions of pitch arise. When the horizon leaves the field of view of the window, the astronauts must rely on their vestibular cues. As previously seen in Figure 4.2, due to the descent engine thruster the otolith signal of GIF is in line with the body axis of the vehicle. This corresponds to being upright and over time drives the perception of tilt towards zero. Thus when the horizon is not within the view of the window, the perception of pitch is an underestimation of the actual vehicle pitch angle. During these periods it can be seen that even the direction of the pitch angle can be misperceived. In fact during these extreme manual control maneuvers the error between actual vehicle pitch angle and the perception peaks at just over 60 degrees. When the vehicle orientation returns to between ±25 degrees and the horizon comes back into view the model predicts far more accurate tilt angle perceptions. It should be noted that the horizon could leave the window view during other types of trajectories. The down range manual control trajectory was simply the only trajectory studied that had vehicle pitch angles exceed the assumed limits for horizon view during the approach phase of descent.

4.2.4 Dust Blowback Simulation

One of the significant concerns for SD during lunar landing is the effect that the dust blowback will have on astronauts' perceived orientation during the final stages of descent. To simulate this, at an altitude of 100 feet where dust blowback is likely to occur, all of the visual cues are deactivated in the model. This corresponds to the dust obscuring the astronaut's out the window view such that orientation perceptions are based entirely on vestibular cues. This was simulated for the automated Trajectory A with the visual angular velocity cues initial activated and the visual gravity cues becoming active during pitch-over. This was previously seen in Figure 4.14, but here in Figure 4.19 the effects of dust blowback are included.

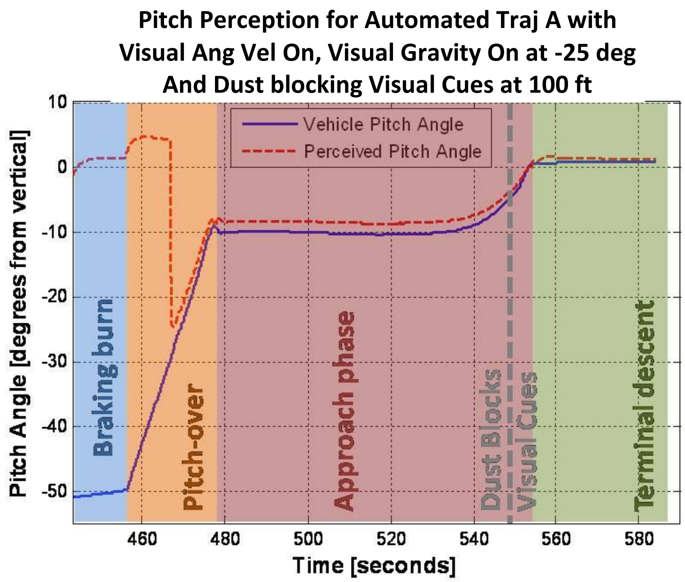

Figure 4.19: Pitch Perception for Automated Trajectory A with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees, Then All Visual Cues off at an Altitude of 100 feet

The effect of the dust blowback on the automated trajectory is fairly minimal (compare Figure 4.14 and Figure 4.19). In this automated trajectory, at the point which the dust first blocks out the visual cues there is not a significant discrepancy between the visual and vestibular perception of the pitch angle. As a result, forcing the system to rely on the vestibular cues does not have a significant influence. If anything, the vestibular based perception is upright just as the vehicle is pitching towards upright. Also, it should be noted that in this simulation of the dust blowback, all of the visual cues have been deactivated at an altitude of 100 feet. While it is not entirely clear which visual cues are likely to be obscured by dust, most Apollo astronauts report being able to see the horizon through the dust because the dust was primarily blowing out away from the vehicle and not up. So it might be unreasonable to deactivate the visual gravity cue during dust blowback. The simulation seen in Figure 4.19 included deactivating the visual gravity cue to show that even when this cue is deactivated there was minimal effect on pitch perception resulting from the dust blowback.

The lack of influence of the dust blowback for automated Trajectory A at 100 ft is to some degree a function of the trajectory. The entirely automated trajectory controls the vehicle upright well above the lunar surface and then descends directly vertically down to the surface. This upright orientation during the portion of the trajectory which dust might obscure the horizon prevents any significant misperceptions from occurring. If however, the vehicle is in manual control and the pilot continues to maneuver the vehicle off of vertical during terminal descent some misperceptions might occur. This can be seen in Figure 4.20 where the cross range trajectory case study previously studied is simulated such that dust obscures the astronauts' out the window view at an altitude of 100 ft. This corresponds to deactivating the visual cues in the model at this point in time.

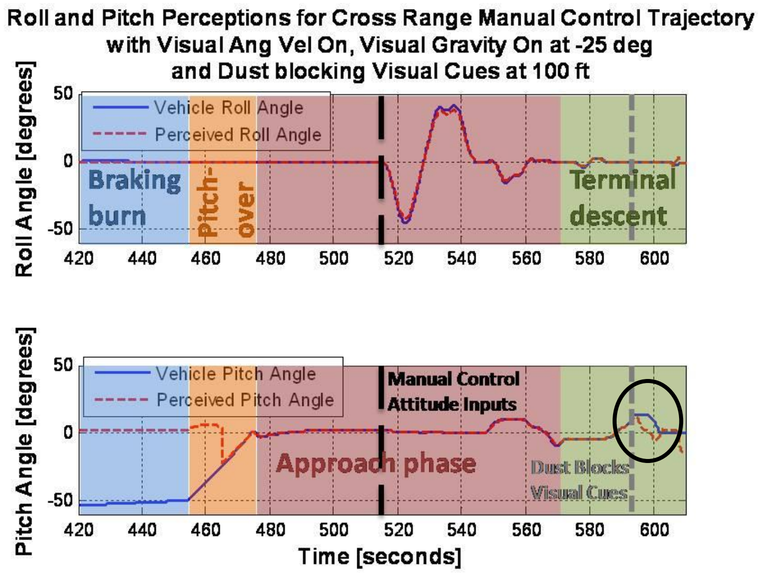

Figure 4.20: Roll and Pitch Perception for Cross Range Manual Control Trajectory with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees, Then All Visual Cues off at an Altitude of 100 feet

The perceptions seen in Figure 4.20 are the same as those shown in Figure 4.17 up until the point when the dust blocks the visual cues (as indicated by the grey dashed vertical line). In Figure 4.17, where dust is not simulated the perceptions are very accurate during the final portions of the descent and landing, however here there are minor deviations. These deviations primarily occur in the pitch angle perceptions, since this is how the vehicle is tilted away from vertical. The misperception is typical of the cases where visual cues are deactivated; the tilt angle is underestimated due to the somatogravic illusion shown in Figure 4.2. This misperception is fairly small since the dust is simulated to not obscure the horizon until the descent reaches an altitude of 100 ft. While the 100 ft mark was set as the assumed altitude of dust initiation, based upon the approximate average height where dust began, in some cases dust was seen to occur even higher. On Apollo 12, dust obscuring visual cues was first reported at 200 ft. This is simulated in Figure 4.21 for the automated baseline Trajectory A.

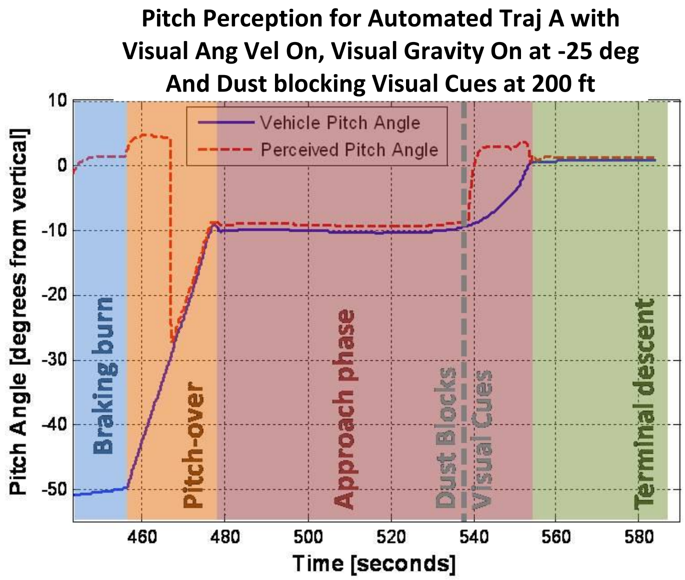

Figure 4.21: Pitch Perception for the Automated Trajectory A with Visual Angular Velocity Cue on and Visual Gravity Cue on at -25 Degrees, Then All Visual Cues off at an Altitude of 200 feet

Contrasting Figure 4.21 with Figure 4.19 where the dust is simulated at 100 ft, it can be seen that the increasing the dust height to 200 ft has a significant influence on perceptions. In this case, with the dust occurring at a higher altitude, the vehicle is not yet completely upright. At this off-vertical attitude, the perception of being nearly upright results in significant misperceptions of actual vehicle orientation. Thus it is possible for misperceptions to occur, even for the steady automated baseline Trajectory A to occur if the dust obscures visual cues at higher altitudes. Similar effects can be seen for the LP redesignation and manual control trajectories.

4.3 Ames Vertical Motion Simulator Experiment

The Ames VMS was used as a motion base simulator to study subjects' perceptions of motion during maneuvers similar to those experienced during lunar landing. A summary of those results are given here. In pre-experimental testing subjects were seen to generally be able to use the indicators to report orientation information effectively. For tilt estimation during landing trajectories, there was significant variability between subjects and between trials. The subjects generally perceived the vehicle as nearly upright for the eyes closed treatment, which is in agreement with the somatogravic illusion predicted by the Observer model. For the eyes out the window treatment, subjects' perceptions tracked the actual tilt angle, but still with significant errors. With the eyes on the displays, subjects performed their best in perceiving tilt. For roll angle the differences between treatments were not significant, while for the pitch angle there were significant differences between the eyes closed and eyes out the window cases when compared with eyes on the displays. The horizontal velocity perception depended on the inclusion of visual cues. The fractional error time for the magnitude perceptions was seen to be significantly different between each of the three treatments with the smallest errors seen in eyes on the displays followed by eyes out the window. Velocity direction perception depended on how large the velocity was as well as how quickly the direction was varying. Large direction perception errors were seen in all treatments during the final stages of landing when the horizontal velocity becomes very small. However, over the time course of the trajectory the MSE was significantly improved between eyes closed to eyes out the window to eyes on the displays.

4.3.1 Baseline Pre-Experimental Tracking Data

Prior to the motion perception experiment in the motion based simulator, subjects were trained and tested on their ability to use the tilt angle indicator and horizontal velocity indicator to track the motion of the display instruments in a fixed based scenario. In general, subjects were seen to effectively use the indicators to track the display instrument motions. Subjects tracked roll and pitch accurately though three of eight subjects employed pitch gains which were significantly greater than one and all of the subjects were seen to lag behind the actual roll angle by 1-2 seconds. Additionally, for tilt tracking subject 5 performed abnormally poorly in terms of MSE over the course of each trial. Horizontal velocity tracking was divided in direction and magnitude. The direction was fairly well tracked though subject 5, and to a lesser extent subjects 2 and 4, performed substantially worse in terms of MSEs over the time course of each trial compared to the other subjects. Horizontal velocity magnitude was tracked discretely as described in Sections 3.2.4.3 and 3.2.4.5 and resulted in a range of magnitude perceptions. The time during each trial in which the actual magnitude was not bounded by the perception ranges was recorded and presented as a fraction of the total time of the trial. It was seen that the perception ranges tracked the actual magnitude quite well, with all of the subjects performing at a similar level.

4.3.1.1 Tilt Angle Tracking Data

In general all of the subjects were able to track the pitch and roll motion of the pitch ladder effectively, however with small errors. An example of a single testing run is seen below in Figure 4.22 and Figure 4.23.

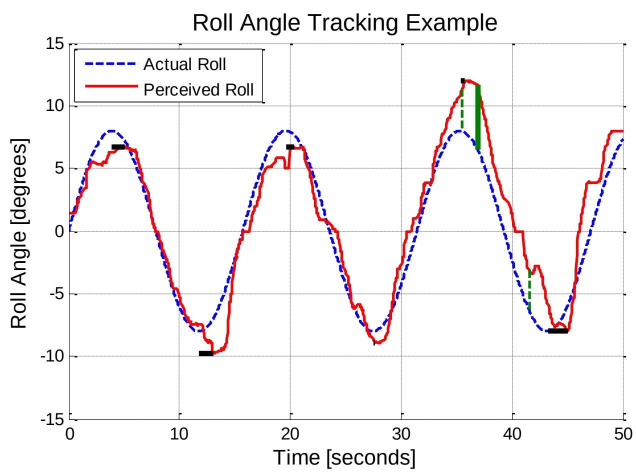

Figure 4.22: Roll Angle Tracking Example

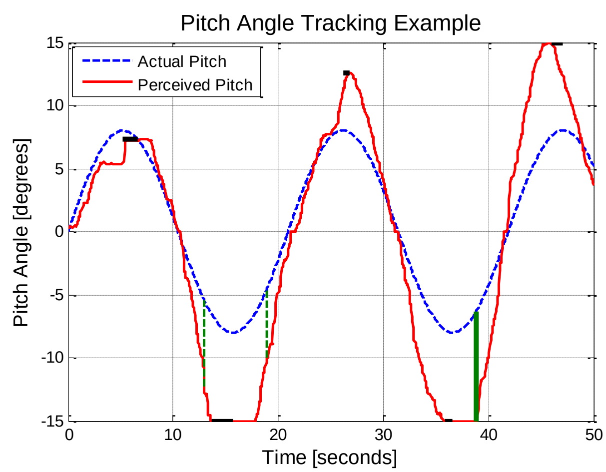

Figure 4.23: Pitch Angle Tracking Example

The pre-experimental tilt angle tracking data seen in Figure 4.22 and Figure 4.23 is the third trial for subject 1002 and is fairly representative of the tracking seen during each of the other trials for other subjects. Figure 4.22 shows the actual roll angle on the pitch ladder graphic as a time history as well as the subject's reported roll angle using the tilt angle indicator. It should be noted that for roll, negative angles correspond to the display showing a vehicle roll to the left which requires moving the tilt indicator to the right while positive angles are vice versa. Also for pitch, negative angles correspond to the display showing the vehicle pitched back (pitched nose up) which requires tilting the stick forward (pitch down). The maximum instantaneous square error between actual and reported roll angle is denoted as a solid vertical green line. In this particular trial this occurs at approximately 36 seconds. In addition the range of the maximum running MSE with a window size of ±3 seconds is denoted by the vertical dotted green lines. In this example, this occurs from approximately 35 to 41 seconds. Finally the leads or lags (phase shifts) between the actual and reported roll angle peaks are denoted by horizontal black bars. Identical nomenclature is used in Figure 4.23 for the pitch angle. Notice that in this case the maximum instantaneous square error does not occur during the window of the maximum running MSE.

In general the roll angle is well reported over the time course seen in Figure 4.22. The pitch angle is also generally well reported, though there is significant over estimation of the peaks. To approximate the overall performance reporting tilt angle for each subject's practice trial and three testing trials, the MSE between actual and reported angles was computed for each run. These are shown as box plots by each subject in Figure 4.24. Note that the first five seconds of each trial were removed from the data set because it may have taken the subject a short period of time to respond to the initiation of the task. Also during this pre-experimental testing phase some of the subjects had issues with direction confusion in which they would occasionally respond to a tilt by moving the tilt angle indicator in the opposite direction before realizing the mistake and correcting. As these mistakes usually occurred infrequently and resulted in unrepresentatively large errors, the trials in which direction confusions occurred were removed.

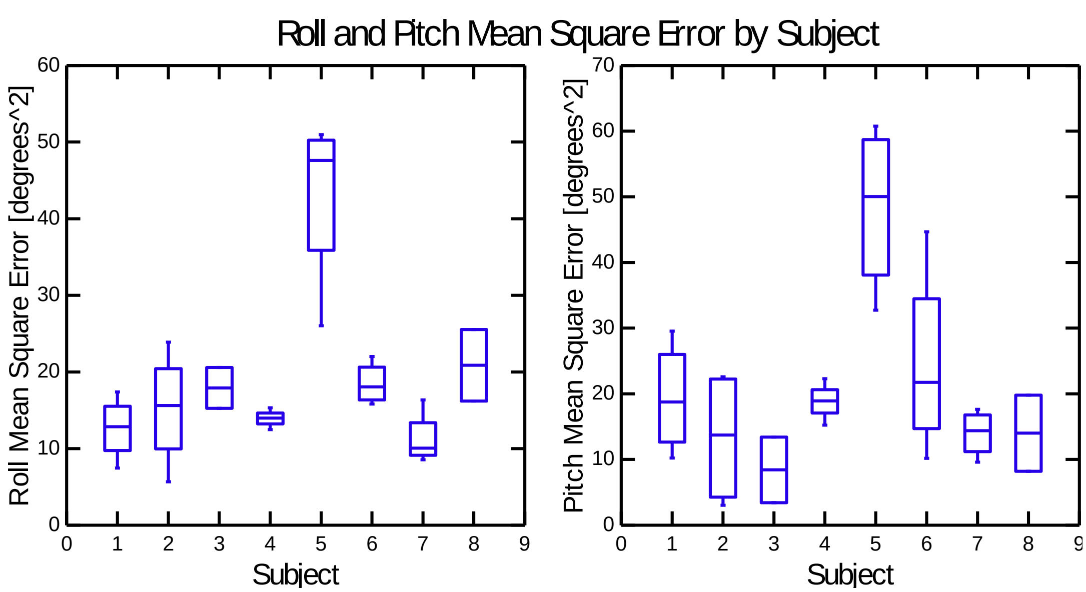

Figure 4.24: Roll and Pitch Mean Square Error by Subject

It can be seen that the MSEs for each trial are generally fairly small (10-20 degrees^2). The exception is subject 5, which appears to report significantly worse (larger MSEs) than the other subjects in both pitch and roll. For more detailed analysis the gain, bias, and phase were calculated of the reported angles relative to the actual angles. This was done as an average over the time course of each trial.

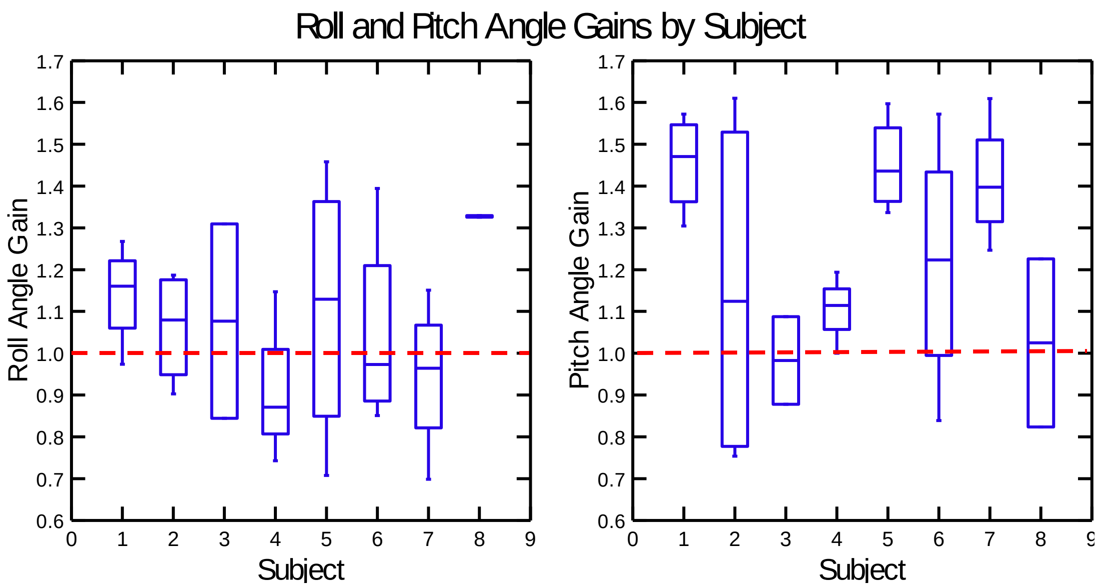

Figure 4.25: Roll and Pitch Angle Gains by Subject

The gain for ideal tracking is one. As seen in Figure 4.25, the roll gains are all fairly close to one except for subject 8. Subject 8 had two of the four trials removed for direction confusion errors, thus there were only two trials from which to calculate gain metrics from and this may have caused the inconsistency of this subject as compared to the other seven subjects seen in Figure 4.25. Other than subject 8, the other subjects all had median gains near one and at least one of their trials on either side of one. Performing a hierarchical mixed regression on the roll angle gain normalized about zero with the fixed effect as the trial number, it was seen the normalized roll angle gain was not statistically significantly different than zero (p=0.693) and thus the roll angle gain was not different than one. Additionally the effect of the order was not statistically significant (p=0.414), supporting the assumption that subjects were not still learning how to operate the tilt angle indicator during the trials.

The pitch reporting, however, resulted in gains which were inconsistent between subjects. Subjects 2, 3, 4, 6, and 8 all appear to have at least one trial on either side of the neutral gain of one, however subjects 1, 5, and 7 all have pitch gains consistently in the 1.4-1.5 range. Despite these three abnormal subjects, performing a hierarchical mixed regression on the pitch angle gain normalized about zero with the fixed effects as the trial number, it was seen that the normalized pitch angle gain was not statistically different than zero (p=0.113), and thus the pitch angle gain was not different than one. Additionally the effect of order was not statistically significant (p=0.991), supporting the hypothesis that subjects were not still learning how to operate the tilt angle indicator during the testing trials. If, however, subjects 1, 5, and 7 are taken an a subpopulation of subjects who have a pitch gain of approximately 1.4-1.5 then the normalized pitch angle gain for these subjects is statistically different than zero (p=0.000), and thus the pitch angle gain was different for one for this subset of subjects. Thus there might be two separate populations of subjects, one which has a pitch gain different than one (approximately 1.4-1.5) and another which has a pitch gain that isn't different one. One potential source of the differences seen between roll and pitch gains is the feedback provided in each case. While the subjects are provided with the roll and pitch angles they are supposed to track from the pitch ladder display, the display provides no information what roll and pitch angles are being reported. The only source of this information is in the physical location of the tilt angle indicator sensed through proprioceptive and visual channels. Visually it is fairly easy to see what roll angle the indicator is at since this angle is in the plane perpendicular to the subject's line of sight, while the pitch angle must be inferred from judgments of depth perception, which might be less reliable. This can be seen in Figure 4.23, where the direction of pitch angle is accurately reported, but the magnitude is often over estimated. The roll and pitch angle biases for each subject are given in Figure 4.26.

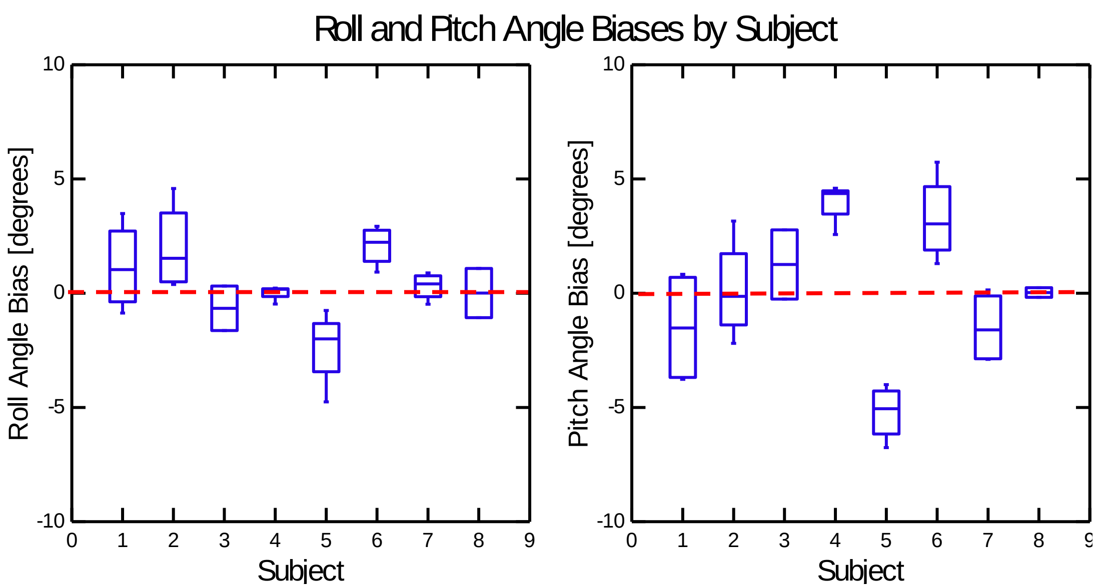

Figure 4.26: Roll and Pitch Angle Biases by Subject

As seen in Figure 4.26, the roll and pitch angle biases for each subject are generally small (<5 degrees). Subject 5 is seen to have the largest bias for both roll and pitch in terms of magnitude. Performing a hierarchical mixed regression with the trial number as the fixed effect found the roll angle bias to be consistent with zero (p=0.769), will the effect of the trial number was not significant (p=0.764). Performing the same test for pitch angle bias found the result to be consistent with zero (p=0.875) and the trial number to not be significant (p=0.888). The time delays for roll and pitch angle are seen by subject in Figure 4.27.

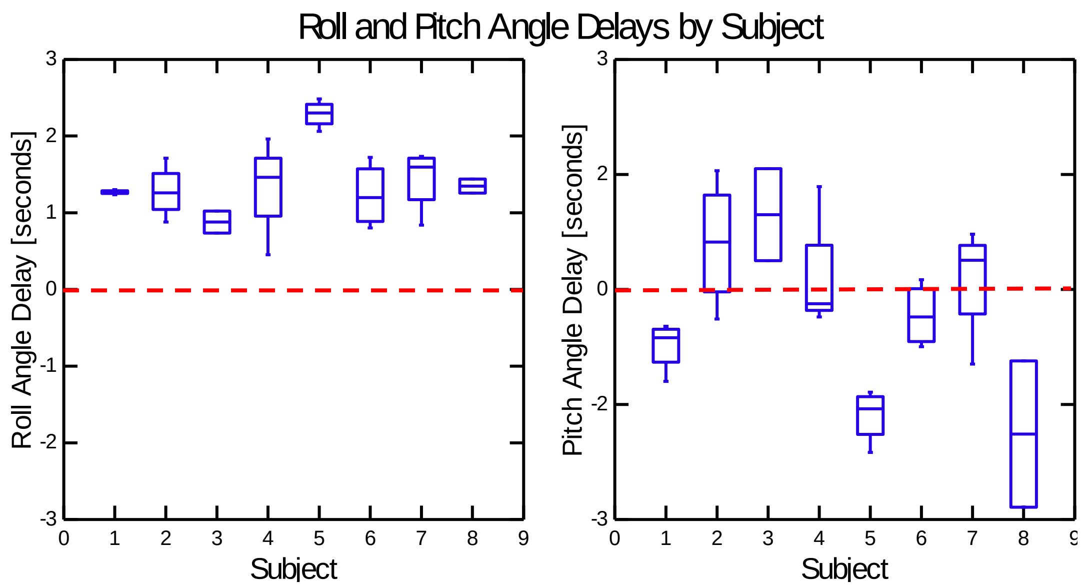

Figure 4.27: Time Delays for Roll and Pitch Angle by Subject

Positive time delays correspond to the reported angle lagging behind the actual angle, while negative delays correspond to the reported angle leading the actual angle. As seen in Figure 4.27, while the reported pitch angles seemed to be well dispersed between leading and lagging the actual angles, every subject reported roll angles which lagged behind the actual roll angle. Generally this lag was between one and two seconds though subject 5 appears to lag behind more than two seconds. Using a hierarchical mixed regression test with the trial number as the fixed effect, the pitch angle time delay the intercept was not statistically different from zero (p=0.527) and the effect of the trial number was not statistically significant (p = 0.968). However, the roll angle time delay was statistically different from zero (p = 0.000) while the effect of the trial number was not statistically significant (0.603). While the roll angle tracking did have a statistically significant time delay, this is not particularly surprising. Most manual control or tracking tasks have been seen to have a time delays in the response when the tracking target was not predictable as was the case here. The time delay for the roll angle, while nonzero, was still relatively small (median = 1.570 grouping all subjects). The pre-experimental testing data helps validate the tilt angle indicator was a useful device for the subjects to report tilt angle information. In general, the MSEs for roll and pitch were fairly small with the exception of subject 5. This subject also had the largest biases for both pitch and roll reporting. The gain of the reported to actual angles was generally near one though there was a subset of subjects (1, 5, and 7) which consistently overestimated pitch angles. The time delays were centered about zero for the pitch angle reporting, but all subjects were seen to lag behind the actual angle in roll. While this lag was statistically significant, it was relatively small (1-2 seconds).

4.3.1.2 Horizontal Velocity Tracking Data

Subjects were seen to be fairly effective in tracking the horizontal velocity and magnitude. Occasionally subjects would make significant direction errors or lose track of the magnitude range. This would result in extended errors in the range followed by a realization the range was being indicated incorrectly and a recovery response. Often, subjects would focus on one of the two tasks (either direction or magnitude estimation) and ignore the other for an extended period of time. An example of a test run for horizontal velocity tracking is seen in Figure 4.28 and Figure 4.29.

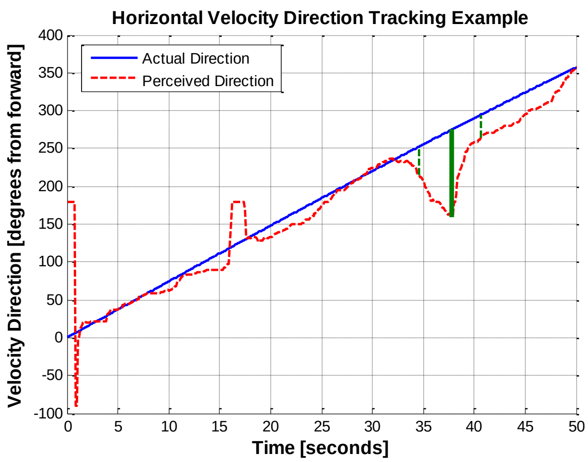

Figure 4.28: Horizontal Velocity Direction Tracking Example

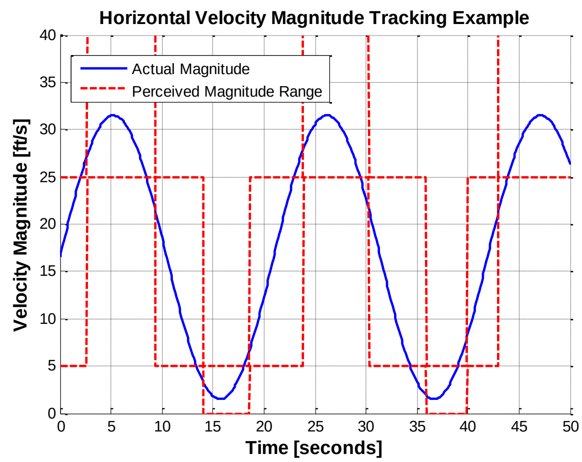

Figure 4.29: Horizontal Velocity Magnitude Tracking Example

As seen in Figure 4.28 and Figure 4.29, the horizontal velocity direction varied linearly going around the display while increasing and decreasing in magnitude sinusoidally. Generally the direction was well tracked, though significant errors developed at times. The maximum error is indicated with the solid vertical line while the largest running MSE (±3 seconds) time period indicated by the dotted vertical lines. The magnitude is fairly well tracked with the perceived magnitude ranges. The dotted boxes indicate the minimum and maximum velocities for the range indicated. For example indicating the medium speed would have a maximum of 25 ft/s and a minimum of 5 ft/s. Thus the errors occur during transitions and are measured by the time in which the actual magnitude is not correctly bound by the perceived magnitude range. The maximum square error and MSE over the entire trial are shown in Figure 4.30 grouped by subject. The box plots consist of the single practice trial and three test trials.

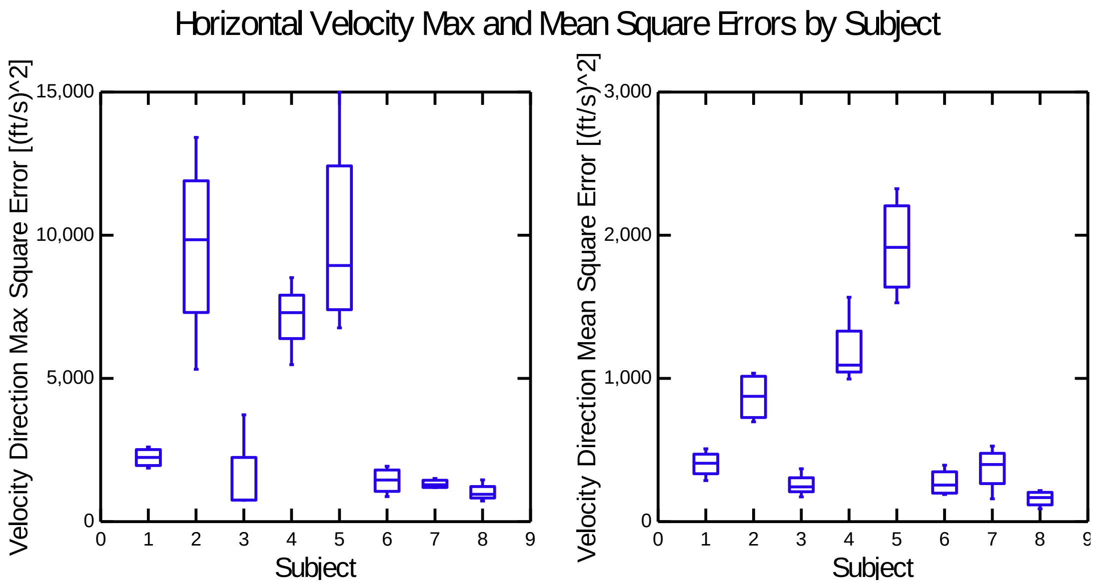

Figure 4.30: Horizontal Velocity Direction Max and Mean Square Error by Subject

It can be seen that most of the subjects were consistently accurate in the tracking of direction and the result is minimal square errors as seen in Figure 4.30. However subject 5, and to a lesser extent subject 2 and 4, were less accurate than the rest of the subjects. In particular, in the direction MSE which is a measure of how well the direction as tracked over the entire time course of the trial, subject 5 performed far less accurately than the remaining subjects.

The magnitude tracking task was analyzed by the fraction of the time in which the actual magnitude was not bound by the perceived magnitude range divided by the total time of the trial. For the pre-experimental tracking task, the velocity magnitude was constantly varying, switching perceived magnitude range nine times during each 50 second trial. Thus it might be reasonable to expect very high fractional errors. The velocity magnitude fractional errors are seen in Figure 4.31 by subject for the practice trial and three testing trials.

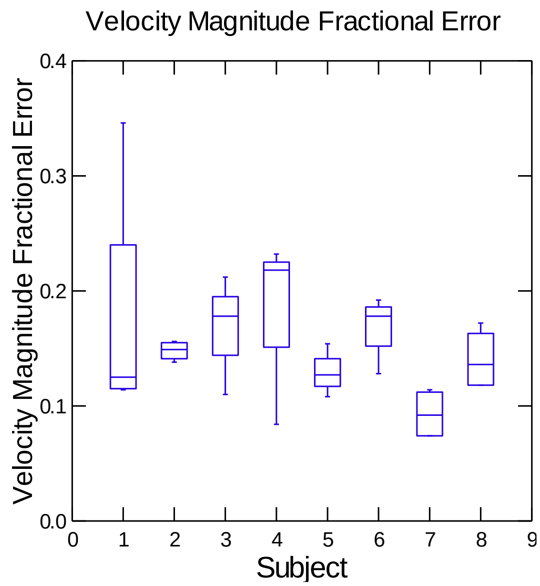

Figure 4.31: Horizontal Velocity Magnitude Fractional Error by Subject

The horizontal velocity magnitude fractional errors are fairly small and generally in the range of 0.1 to 0.2. Additionally it can be seen that most subjects were nearly equally effective in tracking the magnitude, at least compared to the direction tracking where certain subjects performed far worse than the group average.

4.3.2 Comparison of Vestibular, Eyes Out the Window, Eyes on the Display

4.3.2.1 Tilt Angle Perception

An example tilt angle estimation trial is given in Figure 4.32. The trial is for Subject 1 in the eyes closed condition, which is representative of most of the eyes closed trials across all subjects. The pilot was operating the simulator in the RCAH mode for approach and TRCPH for terminal descent with no guidance. This was the seventh consecutive trial done in this control mode and guidance combination.

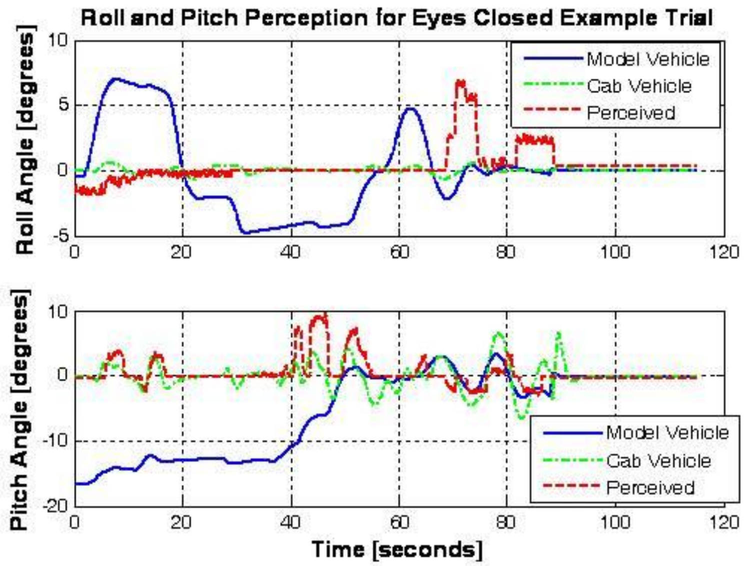

Figure 4.32: Roll and Pitch Perception for Eyes Closed Example Trial

In Figure 4.32, the solid blue line shows the actual orientation of the vehicle as determined by the mathematical model of the vehicle and its dynamics. The dot-dashed green line is the actual orientation of the vehicle cab. This is determined by the mathematical model and the commands issued by the simulator motion drive system. For a more detailed discussion of the vehicle cab motion see Section 5.2.3. Finally, the dotted red line is the perceived orientation of the vehicle as reported by the subject. As described in Table 3.5 and seen in the solid blue line of Figure 4.32, the model vehicle is initially oriented at 16 degrees pitched back and upright in roll. During the time course of a trajectory, the pilot will slowly pitch the vehicle upright and keep it near upright until touchdown. Since the vehicle starts with a cross-range offset with respect to the landing zone the pilot rolls the vehicle to the right (positive roll) to create a cross-range velocity then rolls back to the left (negative roll) to null that velocity out. Despite these significantly large roll and pitch maneuvers, the blindfolded subject perceived the vehicle to be nearly upright for the majority of the trajectory. This was typical of most trials across subjects. Despite the large errors in perception in comparison to the model vehicle, the orientation of the actual cab was perceived fairly accurately. The smaller roll and pitch motions of the cab were tracked fairly well, at least in direction and approximately in phase. This was also typical of most trials across subjects.

An example representative trial for eyes out the window is given below, also for Subject 1. For this trial the pilot was operating the simulator in RCAH mode in approach and TRCPH for descent with attitude guidance. This is the third trial flown in this configuration.

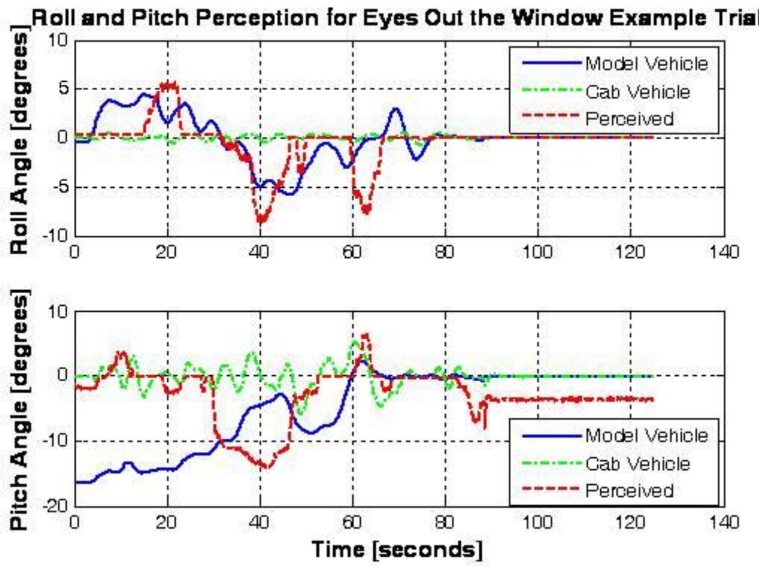

Figure 4.33: Roll and Pitch Perception for Eyes Out the Window Example Trial

Figure 4.33 shows similar, but unique, motions flown by the pilot as those given in Figure 4.32 for the eyes closed example trial. Here the subject generally does better at perceiving the model vehicle orientation. The first right and then left roll motions are at least perceived, though not well tracked. The initial pitched back orientation is not initially accurately perceived, however in the eyes out the window case, the pitched back orientation is eventually acknowledged prior to the vehicle coming upright. This was typical of most subjects' perception in the eyes out the window case. Some subjects, however, were seen to be better at using visual out the window information to perceive orientation and this was seen in how closely perceptions followed model vehicle orientations. Some of these subjects had a tendency to overestimate roll and pitch angles in the eyes out the window case. Subjects typically accurately perceived the roll and pitch velocities and direction of motion, however in many cases did not accurately perceive the absolute magnitude of the roll and pitch. This was particularly the case in pitch. The orientation perceptions generally more closely follow the model vehicle orientation than the cab vehicle orientation. This is due to the visual out the window view being driven by the model vehicle orientation.

An example trial for the eyes on the display case is seen for Subject 1 in Figure 4.34. Here the pilot was operating the simulator in RCAH for the approach and TRCPH for the descent while using velocity guidance. This was the second time this combination had been seen.

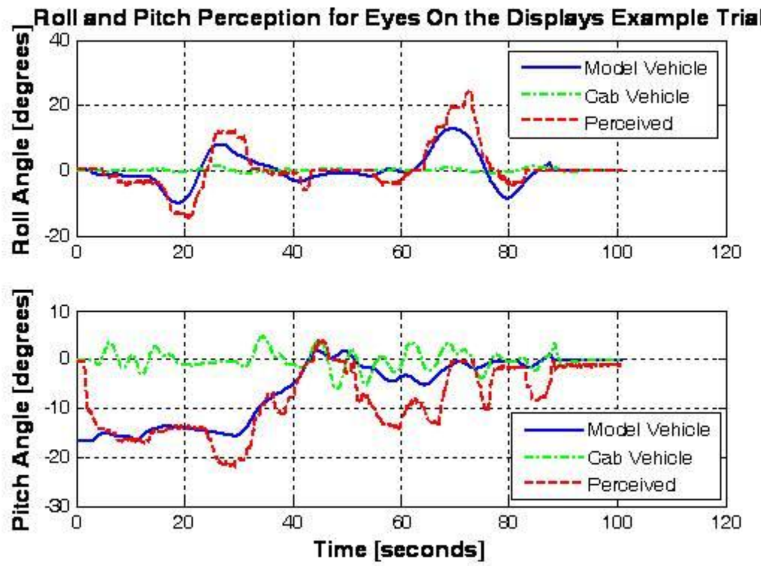

Figure 4.34: Roll and Pitch Perception for Eyes on the Displays Example Trial

The Eyes on the Displays case yields the best perceptions of model vehicle tilt angle. Other than the first few seconds when the simulation begins, the model vehicle roll and pitch angles are well tracked by the subject's perceptions. This is likely due to a delay in the subjects' response to the simulation initiation and therefore the first 5 seconds of each trial are ignored in further analysis. In a few cases during the trajectory the pitch angle perceptions are qualitatively similar to the actual model vehicle angles; however the perceptions are overestimations of the actual angle. This is equivalent to having a gain greater than one between model vehicle pitch and subject pitch perception. The perception angles follow the model vehicle orientation, which drives the instrument displays, more closely than the cab vehicle orientation. The exception to this is when the cab vehicle orientation is very similar to the model vehicle orientation. The accurate perception of model vehicle orientation was seen for most subjects across trials in the eyes on the display case.

To allow for gross comparison of performance between perceptions made in eyes closed, eyes out the window, and eyes on the displays, the maximum running MSE (±3 seconds) was recorded for each trial. The errors calculated here were for the perceptions compared to the model vehicle orientation. The first 5 seconds of each trial were ignored for these calculations. This was done to avoid any effects of the simulation beginning that influence subjects' perception indications.

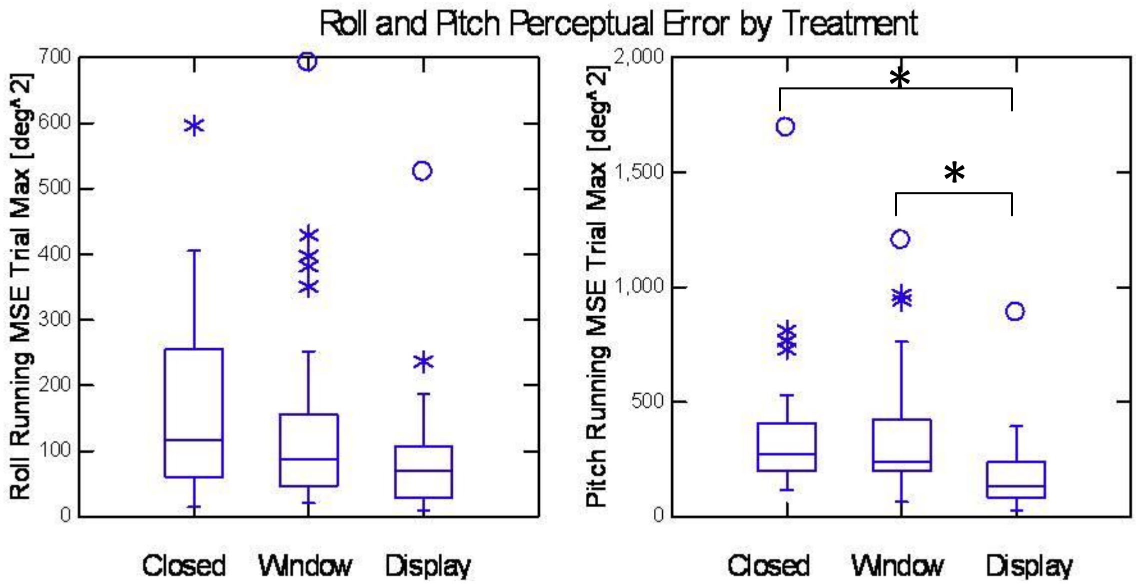

Figure 4.35: Roll and Pitch Running Mean Square Error Trial Max Values by Treatment Condition

The running MSE trial maximums are shown for roll and pitch for each of the treatments in Figure 4.35. In all three treatments for both roll and pitch there are a number of outliers. This is partial due to the fact that the metric used here was the maximum running MSE achieved during a particular trial. Thus a very large value could be obtained by a single short period of large misperception. Despite this, it can be seen that the eyes closed case generally results in the largest misperceptions, with the eyes out the window only improving perception slightly, and the eyes on the display case generally creating the smallest misperceptions. A series of one-sample t-tests were performed on the within-subject differences to test the hypotheses that there are differences between each of the treatments in running MSE trial maximums. This was done for both roll and pitch and the results are seen in Table 4.3. It should be noted that one-sample KS tests were performed to ensure the differences are normal prior to performing the t-tests. It was seen that all of the data studied here was normally distributed.

Table 4.3: Statistical Results of Running MSE Trial Maximum between Treatments for Roll and Pitch

	Roll Running MSE Trial Max	Pitch Running MSE Trial Max
Closed vs. Window	p=0.575	p=0.691
Window vs. Display	p=0.156	p=0.016*
Closed vs. Display	p=0.057	p=0.014*

It can be seen that for roll there was no statistically significant difference between each of the three treatments, though the difference between eyes closed and eyes on the displays is nearly significant. In pitch, there was a statistical difference between the eyes out the window and eyes on the displays treatment cases as well as between the eyes closed and eyes on the displays cases. Thus for pitch, perceptions were significantly better when the displays were used to perceive tilt. This is in accordance with the example trials shown in Figure 4.32, Figure 4.33, and Figure 4.34. In general the pitch misperceptions were greater than the roll. This could have been caused by a variety of factors. The pitch angle varied more drastically during the trajectory, particularly at the beginning of the trajectory when the model vehicle was pitched back by 16 degrees. Since the metric used here is a measure of absolute error, it is likely that it would be greater for larger vehicle motions. As discussed in Section 5.2.1, the visual pitch cue in the eyes out the window treatment is more ambiguous in absolute value than the roll cue. Finally, it was seen during pre-experimental testing that some subjects had gains in reporting pitch angle that were significantly larger than one (1.4-1.5) and this may have played a role.

4.3.2.2 Horizontal Velocity Perception

An example horizontal velocity trial is given in Figure 4.36 for Subject 1 in the eyes closed condition, which is representative of most of the eyes closed trials across all subjects. In this particular trial the pilot was operating the simulator in the RCAH mode for approach and TRCPH for terminal descent with attitude guidance. This was the second consecutive trial done in this control mode and guidance combination.

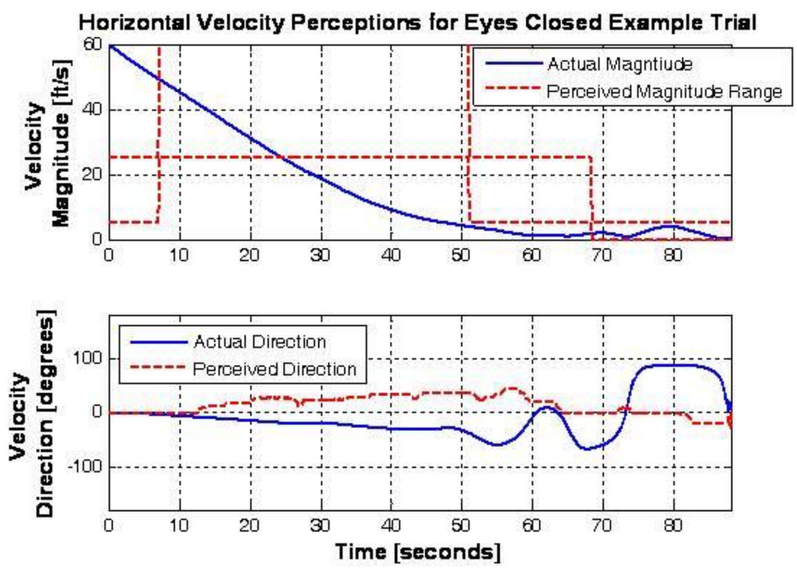

Figure 4.36: Horizontal Velocity Magnitude and Direction Perception for Eyes Closed Example Trial

In the eyes closed case, the subjects' perception of velocity was highly inaccurate. Magnitude perceptions rarely tracked the actual magnitude consistently. Subjects often reported not being able to tell whether or not they were moving and as a result "guessing" what their velocities were based on previous trials. This can be seen in the example case of Figure 4.36. The subject had realized that during the time course of each trial, the horizontal velocity routinely decreased from high to medium to low. Thus despite no true perception of horizontal velocity magnitude, the subjects often was able to estimate the general trend of the magnitude. While the subject used the trends from previous trials to estimate when the speed transitions occurred, they were often very poorly estimated since no perceptual cues were used. The direction perceptions were equally poorly estimated. The subjects were not as capable of using the trends from previous trials to estimate the direction since the cross range offset varied between runs either being to the left or right of the landing point. Thus subjects usually reported their actual perceptions, and these varied significantly with respect to the actual direction as seen in Figure 4.36. Particularly during terminal descent when the actual direction of horizontal velocity would vary drastically, the subjects were generally unable to track accurately with their perceptions.

An example trial for the eyes out the window condition is given in Figure 4.37 for Subject 1, which is representative for this condition. For this trial the pilot was operating in RCAH for approach and TRCPH for descent with no guidance provided. It was the second trial in which this control mode and guidance combination were presented.

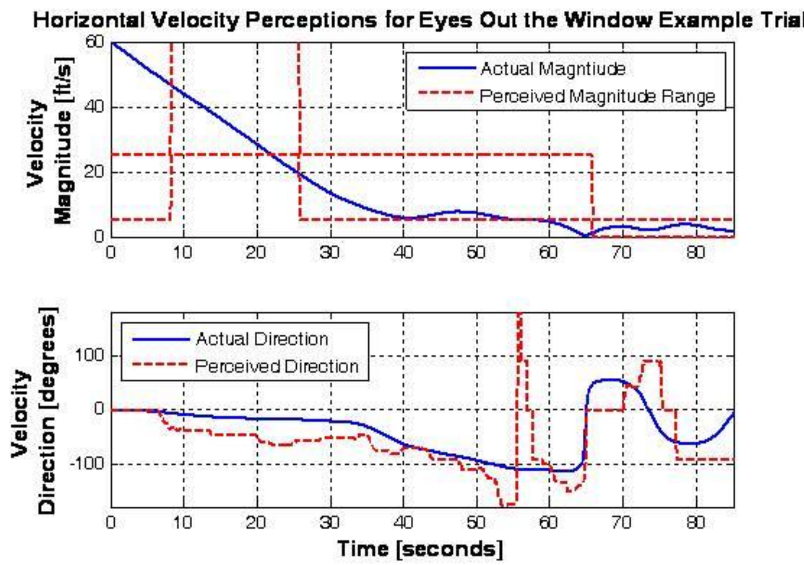

Figure 4.37: Horizontal Velocity Magnitude and Direction Perception for Eyes Out the Window Example Trial

The horizontal velocity perception were vastly improved for the eyes out the window trials compared to the eyes closed. In general, the subjects were able to accurately track the velocity magnitude. The error at the beginning of the trial was characteristically seen and corresponds to the subject's delay in remembering to use the thumb indicator for velocity magnitude perception at the beginning of each trial. For this reason the initial 10 seconds of each trial are ignored. The longer time than the 5 seconds normally used was required for many of the trajectories to account for the subject's response delays. Following this portion, the perceptions of velocity magnitude are fairly accurate. There are still misperceptions between when the actual transitions between magnitude ranges occur and when those changes are perceived and reported by subjects. However these errors are usually less than five seconds and result in maximum magnitude errors of around 5 ft/s. This is vastly improved compared to the eyes closed case seen in Figure 4.36 where the errors would persist for 25 seconds and error in magnitude by as much at 20 ft/s. The velocity direction perception also is improved, though sizable errors persist. While the perceptions generally track the actual direction, this is not done accurately. In particular, during the terminal descent when the velocity direction rotates in direction significantly, the perceptions become less accurate. At approximately 55 seconds there appears to be a significant error, however the large jump in the direction perception is due to the convention of having "backward" being the transition point where the direction is either -180 degrees of 180 degrees. Thus rotating through this direction causes the appearance of an asymptote in the plot. This direction perception quickly returns to relatively accurate tracking of the actual direction in a few seconds.

Figure 4.38 shows velocity perception for the eyes on the displays example trial for Subject 1. The pilot was operating the simulation in the RCAH approach mode with TRCPH terminal descent mode with no guidance. This was the third time that this guidance and control mode combination was presented.

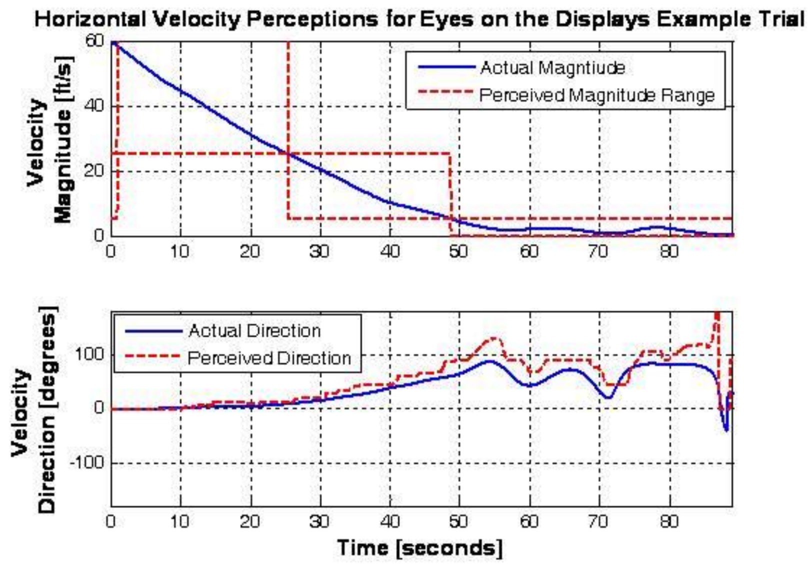

Figure 4.38: Horizontal Velocity Magnitude and Direction Perception for Eyes On the Displays Example Trial

The eyes on the displays case resulted in the best perceptions of the horizontal velocity. In particularly the transitions between magnitude ranges were perceived very precisely since the exact digital read-out of the horizontal speed was provided. The only errors seen were the result of poor monitoring of the speed. The velocity direction perception was improved over the other two cases. However, small errors still persisted. The subjects were generally able to perceive the change in the velocity direction and make the corresponding inputs in the velocity indicator, however often this resulted in steady offsets as seen in Figure 4.38. As the error progressed to a large enough value, particularly if it transitioned between quadrants (ie. forward and to the left vs. backward and the left), this would result in a sudden corrective stick input.

For each trial, the magnitude perception was quantified by calculating the fraction of the trial for which the perceived magnitude ranges bounded the actual magnitude. In the calculation of this metric, the first 10 seconds of each trial were ignored because subjects often failed to remember to use the magnitude indication button right as the trial begins. An example of this can be seen in Figure 4.37 where the subject accidently indicates a medium velocity for approximately the first 9 seconds of the trial. The velocity magnitude fractional error is seen for the three treatments in Figure 4.39.

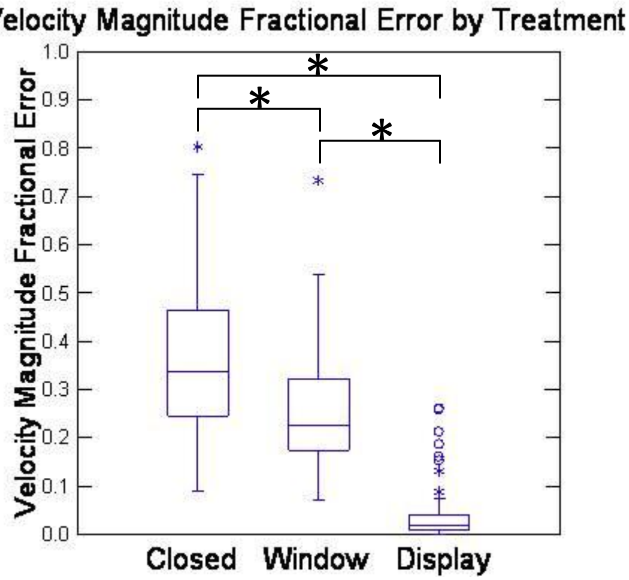

Figure 4.39: Velocity Magnitude Fractional Error for each Trial by Treatment

As seen in Figure 4.39, the eyes out the window case appears to improve the velocity magnitude perceptions over the eyes closed case while the eyes on the display case appears to improve perceptions over the eyes out the window case. To test each of these hypotheses, one-sample within-subjects t-tests were performed on the mean differences between treatments for each subject. These results can be seen in Table 4.4. It should be noted that one-sample KS tests were performed on the data to ensure normality prior to performing the t-tests. All data were seen to be normally distributed.

Table 4.4: Statistical Results of Velocity Magnitude Fractional Error between Treatments

	Velocity Magnitude Fractional Error
Closed vs. Window	p=0.021*
Window vs. Display	p=0.000*
Closed vs. Display	p=0.000*

Table 4.4 shows that for the metric of fraction of time in which the actual velocity magnitude was not bound by the perception range, significant differences can be seen for each of the treatments. The smallest differences were between the eyes closed case and eyes out the window case, in which many subjects struggled to perceive velocity magnitude accurately, even with visual cues from looking out the window. In the eyes on the displays case where a digital readout of speed was provided, the velocity magnitude was significantly better tracked than in either of the other two treatments. The only errors when using the display were due to subjects over focusing on tracking the velocity direction and failing to allot attention resources to the velocity magnitude.

A variety of metrics were used to study the velocity direction. For all of these analyses, subject 5 was removed from the subject pool. This was done because of the poor velocity direction tracking during pre-experimental testing seen in Figure 4.30, as well as abnormal perceptual responses seen during experimentation. Maximum instantaneous square errors were calculated for each trial, however it was seen that nearly every trial had at least one very large instantaneous error even when accurate tracking was seen for the remainder of the trial. Generally these large instantaneous misperceptions in velocity direction occurred late in the trajectory when the velocity magnitude was very small. Additionally, a similar metric as was used for the roll and pitch perception was attempted here. A running mean MSE of ±3 seconds was computed over the duration of each trial, again ignoring the first 5 seconds. The maximum value that the running MSE obtained for each run was recorded as a metric for the accuracy of velocity direction perception. This was done over the entire trial as well as for the terminal descent portion of the trial. The terminal descent portion of the trajectory is studied here because it is during this portion of the descent when the astronaut is tasked with nulling out the horizontal velocity if the vehicle is in a manual control mode. Misperceptions in direction could result in incorrect control motions. The terminal descent portion was defined as the portion after which the horizontal velocity dipped below 5 ft/s. The 5 ft/s mark was defined because it was the point at which the flying pilots were recommended to transition to the terminal descent control mode for the trials in which this was possible. The running MSE maximum metric for velocity direction perception was equally large when considering the entire trajectory as it was for the just the terminal descent portion of the trajectory. Thus the metric for the terminal descent is the only one included in Figure 4.40.

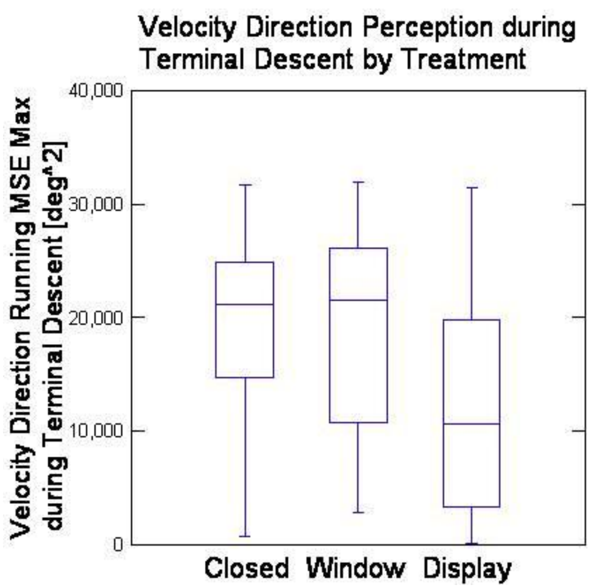

Figure 4.40: Velocity Direction Running MSE Max during Terminal Descent for each Trial by Treatment

As seen in Figure 4.40, the velocity direction misperceptions can become very large during terminal descent across all of the treatments. This is the result of the magnitude becoming very small during portions of terminal descent. A very small magnitude makes perception of direction of magnitude increasingly challenging even in the eyes out the window and eyes on the displays treatment cases. Thus a more general metric was used to study the effect of different treatments on velocity direction perceptions. The MSE of the velocity perceptions over the entire time course of the descent was calculated for each trial. Again the first 5 seconds were ignored to eliminate any effects due to the simulation beginning. These results are given in Figure 4.41 for each treatment.

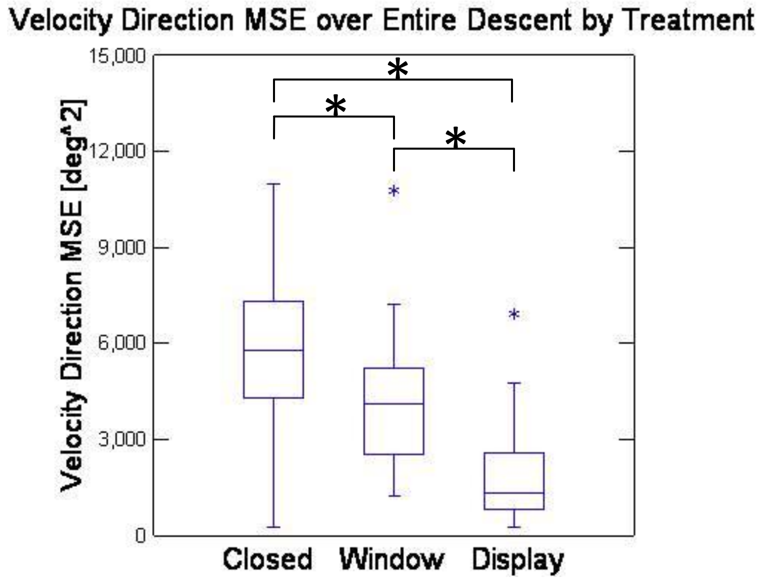

Figure 4.41: Velocity Direction Mean Square Error over Entire Descent by Treatment

While there is significant variability across subjects and trials, Figure 4.41 shows that the eyes out the window improves velocity direction perceptions for the metric of MSE over the entire descent. Similarly the eyes on the display treatment appears to result in less misperception than both the eyes out the window and eyes closed treatments. To test each of these hypotheses, one-sample within-subjects t-tests were performed on the mean differences between treatments for each subject. These results are seen in Table 4.5. It should be noted that one-sample KS tests were performed on the data to ensure normality prior to performing the t-tests. All data were seen to be normally distributed.

Table 4.5: Statistical Results of Velocity Direction Mean Square Error between Treatments

	Velocity Direction MSE
Closed vs. Window	p=0.024*
Window vs. Display	p=0.004*
Closed vs. Display	p=0.004*

In Table 4.5, each of the differences between treatments is statistically significant for velocity direction perceptions using the MSE metric.

4.3.3 Comparison to the Observer Model Predictions

For tilt, the reported perceptions are directly compared to Observer model predictions for the eyes closed and eyes out the window example trajectories. This is done by providing the Observer model inputs from the VMS trajectory's mathematical model of vehicle motion. Thus the motions the VMS is attempting to simulate are provided to Observer as inputs for vehicle motion. The eyes closed treatment example analyzed in Figure 4.32 is considered again in Figure 4.42 now with the inclusion of the Observer prediction of tilt perceptions.

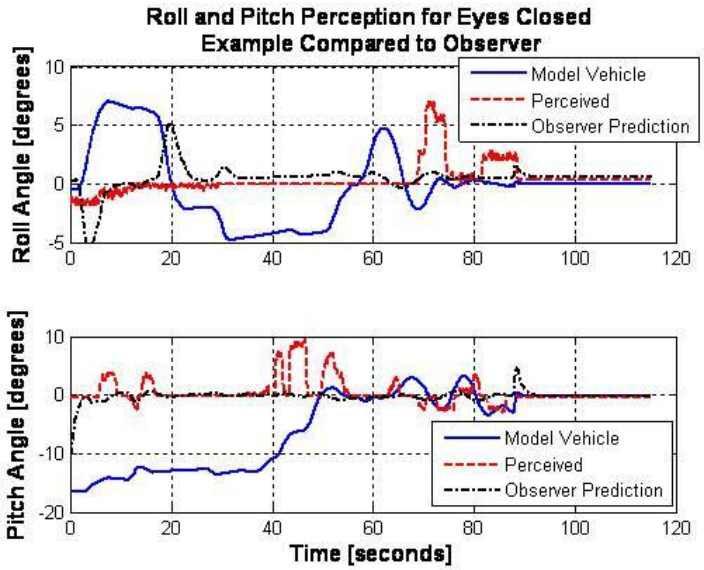

Figure 4.42: Roll and Pitch Perception for Eyes Closed Example Compared to Observer Model Predictions

Figure 4.42 shows the eyes closed example trajectory, with the mathematical model vehicle motion, the subject's perception, and the Observer model prediction of perception. It can be seen that in general the subject's perception of roll and pitch matches the Observer model prediction of perception. The subject perceives the vehicle as being upright with the roll and pitch angle near zero throughout the trajectory. Similarly the Observer model prediction of tilt perception corresponds to nearly upright. For roll, there were deviations in the Observer model which were not realized in the subject's perception. Meanwhile in pitch there were deviations in the subject's perception which were not part of the Observer model prediction. However, overall the Observer model predictions match the subject's perceptions fairly well for this trajectory. Both model predictions and subject's responses correspond to misperceptions of being upright.

The subject's perception for the example eyes out the window case was also compared to Observer model predictions. In this case the visual pathways were activated within the model to account for the subject being able to see out the simulated window in the VMS. The motions of this particular trajectory from the mathematical model for the vehicle were provided as inputs into Observer. The results previous seen in Figure 4.33 are again shown in Figure 4.43 along with the Observer prediction.

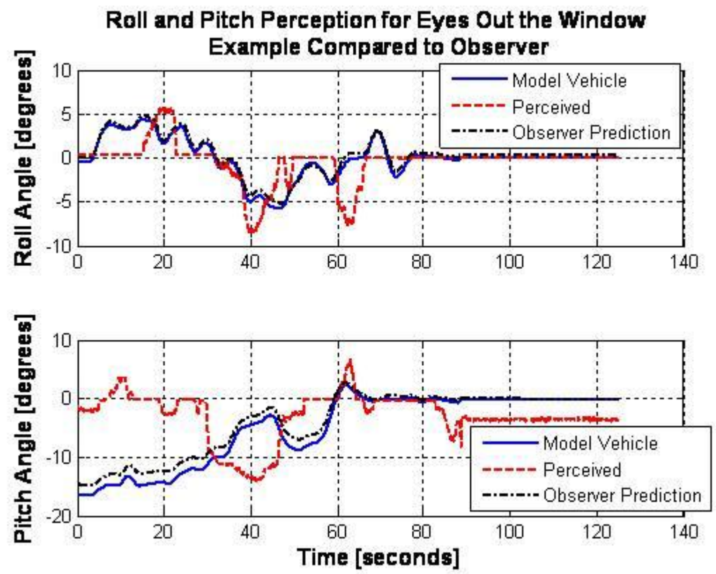

Figure 4.43: Roll and Pitch Perception for Eyes Out the Window Example Compared to Observer Model Predictions

In the eyes out the window case, the Observer model predictions of perceptions are more accurate than the subject's reported perceptions. While the subject's perception loosely follows the mathematical model of the vehicle tilt, the Observer model prediction very closely follows the vehicle tilt.

5 Discussion

5.1 Numerical Observer Model and Simulation – Vestibular and Visual

5.1.1 Discussion of the Results

Without visual cues active, the Observer model predicts astronauts will perceive themselves nearly upright even at significant tilt angles. This creates the greatest misperceptions during the braking burn when the actual vehicle is pitched backwards by as much as -88 degrees. While the greatest misperceptions are likely to occur during the braking burn, this is also the portion of the landing in which astronauts are likely to be least involved. During this portion, they will likely only be monitoring automated systems and not be actively involved with the control of the vehicle. In the automated trajectories the vehicle comes upright and remains upright during the approach and terminal descent and therefore large misperceptions do not occur during these phases of landing. However, in the LP redesignation and manual control trajectories the vehicle will enact significant maneuvers which cause the orientation to deviate from upright. The Observer model predicts the orientation perception to remain nearly upright during these maneuvers resulting in misperceptions. It is during the approach and terminal descent portion of the trajectories in which astronauts are likely to most closely interacting with vehicle control especially if LP redesignations are being made or if the astronauts take over in a manual control mode. How attitude misperceptions during approach and terminal descent would influence the astronauts' ability to control the vehicle is beyond the scope of this work. It is expected that attitude misperceptions would result in decreased astronaut performance and in the case of manual control incorrect control responses. Aviation pilots are often taught through extensive training to “fly through” episodes of SD, and while this is possible it often results in increased workload. Thus even if SD or misperceptions do not directly result in incorrect control responses, increased workload may cause performance to suffer. Finally, in the worst case scenario it has been seen that severe cases of SD are often the cause of accidents.

The effect of the astronauts’ head location within the vehicle for different designs was also studied. The concern was that if the astronauts’ heads are located far from the vehicle CoM, significant centripetal and tangential accelerations would be experienced. This could result in illusory otolith cues and misperceptions, particular without the visual pathways of the Observer model activated. For the head locations studied (see Table 3.4), the effect of head location was seen to be fairly minimal (<3.9 degrees) for the automated trajectories. Even for LP redesignation and manual control trajectories the effect of head location on perceptions was less than 4.1 degrees. Thus for reasonable head locations and the current trajectory trade space, the head location is not likely to have a significant impact on orientation perceptions or cause SD. It is however important to consider the influence of head locations for future vehicle designs which might place the head location farther from the vehicle CoM or have trajectories which include larger angular velocities or accelerations. Either of these parameters results in a larger influence of the head location on orientation perceptions.

By activating the visual pathways in Observer the predicted perceptions of tilt are far more accurate. In particular, the visual gravity cue is critical in improving the accuracy of perceptions. It has been assumed that for the visual gravity cue to be activated the horizon must be within the astronaut’s field of view. For most vehicle designs it is assumed that if any windows are provided they would be facing forward and have a limited view field. Thus for most simulations the visual gravity cues was not activated within the model until partially through the pitch-over maneuver. Therefore even with the use of visual cues, it is reasonable that a strong somatogravic illusion may persist during the braking burn and the first portion of the pitch-over maneuver. This again is the portion of the trajectory in which illusions of being upright result in the largest misperceptions. Furthermore, if the visual gravity cue is only activated when the horizon is within the astronauts’ window view than it is conceivable that extreme pitch maneuvers in manual control could cause the horizon to leave the field of view. This was simulated in Figure 4.18. The result is that when the horizon leaves the assumed field of view of the window (± 25 degrees) the orientation system is entirely reliant on the illusory vestibular cues and the subject perceives an underestimation of tilt. Again this is caused by the somatogravic illusion due to the descent engine thruster creating a gravito-inertial force vector aligned with the vehicle body axis. The otoliths misperceive this as the direction of gravity yielding a perception that is much closer to upright than to the actual vehicle orientation. This misperception, during large pitch angles when the horizon is out of view, might be disorienting. However, what potentially might be more disorientating is when the vehicle begins to pitch back upright and the horizon comes into the top or bottom of the window view. The instantaneous realization of the misperceptions might create a type 3 (incapacitating) SD case, making decreased performance and safety a serious concern. This would occur routinely during the pitch-over maneuver as well as during extreme manual control pitch maneuvers.

Dust blowback was also modeled using Observer. Similar to the other simulations, the deactivation of visual cues can lead to misperceptions due to the somatogravic illusion occurring when the system is reliant on exclusively vestibular cues. However in the case of dust blowback, how large the misperceptions are depends largely on the point in which dust begins to obscure visual cues. The baseline assumption for the height in which dust first begins was set at 100 ft. At this altitude, for automated lunar landing trajectories the vehicle is nearly upright. Thus the descent engine thruster aligns with the GIF vector with the direction of gravity and the orientation is accurately perceived. In general, most LP redesignation and manual control trajectories would likely also have the vehicle oriented upright by an altitude of 100 ft. It is possible that a velocity could begin to accumulate during terminal descent just prior to landing, and the pilot would have to enact control inputs rotating the vehicle off of vertical. In this case these tilt angles would likely be underestimated. This could lead the astronaut to putting in larger control inputs and could lead to over controlling or pilot-induced oscillations (PIOs). At a low altitude the likelihood that these inputs would result in an accident becomes increasingly high. However, normally by an altitude of 100 ft the vehicle would be aligned upright and misperceptions would be very small. There is a reasonable possibility that the dust could begin to obscure the view at altitude of higher than 100 ft. In particular, the Apollo 12 astronauts first reported dust at an altitude of 200 ft (Apollo 12 Mission Report 1970). If dust were to begin to obscure the visual field at this altitude, in many trajectory approaches the vehicle is not yet entirely upright and misperceptions are likely to occur. Two other factors have the potential to alter the altitude at which dust blowback first obscures visual cues in comparison to the Apollo experiences. Future landings are likely to occur at different locations (particularly the lunar poles) than the Apollo missions. Since there was significant variability of the height of dust appearance from location to location during Apollo it is not unreasonable to think that new locations might have different dust height levels. Additionally, future lunar landings may have a much larger vehicle than the Apollo LM. A larger vehicle with a more powerful descent engine could cause dust to appear at a higher altitude than was seen during Apollo. Thus dust remains a serious concern for orientation perceptions and SD and warrants further study.

5.1.2 Limitations and Assumptions

The Observer model is a highly useful tool for predicting orientation perceptions of motion profiles which are not easily testable, however there are limitations. For example, the model assumes the human is an unbiased observer. Thus if the astronauts are expecting to be on their backs during the braking burn, the illusion of being upright may still exist but may not be as compelling. Additionally the Observer model assumes the human to be passive. During manual control the pilot may expect the vehicle to respond to a particular orientation due to control inputs. However, this is not included in the model. Additionally the model is limited to vestibular and visual cues. While it is reasonable to assume that these are the two most important sensory modalities, the orientation system does use other sources. In particular the model does not include any proprioceptive sensory pathways. The finally limitation of the model itself is that it is deterministic. Thus while the model provides useful predictions of orientation, there is no variability in these perceptions. It simply predicts the average orientation perceptions. However, it is well understood that depending on a variety of factors including training and prior experiences, that different people are likely to perceive (or misperceive) the same motions differently. This is often seen in aircraft when contingency procedures have a second pilot take over control of an aircraft if the primary pilot becomes disoriented. Thus while the model proves useful predictions as to what perceptions are likely to occur it is unreasonable to expect every astronaut to have precisely the same predicted perceptions. Furthermore, even the same subject can have different perceptions of the same motions if experienced more than once. This can be seen in different training scenarios where the orientation system adapts to different environments and motions to more accurately perceive them. Therefore it is unreasonable to treat the model predictions as precise orientation perceptions that each astronaut will always experience. Instead the model predictions can guide the identification of particular illusions that are likely to occur during a series of motions in a given environment.

While there are limitations of the Observer model there are also limiting assumptions made in the implementation of the model. For example the model's visual gains, which determine how reliant a simulated subject is on different sensory pathways, were set to yield similar perceptions as a previous model (Borah, Young and Curry 1978). However, these gains assume a complete visual field. In the case of lunar landing, it is likely that the visual field will be provided by a small forward window. Furthermore astronauts will be faced with the visually challenging lunar terrain as discussed in Section 2.2. The orientation system may not be getting complete visual information and may be less reliant on these cues. However, the visual gains were not altered because there is not any experimental data as a basis for this scenario. Future experiments including high fidelity simulation of the visual lunar terrain could be used to provide guidance to the assumption made here.

For visual simulations it was assumed that for the visual gravity cue to be activated the lunar horizon had to be in view. Given that its likely future lunar landing vehicles will only provide the astronauts with a small forward window it was assumed that when the vehicle pitches too far forward or backward that the horizon would go out of the window view. These bounds were arbitrarily set to ±25 degrees. While the exact limits are likely not precise, it is reasonable to assume that at a certain extreme pitch angle the horizon will go out of view if there is only a small forward window. It should be noted that even when the horizon goes out of view, the short term memory of where the horizon went out of view could still provide astronauts a cue of tilt angle. For example, if the vehicle pitches far forward and the horizon goes out of the top of the window view, then the entire field of view is filled with the lunar surface. The presence of the lunar surface in the window provides a visual cue to the astronaut that the vehicle is pitched far forward. There is no visual cue for exactly how far forward since the horizon cannot be seen, but it can be seen that it is significantly far forward. The Observer model simulation does not include this added cue. The model assumes that when the horizon goes out of view the visual gravity cue should be deactivated. This results in the perception of being nearly upright since without the visual gravity cue the orientation system relies on the vestibular cues which create a somatogravic illusion. The model is simulating the equivalent of the astronaut closing his/her eyes when the horizon goes out of the window field of view. The model is currently unable to simulate limited visual cues. Instead the sensory pathways are either activated or deactivated. This unfortunately limits the models applicability to this type of scenario in which some "visual gravity" cue is available, but not a complete cue.

The limitation of the binary activated or deactivated states of the visual sensory pathways can also be seen for the simulation of the dust blowback. In the current analysis, an arbitrary reasonable altitude for dust blowback to first occur and begin to obscure the visual scene was selected (100 ft). At this point the visual sensory pathways were all deactivated instantaneously. A more likely scenario is the dust would begin at a certain altitude and slowly start to degrade the visual scene as the vehicle descends toward the lunar surface. This cannot be accurately simulated using the binary activation of the visual pathways within the model. Currently the model assumes that if the cue is activated it is an ideal cue being provided. Potentially a level of noise could be added to the visual sensor corresponding to the quality of the visual scene. Thus as the dust begins to obscure the visual scene the noise of the sensor could be increased. Prior to implementing this, some experimental efforts would need to be made to validate this concept and determine appropriate noise levels. It should also be mentioned that it was assumed that dust blowback would obscure all visual cues and so all of the visual pathways were deactivated in the model. However, Apollo astronauts have reported being able to see the horizon during dust blowback (Duke 2010)(Mitchell 2010). The astronauts have reported that the dust blows primary out away from the vehicle parallel to the lunar surface. Thus it was very difficult to see the lunar surface, locate craters or rocks, and judge horizontal velocity, but that the horizon remained visible. While the horizon might remain visible at lower altitudes it is possible that it could become obscured degrading the visual gravity cue. Again this cannot be simulated using the binary activation design of the Observer model. If the model is simulated such that the visual gravity cue remains activated, but all of the other visual pathways are deactivated for dust blowback, the model predicts accurate perception of orientation (not shown in Section 4.2.4). Thus the simulations shown where the visual gravity cue is deactivated represent a worst case scenario in which the dust obscures the horizon to the point of it not serving as a useful orientation perception cue.

The model allows for the activation and deactivation of visual sensory pathways, however the time course in response to a transition occurring has not been verified experimentally. When the visual pathways are deactivated the model's prediction of orientation perception nearly instantly reverts to an orientation corresponding to vestibular cues. It is valid that when a subject closes their eyes during motion, perceptions are likely to change. However, the time history of these changes and how the transitions might occur is not modeled within the Observer simulations. Thus the instantaneous "jumps" in the predicted perceptions at the points of sensory pathway activation and deactivation should be taken as an artifact of the model and not a physical prediction. The critical component of sensory path activation or deactivation within the Observer model is that when the orientation system transfers which sensory cues are being provided, perceptions can change significantly.

5.1.3 Application of the Results and Implications

The Observer simulation results have some important applications. The primary finding is that for a lunar landing vehicle the descent engine thruster creates a GIF that is nearly directly aligned with the body axis of the vehicle and through the feet of the astronauts. Due to the equivalence principle the otolith organs cannot disambiguate GIF into gravity and acceleration independently. Over a period of time the direction of GIF is perceived as the direction of gravity, resulting in the perception of being nearly upright even when the vehicle is at large tilt angles. This misperception is likely to occur in the absence of strong visual cues, particularly the presence of the horizon within the visual field of view. This has important implications for future lunar landing missions. Precautions need to be taken to avoid astronaut SD during landing. The model predicts significant improvements in orientation perception when visual pathways are activated. Thus, it would likely help limit misperceptions and SD if astronauts are provided larger windows. However, large windows would add significant mass to the vehicle. Alternatively using improvements in technology since the Apollo era, synthetic displays of the lunar surface could be used to provide the astronauts with visual orientation cues. Beyond the potential weight savings this provides another excellent advantage. As discussed in Section 2.2 the lunar surface has a variety of visual challenges which could limit the abilities of the astronauts to perceive orientation from an out the window view. A synthetic version of an out the window view could be artificially lighted and presented such that these visual challenges are overcome. In addition to synthetic out the window views other advanced display concepts could be employed to provide the astronauts with improved orientation perceptions and limit the likelihood for SD. Beyond display countermeasures, training regiments could be developed in an attempt to expose the astronauts to illusory motions prior to their actual landing. This potentially could help limit their susceptibility to SD as well as help them self diagnose when they are becoming disoriented and hopefully take appropriate actions.

Beyond the development of countermeasures, SD could be prevented by attempting to limit the disorienting stimuli. The Observer model predictions show that misperceptions occur when the vehicle is at unusual or extreme attitudes. Thus the trajectories could be modified to minimize these types of maneuvers. The physics of the landing require a pitched back braking burn, but during the approach and terminal descent when the astronaut is most likely to be actively controlling the vehicle these orientations could be avoided. For example, the magnitude of tilts allowable could be limited during LP redesignations or manual control. It should be noted that this would be done at the expense of vehicle handling qualities and maneuverability. Additionally head location was seen to potentially have an impact on orientation perceptions. Vehicle designers should attempt to keep the astronauts located as close to the vehicle CoM has possible in order to prevent the astronauts from experiencing large centripetal and tangential accelerations which could become disorienting. Finally, if the astronauts are likely to become disoriented their role in the human-machine system could be modified to limit the effect on system performance and safety. During potentially disorienting maneuvers, the system could be highly automated so that the astronauts serve only a passive role. Therefore if they do become disoriented, vehicle maneuvers will not be adversely affected. The vehicle design could include graceful transitions between automation levels, so in the case of a pilot becoming disoriented, control could easily and safely be reverted to the automated systems.

The analysis done here was for the example case of future lunar landings; however these methodology and results can be applied to other landing scenarios. The Observer model provides a powerful tool for predicting orientation perceptions in unique environments where direct experimentation is unpractical. The precise misperceptions which might occur depend on the exact landing trajectory, so the results here are fairly specific to lunar landings. Despite this, perceptions during Mars landings may have some similarities with these results. During a Mars landing, it is likely that the vehicle will have some aeronautical surfaces to use atmospheric drag to assist in braking. Thus the maneuvers and motions during the braking portion of the descent are likely to vary significantly between the Moon and Mars. The final approach and terminal descent, however, could be quite similar. Without a runway, a Mars lander will most likely have to use a descent engine thruster to hover and descend vertically just as with future lunar landers. Thus for these phases of descent the somatogravic illusion and underestimation of tilt angles is likely to occur during Mars landings as well as lunar landings. The model could also be applied to “landings” on asteroids. Though how the orientation system perceives “down” in microgravity is not well defined.

5.2 Ames Vertical Motion Simulator Experiment

5.2.1 Discussion of the Results

The Ames VMS experiment provided an opportunity to experimentally investigate orientation perceptions during motions similar to those experienced during lunar landing. Two different indicators were developed for the subjects to report their orientation perceptions: the tilt indicator to report attitude perceptions and the horizontal velocity indicator to report the direction and magnitude of horizontal velocity. Pre-experimental testing for these indicators found them to be serviceable for the task of reporting orientation perceptions. While certain subjects (subject 5) struggled to track actual motions provided on a display using the indicators, most subjects were able to use the indicators with acceptable accuracy.

To determine the importance of different sensory cues, three cases were studied: eyes closed, eyes out the window, and eyes on the displays. It was seen that tilt perceptions were inaccurate and generally underestimated in the eyes closed case. This agrees with the somatogravic illusion predicted by the Observer model simulations. The addition of visual cues in the eyes out the window case created more variable perceptions than the eyes closed case, but did not significantly reduce the running MSE for either roll or pitch. This does not agree with Observer model predictions which expect a significant improvement in perceptions when visual cues are provided. There are a number of contributing factors why this was not seen in the VMS experiment. First, the simulation of the visual out the window view was not of the highest fidelity. The images were projected onto a screen in front of the subjects. These projections were not very high resolution, which may have limited the subjects’ ability to pick out visual cues from the scene. Additionally, the scene was not an accurate depiction of the lunar surface. A horizon was provided with mountains and features. The lunar surface was essentially flat with only minor features, which differs significantly with the rock and crater filled surface of the actual moon. In addition to the low resolution and somewhat unrealistic lunar surface depiction, the assumed eye location for the projection was slightly incorrect. The projection was centered for the flying pilot’s eye location and thus was slightly misaligned for the orientation perception subject’s eye location. This error would result in images being perceived offset in yaw in comparison to the mathematical model. The exact effect of this offset is unknown but is expected to relatively small (<10 degrees). Furthermore, the eye location was not adjusted for subjects with different heights. This effect would cause the scene to be misaligned in pitch, however is expected to be nearly negligible. In a more controlled experiment these eye location effects would be accounted for.

Another potential cause for the lack of improvement in perceptions resulting from adding visual cues is the limited field of view provided during the VMS experiment. The limited window view can be seen in Figure 3.22. The reduced field of view used in the experiment is likely more realistic in comparison to actual window views in upcoming lunar landing vehicles. However, the Observer model did not attempt to account for the reduced field of view. Instead it assumes a complete visual field. The limited field of view can only be simulated by deactivating cues that are unlikely to be perceived due to the reduced field of view. One result of the reduced field of view in the VMS experiment was the subjects' misperception of pitch angle in the eyes out the window case. This may have been the result of the only visual cues being out a forward looking window. From this window the pitch cue was usually abstracted from how high in the window the horizon was. For pitched back orientations the horizon would be low in the window, while for pitched forward orientations the horizon would be high in the window. While subjects could accurately perceive whether the horizon was moving up or down in the window, they often had difficulty anchoring their scale and determining what horizon level corresponded to an upright pitch orientation. This was particularly difficult because during the descent the pitched upright horizon level would change as the horizon becomes higher in the sky simply due to losing altitude. The roll angle perception was far easier since the primary cue in the forward looking window was the angle the horizon makes with the frame of the window. In this case a clear absolute zero roll angle cue was provided when the horizon and window frame created a 90 degree angle. Since most trajectories are primarily pitch maneuvers, this difficulty in perceiving absolute pitch angle even with visual cues could result in disorientation. One potential solution would be to provide the astronauts with a window view out of the side of the vehicle. This would allow for pitch to be perceived in a similar manner to roll by estimating the angle between the horizon and the window frame.

The lack of significant improvement for the eyes out the window case was primarily due to the variability between subjects and between trials. As is discussed in Section 5.2.2, the simulations were manually controlled and as a result the vehicle motions for each trial were unique. Thus misperceptions on a particular trial could be created by the given treatment (ie. eyes out the window) or by the pilot flying motions which were more difficult to perceive. Often times if the pilot kept the vehicle under control and upright through most of the trajectory the eyes closed perceptions (which were generally upright) did not result in large misperceptions. Alternatively, if the pilot had trouble handling the vehicle and enacted large roll and pitch maneuvers, even if the subject was provided visual cues it is unlikely the perceptions are going to be highly accurate. In addition to each trial's motions being unique, there was significant variability between and within subjects. While the Observer model would predict one set of perceptions for a certain set of motions, actual subject perceptions varied significantly. These variations occurred between different subjects but also from trial to trial of an individual subject. This points to how perceptions can be highly variable. The Observer model only provides predictions of the average perceptions.

The eyes out the window case did generally improve the horizontal velocity perceptions. This is not surprising since the vestibular organs do not have a "horizontal velocity sensor." The otolith organs can provide information regarding accelerations through GIF, but this information must be integrated over time in order to estimate linear velocities. This integration process is not near perfect and as a result over a short period of time these perceptions become highly unreliable. With a sufficient visual scene it is possible for visual cues to accurately infer information about horizontal velocity through optical flow. The period during the trajectory in which horizontal velocity perception is most important is during the final approach and terminal descent. If the pilot is operating the vehicle in manual control during these phases the primary task is to null out horizontal velocities in order to land softly. Accurate perceptions of horizontal velocity are necessary for the manual control task. Unfortunately, during the final terminal descent it is quite likely that dust blowback will obscure visual cues and the astronauts will have to rely on inaccurate vestibular or proprioceptive cues. Alternatively the pilot could abandon out the window information and fly off of the instruments.

The eyes on the displays case was seen to generally improve perceptions though it was only statistically significantly different from the eyes close and eyes out the window cases for pitch perceptions. This shows the importance that the actual motions play in the accuracy of perceptions. During the lunar landing trajectories the maneuvers were primarily pitch maneuvers. As a result any misperceptions of these maneuvers were significant and resulted in large errors. In the roll direction the maneuvers were relatively small and it was easier for perceptions to track the actual orientation. The fact that the eyes on the displays treatment results in the most accurate perceptions has some important implications. It may appear that misperceptions and SD can be avoided by simply having the subjects focus their attention on the displays. While this might improve orientation perception, a few challenges still exist. Having display information available while strong illusory perceptions persist does not prevent the onset of SD. Additionally, the task of "flying through" SD by relying on the instruments usually results in increased workload. It is also possible that these illusory perceptions could lead to motion sickness. Finally, in the event that the instruments are malfunctioning the pilot would be required to rely on orientation perceptions which might be inaccurate.

The subjects' perceptions during the VMS experiment were also compared to the Observer results for the tilt angle example trajectories analyzed. In the eyes closed case the subject's perceptions were well predicted by the Observer model predictions. While there were deviations, they were generally small. Both model and subject perceptions correspond to being nearly upright despite vehicle tilt motions. Deviations between model and subject perceptions for the eyes closed case are likely due to the use of the indicators for reporting and trial to trial variations. Another factor could be the VMS not replicating the motions precisely. In the eyes out the window example case, the Observer model predictions and subject's reporting are similar, but do not match very precisely. There are many factors which could contribute to this. The Observer model predictions assume idealized visual conditions, while the VMS visual scene was far from ideal. Also in reporting dynamic perceptions there is a greater likelihood errors occur from using the indicators for reporting.

5.2.2 Limitations and Improvements

The primary limitation of the VMS experiment was the uniqueness of each trial. While the intention of the experiment was to determine the effect of different treatments (eyes closed, eyes out the window, and eyes on the displays) on misperceptions of vehicle motions, there were a variety of confound factors. This can best be seen in Figure 5.1.

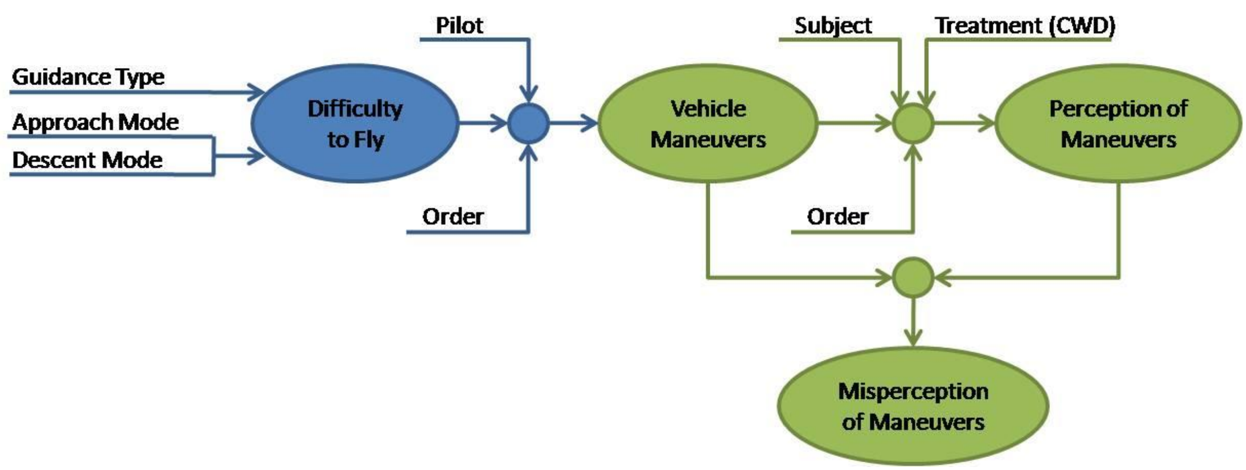

Figure 5.1: Confounding Effects for the VMS Experiment

The different parameters which might have a direct effect on the subject's perception of maneuvers are the subject themselves, the treatment for the particular trial, the order of the trial, and most importantly the actual vehicle maneuvers. Different subjects have different perceptions and potentially different abilities to operate the indicators. The treatment limits which cues the subject is provided in order to make orientation perceptions. Also if the subject experiences a series of runs, there could be an effect of the order of presentation. The subject might become more proficient at operating the indicators, learn the types of motions which he/she might experience or become fatigued. Finally, the perceptions of maneuvers are going to depend upon the actual vehicle maneuvers. In an ideal experimental design the vehicle maneuvers would be held constant such that each trial was a repetition. This would allow for the variability created by order and subject to be accounted for and the effect of treatment to be accurately determined. Additionally repetitions of the same motions would allow for averaging of the perceptions to effectively create a nominal time history of perceptions analogous to an Observer model prediction. Unfortunately due to the constraints of the piggy-back experiment the trials were manually flown resulting in each trial having unique vehicle maneuvers. This prevented the ideal comparison between trials. While a certain trial could results in large misperceptions, it was never clear whether that was due to the particular treatment (ie. eyes closed) or because of the unique maneuvers experienced during that trial. Furthermore, there were a variety of factors which influenced the vehicle maneuvers for each run. The pilot's skill, how much practice he/she had, and how difficult the vehicle was to fly all influenced the vehicle maneuvers on each trial. With unique vehicle maneuvers it became impossible to directly compare perceptions across trials.

In a future experiment the vehicle maneuvers should be held constant. A small set of trajectories of interest should be selected. The set used for simulation in the Observer model would be an excellent set because it includes automated, LP redesignation, and manual control trajectories. These motions of each of these trajectories should be repeated multiple times such that the variability from trial to trial can be captured and an average perceptual time history can be created. Without this repetition it is difficult to determine the factors of importance.

Another limitation of the VMS experiment is that it only studied the final approach and terminal descent. This is unfortunate since the Observer model simulations predict the largest misperceptions during the braking burn prior to pitch-over. An ideal experiment would include this portion of the trajectory, however it is unlikely that this would be possible because of the extreme rotation requirements that would be needed for the motion based simulator. An additional limitation of the VMS experiment is that the visual scene did not incorporate a dust model. Thus the subjects were provided visual cues all the way down to touchdown. In order to determine the influence of dust blowback on perceptions it would be necessary to include this in the simulation. Furthermore, due to the unique properties of the lunar dust and the blowback that is expected to occur from the descent engine thruster the fidelity of the dust model is critical. The final limitation that should be mentioned is that the VMS experiment was obviously conducted here on Earth in a 1G environment. This does not accurately model the vestibular cues that are likely to occur in lunar gravity. However, it is likely unfeasible to recreate the lunar landing motions in partial gravity. Parabolic flight experiments can recreate the partial gravity environment for short periods of time, however accurately creating the lunar landing vehicle motions while in parabolic flight would require a motion based simulator on flight. Thus while the experiment being performed in the incorrect gravity environment is a limitation, it is likely one which future experiments will also suffer from.

5.2.3 VMS Cab Motion vs. Mathematical Model Motion

While the motion based simulator cab provides motion cues to the subject, these motions are only an approximation of the actual vehicle motions from the mathematical model. In particular there are motion limitations of the VMS which cannot be exceeded. Therefore extreme orientations cannot be reached and high speed motions take time to build and cannot be maintained for long periods of time. Furthermore the motions which the simulator attempts to replicate are limited. The VMS does not attempt to match the mathematical model's steady state tilt angle or linear velocity. Instead the transient angular velocities and linear accelerations are reproduced and the simulator expects the visual cues to account for the steady state motion. Thus while initial inspection might propose that the subject's perception in the eyes closed case of being upright confirms the Observer model prediction of a somatogravic illusion, this is not by chance. The motion drive algorithm determines the GIF direction to be in line with the body axis of the vehicle. The VMS motion drive system cannot maintain the steady accelerations necessary to create this GIF direction at a tilt angle. Thus the GIF direction is maintained by orienting the cab with the direction of gravity and not enacting the steady acceleration. Thus while the upright perceptions correspond accurately with the Observer model predictions, they are the result of the cab actually being upright not the result of actual cab tilt being misperceived due to the GIF direction. Additionally in this particular experiment the motion drive algorithm malfunctioned for the roll maneuvers. The actual roll cues provided were far less than they should have been based on the mathematical model. While most trajectories were primarily pitch maneuvers, this motion drive algorithm error in the roll likely had an influence on perceptions.

6 Conclusions and Recommendations

6.1 Summary of Important Results

6.1.1 Numerical Observer Model and Simulation – Vestibular and Visual

The spatial orientation model known as Observer was simulated with lunar landing trajectories to predict astronaut perceptions of vehicle orientation. Various automated trajectories as well as simulated LP redesignation and manual control trajectories were studied. Without visual cues activated in the model, the predicted perceptions for the automated trajectories corresponded with large misperceptions of pitch angle. While the actual vehicle orientation was significantly pitched back throughout most of the trajectory, the pitch perception was nearly zero corresponding to feeling upright. This misperception is a somatogravic illusion. The descent engine thruster creates a GIF vector that is essentially in line with the body axis of the vehicle and through the astronauts' feet. Over a period of time the orientation system misperceives the direction of GIF as the direction of gravity as a result of the otolith organs' ambiguous measurement of GIF. Since this is in line with the body axis of the vehicle this creates a perception of being upright. For automated trajectories the largest misperceptions occur during the braking burn when the vehicle is pitched far from the perception of being upright. However, in LP redesignation and manual control trajectories when the vehicle rolls and pitches as it maneuvers during the approach and terminal descent, these tilts are underestimated as well due to the somatogravic illusion. In addition the effect of the astronauts' head locations within the vehicle were studied. If the astronauts are positioned far from the vehicle CoM, they will experience centripetal and tangential accelerations as the vehicle rotates in addition to the accelerations of the vehicle CoM. Since these accelerations can be misperceived, they could influence tilt perception. It was seen for the head locations analyzed that the effect of the added acceleration has a minimal impact on tilt angle perception (< 5 degrees).

The activation of visual cues in Observer generally improves orientation perceptions. When all of the visual cues are activated, the somatogravic illusion is vastly reduced and misperceptions are limited to only a few degrees. However, the "visual gravity" cue is assumed to only be activated when the horizon is within view. Since future lunar landing vehicles will likely only have a small forward window the horizon will not be in view and the cue not activated until the pitch-over maneuver as the vehicle comes upright and the horizon comes into the window view. After this point the orientation is accurately perceived for the remainder of the trajectory for automated, LP redesignation, and manual control trajectories. The exception to this is if the manual control inputs result in a large enough vehicle pitch angle such that the horizon leaves the window view. In this case, the visual gravity cue is deactivated and the model predicts underestimation of the tilt angles and a somatogravic illusion as the orientation system is again reliant on only vestibular cues. Finally, dust blowback from the descent engine obscuring the visual field is simulated by deactivating visual pathways in the model at the altitude in which dust is assumed to occur. If the vehicle is at a significant tilt angle when dust occurs than misperceptions result as the tilt angle is underestimated without the presence of visual cues. Therefore misperceptions due to dust blowback depend heavily on the altitude at which it is assumed to begin to obscure the visual field. At an assumed altitude of 100 ft the vehicle is nearly upright in the trajectories studied and no large misperceptions are seen. However, if the dust occurs as high as 200 ft, as was the case on Apollo 12, then significant misperceptions are seen for all of the trajectories studied since the vehicle is generally not yet upright at this altitude. Thus even with visual cues activated in the model, orientation misperceptions may still occur when they are deactivated due to the limited window view and dust blowback.

6.1.2 Ames Vertical Motion Simulator Experiment

The Ames VMS was used as a motion based platform to study human perception of vehicle orientation to motions similar to those that would be experienced during lunar landing. The experiment was part of an existing experiment studying pilot handling qualities. As a result many manually controlled landing trajectories were flown, each of which was unique. Subjects reported one of two aspects of orientation perception, either horizontal velocity in magnitude and direction or tilt in pitch and roll. Three different treatments were given in which the subjects were either blindfolded for the eyes closed case, asked to look out the window at a simulated lunar surface, or to look down at instrument displays to perceive their orientations. It was seen that for the eyes closed case when subjects were reliant on their vestibular cues that they generally misperceived the mathematical model vehicle tilt angle substantially by perceiving themselves as upright. This corresponds with the somatogravic illusion predicted by the Observer model. In the eyes out the window case, subjects no longer perceived themselves as upright, but still had significant errors in reported tilt perceptions compared to the actual vehicle tilt. This may have resulted from an imperfectly simulated visual field, the limited field of view of the forward window, or trial to trial variability. Finally in the eyes on the displays case the perceptions generally improved and there was statistically significant improvement for the pitch angle maximum running MSE (± 3 seconds). While using the instrument displays may provide better information about orientation, it is still likely that perceptual cues may vary with actual vehicle orientation and SD is still possible. Also, this scenario would require the astronauts to keep their eyes inside the vehicle and would limit their ability to recognize landing areas or avoid hazards.

Horizontal velocity was poorly perceived in both direction and magnitude for the eyes closed case. The vestibular system does not provide a direct linear velocity cue, so acceleration perceptions derived from the otolith organs would have to be integrated over time to yield a velocity perception. This is highly unreliable and results in inaccurate perceptions. In the eyes out the window case, the velocity perceptions were generally fairly accurate. There were errors in the precise times in which the perceived transitions occurred between different velocity magnitude ranges as well as some errors in velocity direction. The eyes on the display case resulted in the most accurate reporting of velocity perceptions. Small errors would still occur in the direction estimates and occasionally magnitude transitions were missed, but generally the reported perceptions were quite accurate.

6.2 Impact of Spatial Disorientation on Pilot/System Performance

Large misperception of orientation often leads to episodes of SD. SD can have a number of detrimental impacts on pilot and system performance and safety. In the case of unrecognized SD, misperceptions of vehicle orientation can result in incorrect control responses and inputs. In the best case these inputs will result in inefficient vehicle control, but in the worst case unusual or even dangerous maneuvers could result which could lead to decreased landing performance or even an accident. SD is a contributor to a significant number of aircraft accidents, may have played a role in a dangerous Shuttle landing, and could impact the safety of a lunar landing. In the case of incapacitating SD, the pilot might not accidently make incorrect control inputs, but might be unable to make the necessary control inputs. If the vehicle is in a lower level supervisory control or manual control mode, it is possible that a lack of control inputs by the pilot could influence vehicle performance and safety. Finally, in many cases pilots are able to recognize SD and "fly through" it by relying on instrument displays. However, this often requires increased workload which could indirectly impact performance and safety. Thus the occurrence of SD is likely to have a serious detrimental impact on vehicle performance and create an increased likelihood for an accident.

6.3 Development of Spatial Disorientation Countermeasures

In order to minimize the impact of SD during lunar landing, countermeasures can be developed to either minimize the likelihood of SD or to mitigate the effect of the occurrence of SD on vehicle performance and safety. Limiting the likelihood of SD can potentially be done with a series of countermeasures. In concept disorienting maneuvers could be avoided to prevent the onset of SD. However, in lunar landing most of the maneuvers are determined by the physics constraints and thus are not easily avoided. There are two potential exceptions. First, large tilt angles could be explicitly avoided for LP redesignations and manual control maneuvers. This would limit the vehicle's handling capabilities and maneuverability and make maneuvers more costly in fuel, but it might avoid attitudes which would likely be misperceived. Secondly, since dust blowback during terminal descent might impact orientation perceptions, all tilt maneuvers could be completed prior to the altitude at which dust blowback is expected to begin. Otherwise the vehicle attitude is essentially determined by the physics constraints of the descent.

As an alternative to avoiding maneuvers which might stimulate SD, countermeasures could be developed to prevent the onset of SD. For example, advanced display countermeasures could be developed which would assist the astronaut in maintaining accurate orientation perceptions. This could be done using spatial awareness type displays as well as synthetic out the window views which would provide natural orientation cues to the astronauts in an effort to mitigate SD. A further advantage to synthetic displays is that many of the visual challenges of the lunar surface including poor lighting, non-Lambertian reflective properties, a lack of atmosphere, and no objects of familiar size could be artificially removed to provide useful visual cues. In contrast to display countermeasures, training countermeasures could be developed as well. It has previously been seen that prior exposure to motion stimuli reduces the likelihood that SD occurs on future exposures. Training regiments could be designed to expose astronauts to lunar landing motions, partial gravity, and visual conditions expected on the moon in an effort to prepare them for lunar landings. It should be noted that these countermeasures should be developed in a focused manner and not in a trial and error fashion. In addition to hopefully minimizing the likelihood of SD, training countermeasures may help increase the astronauts' ability to identify when SD is occurring and hopefully take actions to minimize the effect on performance and safety.

Finally, if SD is still likely to occur even with the development of potential countermeasures, the human-machine system should be designed in such a way that SD has a limited impact on vehicle performance and safety. For example if a particular maneuver is likely to cause SD, the system should be designed such that the pilot does not have active control of the vehicle during this maneuver. In this way, even if SD occurs during a landing the automated system could assist the pilot in maintaining safe control of the vehicle and preventing a SD related accident. In order to ensure high levels of performance and safety, a series of countermeasures should be implemented to help minimize the likelihood and impact of SD during lunar landing.

6.4 Future Work

While potential illusions experienced during lunar landing have been predicted and identified, further work needs to be done to solidify the likelihood of SD and understand the effect it could have on performance and safety. Experimentation here on Earth cannot capture all of the components of the unique environment of lunar landing, particularly the partial gravity following 0G exposure. However, further experimentation could be used to help inform and modify the Observer model. Currently the Observer model assumes a complete and ideal visual scene when the visual pathways are activated. Experiments can be done to study how visual cues of the lunar surface through a single forward window with restricted view effect motion perceptions. For example, the preliminary experiment done here has hinted that pitch angle perception is done qualitatively different than roll angle perception as a result of the forward looking window. To solidify this finding, experiments with repeated trials of the same motion trajectory need to be completed to form an "average" perception which can be compared to Observer predictions. Also the visual scene provided to the subjects needs to have higher resolution and greater fidelity depiction of craters and rocks as well as the limited lighting conditions that are expected to be experienced during real lunar landings. These types of experiments will allow for structural and gain modifications to Observer that allow the model to more accurately be applied to the unique scenario of lunar landing.

Beyond motion based experiments here on Earth, further experimentation should be done to understand the effect of different levels of gravity on orientation perception. The Observer model currently does not account for orientation system adaptation that is likely to occur during the extended stay in 0G that astronauts will experience prior to landing on the moon. While there is a qualitative understanding of how the orientation system might adapt in 0G (Young, et al. 1984)(Parker, et al. 1985)(Merfeld 2003), precisely how the Observer model function would be modified still needs to be validated. The model provides an opportunity to study the effect of 0G adaptation on the perception of lunar landing motions in partial gravity that could not be obtained experimentally. In addition to including 0G adaptation in the Observer model, further effort needs to be put into the modeling of dust blowback. Currently the model deactivates all of the visual pathways instantaneously at the assumed altitude at which dust blowback occurs. However, further considerations need to be put into which visual pathways should be deactivated during dust blowback as the evidence from Apollo points to the horizon remaining visible through the dust blowback. Furthermore, the dust likely does not instantaneously obscure all of the visual cues. Instead, during the dust onset the visual cues will likely become noisier as they slowly become obscured. Further efforts need to be made in the modeling of the dust onset and potentially redefining the binary activation system for visual pathways current used in Observer. Through the combinational efforts of experiments and modeling, the potential of SD during lunar landing can be more precisely studied.

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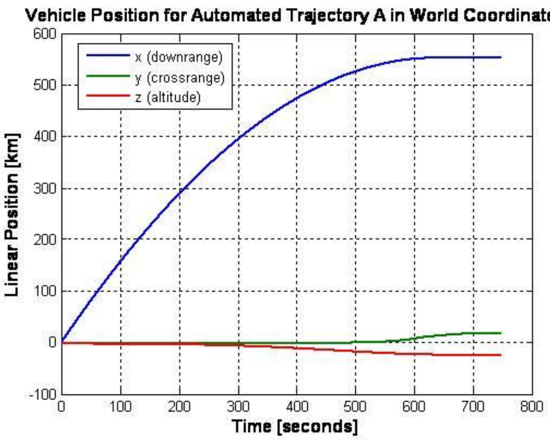
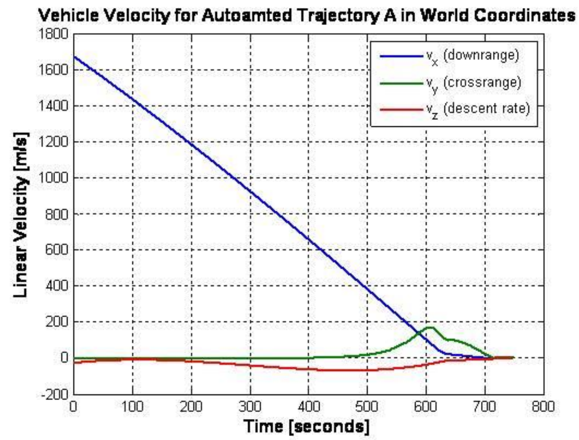
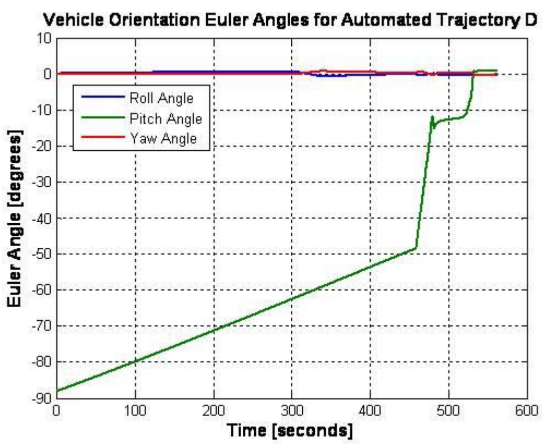
APPENDIX A – Additional Observer Inputs

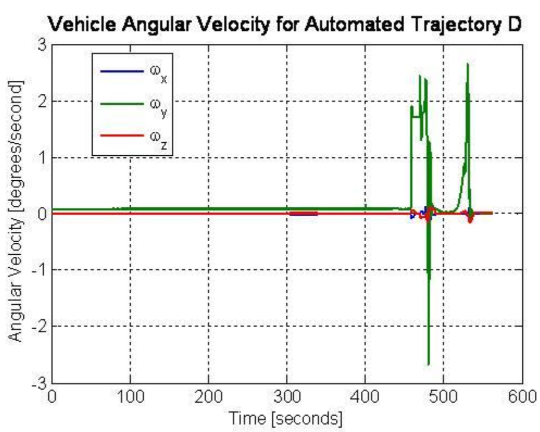
Vehicle Linear Position and Velocity for Automated Trajectory A in World Coordinates

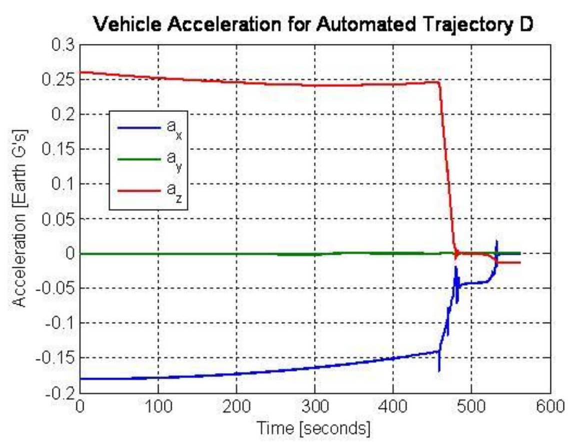




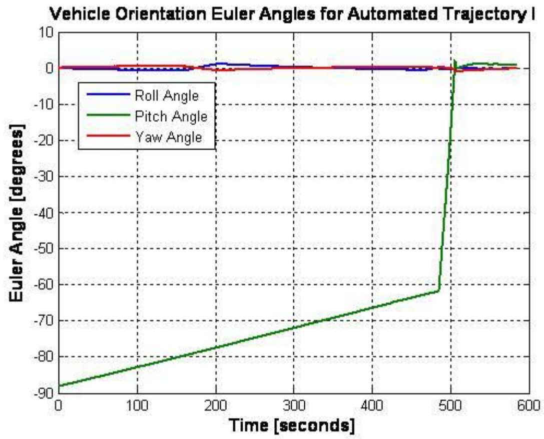
Vehicle Motion Parameters for Automated Trajectory D

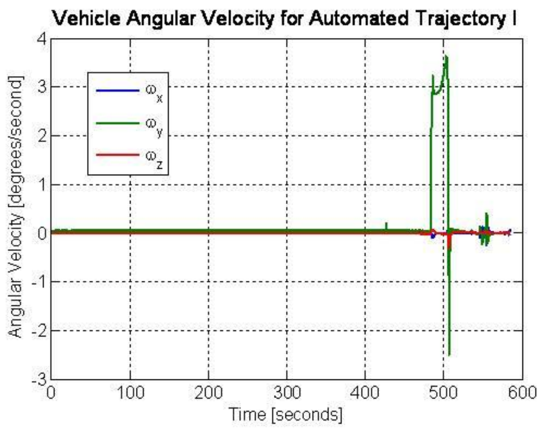


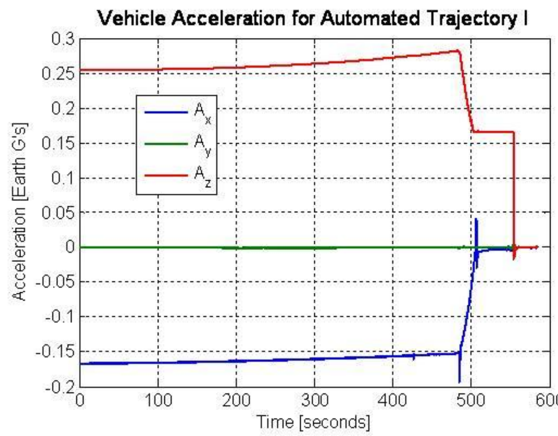




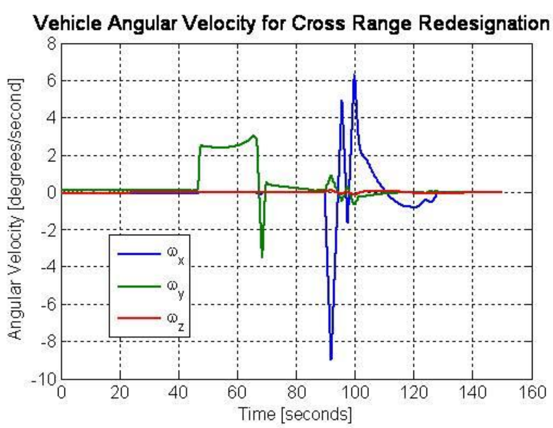
Vehicle Motion Parameters for Automated Trajectory I

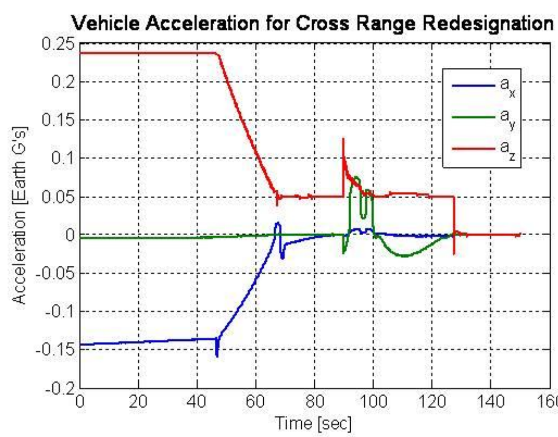


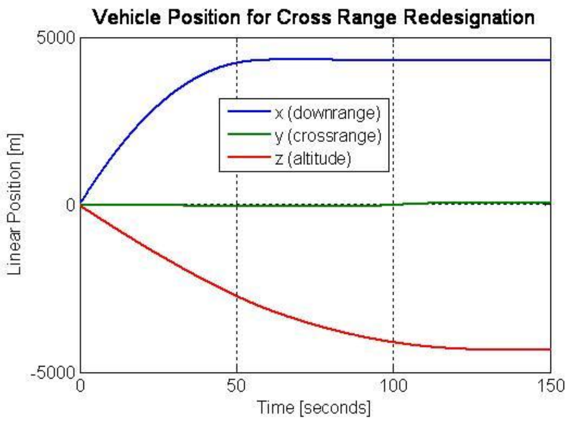


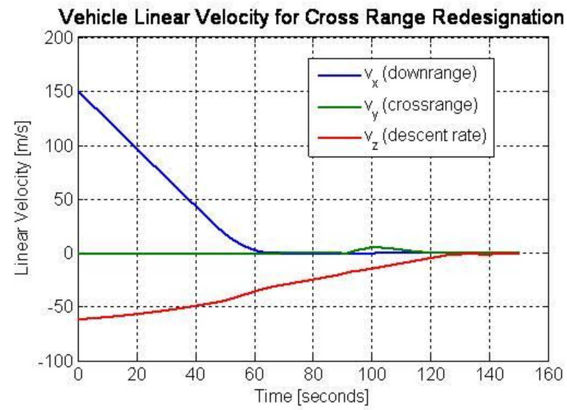


Vehicle Motion Parameters for Cross Range Redesignation Trajectory

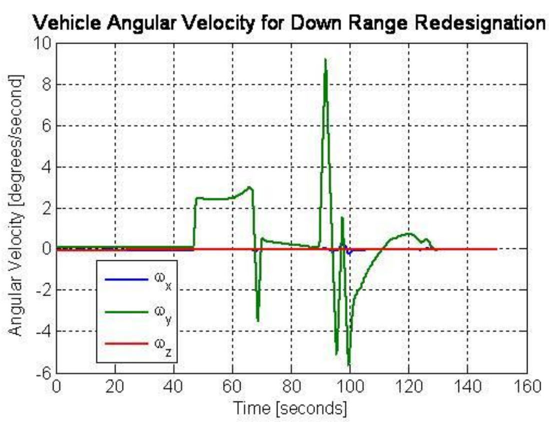


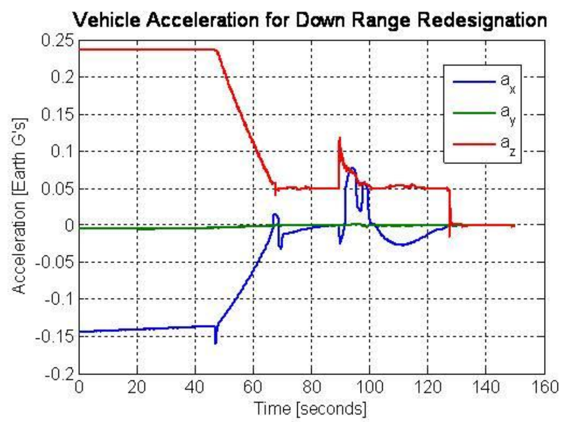


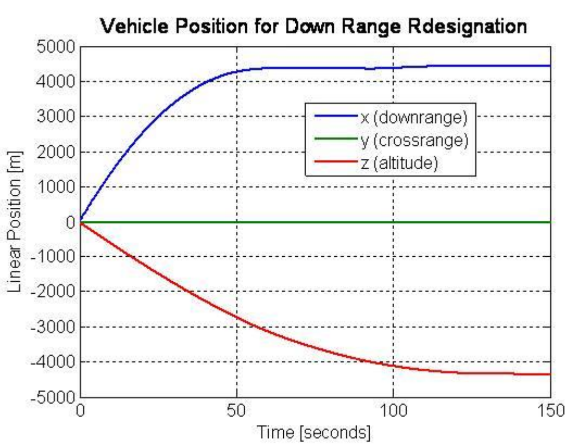


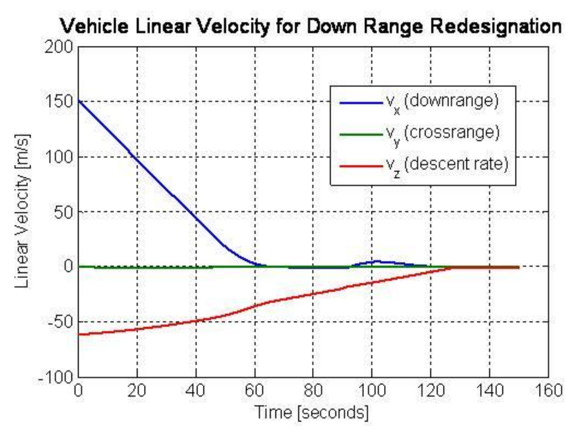


Vehicle Motion Parameters for Down Range Redesignation Trajectory

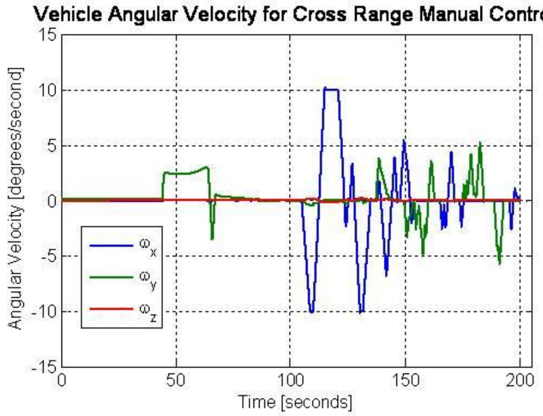


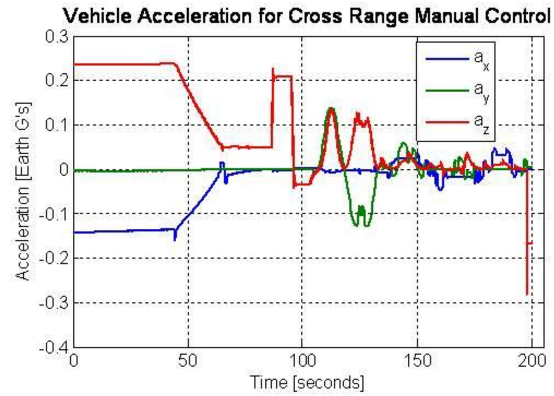


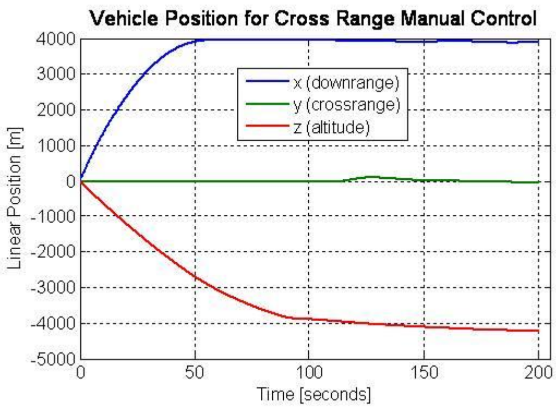


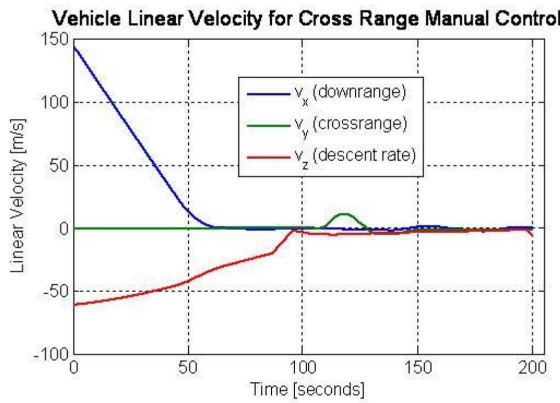


Vehicle Motion Parameters for Cross Range Manual Control Trajectory

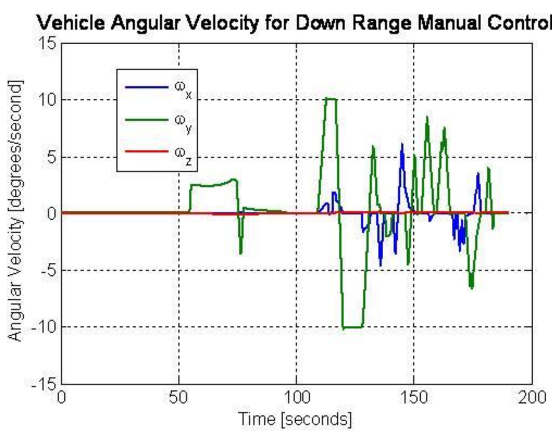


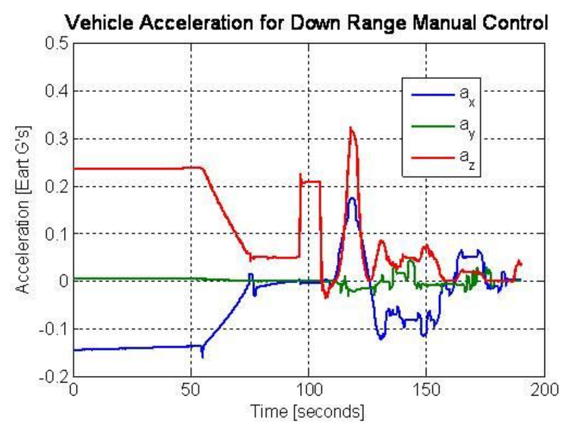


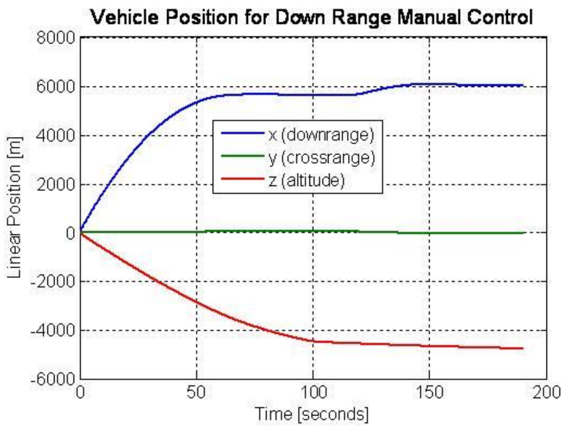


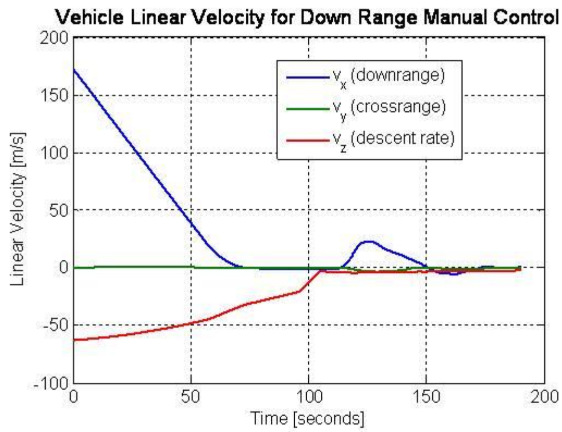


Vehicle Motion Parameters for Down Range Manual Control Trajectory









APPENDIX B – Additional Information for VMS Experiment

MIT COUHES AND ARC HRIRB APPROVED CONSENT FORM

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035-1000

Human Research Category I Sample Consent Form
Part 1

Title: Spatial orientation estimation during piloted lunar landing terminal descent trajectories

A. Purpose
This study, conducted in collaboration with MIT, will use the NASA Ames Vertical Motion Simulator (VMS) outfitted to run piloted lunar landing trajectories to quantify human orientation perception. The VMS moving base simulator, which can rotate on three axes and translate on two, will provide an earth based analog to the trajectories actually experienced by astronauts during a lunar landing allowing for the vehicle motions to be reproduced. The data collected on vehicle orientation and perceived orientation of the subject within the vehicle will be used to better inform models of human orientatin perception, with the goal of using those models to develop systems that prevent spatial disorientation during flight, and the accidents that often follow.

B. Investigators
Principal Investigator: Laurence R. Young, Sc.D. (MIT), (617) 253-7759, lry@mit.edu
Co-Investigator: Charles M. Oman, Ph.D. (MIT), (617) 253-7508, coman@mit.edu
Co-Investigator:Kevin R. Duda,Ph.D.(Draper Laboratory),(617)258-4385, kduda@draper.com
Co-Investigator: Eric Mueller (Ames Research Center), (650)604-3529, eric.mueller@nasa.gov
Graduate Research Assistant: Torin Clark (MIT), (617) 253-5487, torin@mit.edu
Co-Investigator: Arthur Estrada, Ph.D. (U.S. Army Aeromedical Research Laboratory), (334)255-6928, art.estrada@se.amedd.army.mil

C. Nature of Tests and Experiments
In order to determine the likelihood and types of spatial disorientation that will occur to astronauts during lunar landing, the NASA Ames Vertical Motion Simulator has been outfitted for manually controlled lunar landing trajectories and will used in this experiment. Subjects will be placed within the simulator cab and be asked to report their perceived orientations during landing simulations. This will be compared to the actual orientation of the

vehicle to determine where and how severely disorientation occurs. Subjects will report their perceived orientations for multiple runs of landing trajectories in a variety of scenarios of being blindfolded, being provided visual out-the-window cues, and being provided with visual instrument displays.

D. Manner in which Tests or Experiments Will Be Conducted

You will be one of fifteen subjects participating in this experiment who will be asked to come to the Vertical Motion Simulator (VMS) at the Ames Research Center on one day for up to a four hour period. You will be briefed and trained on operating and safety procedures of the VMS as well as the methods of reporting your perceived orientation during simulation runs. We will ask that you enter the VMS and take the position within the cab not occupied by the flying pilot. The pilot will be flying the approach-to-landing trajectory, and you will be reporting your orientation estimate. You will follow a procedure of reporting your perceived orientation using one of two joysticks within the cab. One joystick will be used for estimating the direction of gravity – that is, to keep the long axis of the joystick parallel to the direction in which a ball would fall if it were dropped at that instant. The other joystick and the thumb buttons on it will be used to indicate the direction and the magnitude of your perceived motion. You have been or will be instructed on techniques for operating the joysticks. We may ask that you alternate the use of the joysticks between each run. In addition, for some of the runs you might be blindfolded, while for others you will be provided with a combination of an out-the-window view of the planetary surface or instrument displays. A series of runs will be conducted for up to an hour, and then you will be given a break before the next set of runs. In totally there should be no more than 45 runs, all within a single day, each of which should last approximately 1 minute.

E. Duration

The testing all occur on one day and make take up to four hours. There will be breaks between each set of runs and a break for lunch.

F. Foreseeable Inconvenience, Discomfort, and Risks

There are no major foreseeable safety concerns as you will be safely strapped into the vehicle harness. There is a small likelihood that you will experience motion sickness while in the simulator cab as it moves about. A pre-experiment survey will be used to determine whether you are likely to suffer from motion sickness while in the Vertical Motion Simulator. Subjects that experience motion sickness can stop the experiment and exit the cab at any point during the experiment. Additionally due to the motion of the cab and the standing configuration within the cockpit, there may be stresses or forces on your knees or ankles in excess of those typically seen on a daily basis. These stresses are no expected to cause any serious damage or discomfort, but if you have previous knees or ankle problems pleas notify the experimenter. There is also the potential risk of injury while entering or exiting the cab as well as risks due to an operational failure of the Vertical Motion Simulator. You have been briefed on the operational and safety procedures of the VMS and have read the VMS Pilot Briefing document. This includes knowledge of the emergency exit routes, evacuation procedures, and locations of emergency items including fire extinguishers, flashlights, and air capsules. The VMS motion operator will direct you in the event of a VMS malfunction.

G. Right to Withdraw from the Study and the Penalties/Hazards Associated with Withdrawal

Participation is voluntary. You have the right to withdraw from the study at any time for any reason, although we hope you will not volunteer for the study unless you intend to complete it. There are no hazards or penalties associated with withdrawal at any time during this study.

H. Answers to Questions

You may receive answers to any questions related to this study by contacting the Principal Investigator (Laurence R. Young at MIT) at (617) 253-7759 and/or Ralph Pelligra, M.D., NASA Ames Medical Officer/Chief Human Research Institutional Review Board, Ralph.Pelligra-1@nasa.gov, 650-604-5163. If any problems related to the study occur during its course, please contact the Principal Investigator at that number. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

I. Remedy in the Event of Injury

In the event of physical injury resulting from this study and calling for immediate action or attention, NASA will provide, or cause to be provided, the necessary treatment. If you are eligible for California Workers' Compensation benefits while participating in this study, you cannot sue your employer because the law makes Workers' Compensation your only remedy against your employer. You may have other remedies against other persons or organizations depending on the circumstances of the injury. NASA will pay for any claims of injury, loss of life or property damage to the extent required by the Federal Employees Compensation Act or the Federal Tort Claims Act.

J. Remuneration for Participation
You will not receive payment for participation in this experiment.

I certify that the series of tests for which (Printed Name of Subject) is to serve as a subject has been explained to him/her in detail.

_____________________________ ___________________
Signature of Principal Investigator Date

_____________________________ ___________________
Signature of Medical Monitor Date

Part 2

TO THE TEST PARTICIPANT: Read Part 1 carefully. Make sure all your questions have been answered to your satisfaction. Do not sign this form until you have read Part 1 and it has been signed by the Principal Investigator and the Government Medical Monitor. You will receive a copy of this consent form.

A. I, __________________, agree to participate in the tests and experiments described in Part 1 of this form.

B. I am aware of the possible foreseeable harmful consequences that may result from such participation, and that such participation may otherwise cause me inconvenience and discomfort as described in Part 1.

C. My consent has been freely given. I may withdraw my consent, and thereby withdraw from the study, at any time. I understand that the Principal Investigator may request my employer to dismiss me from the study if I am not conforming to the requirements of the study as outlined in Part 1; (2) that the NASA Medical Monitor may request my employer to dismiss me from the study if, in his opinion, my health and well-being are threatened; and (3) that the Facility Safety Manager may terminate the study if that unsafe conditions develop that cannot be immediately corrected.

D. My agreement to participate does not release NASA or any third party from future liability that may arise from the study described in Part 1. If I receive Workers' Compensation benefits while participating in this study, I understand that I cannot sue my employer because the law makes Workers' Compensation my only remedy against him/her. I understand that NASA will pay for any claims of injury, loss of life or property damage to the extent required by the Federal Employees Compensation Act or the Federal Tort Claims Act.

E. I hereby agree that all records collected by NASA in the course of this experiment are available to the Medical Monitor and the Principal and Co-Investigators and duly authorized research review committee. Any other requests for access to information will require a specific request for release. I grant NASA permission to reproduce and publish all records, notes or data collected from my participation provided that there will be no association by name with the collected data and that confidentiality is maintained. I understand that while all stated precautions will be taken to protect participant anonymity, there is a small risk that some or all data could become identifiable.

(1) I understand that I have the right to request the Chair of the Ames Human Research Institutional Review Board (HRIRB) to convene a Board Meeting if, at any time, I feel that my rights as a human research participant have been abused or violated.

F. I have had an opportunity to ask questions and I have received satisfactory answers to each question I have asked.

____
Printed or Typed Name of the Test Subject

________________________ _____________________
Signature of Test Subject Date

PROOF OF ARC HRIRB APPROVAL

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

October 15, 2009

Reply to Attn of: QH/243-2

TO: Laurence R. Young, Sc.D., Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139 ; NASA Point of Contact: Thomas Alderete, Code AF.

FROM: Ralph Pelligra, Chair, NASA Ames Research Center (ARC) Human Research Institutional Review Board (HRIRB)

SUBJECT: HRIRB Approval of Protocol **HRI-289**, "Spatial Orientation Estimation during Piloted Lunar Landing Terminal Descent Trajectories"

Approval Period: October 15 2009 through October 14 2010

Protocol **HRI-289** was presented to the Human Research Institutional Review Board (HRIRB) on October 01, 2009 and approved with conditions. The HRIRB requested modifications to the consent form, which were reviewed and approved by the Chair, HRIRB on October 15, 2009.

The Principal Investigator is authorized to conduct research, subject to the requirements as outlined in APR 7170.1, Human Research Planning and Approval.

Additional review of HRI-289 will be required by the HRIRB

- before changes are made to the protocol, except when necessary to prevent harm to the participant
- should any unexpected problems or unusual complications develop. Immediately notify the Chair, HRIRB, of any injury to a human participant, whether or not it was considered a risk inherent to the research.

In addition, all recruiting documents and publicity must be presented to the HRIRB for review and approval

Contact the Office for the Protection of Research Participants (OPRP), M/S 243-2 for the renewal request/study completion form. The renewal process should be undertaken **six weeks** prior to **October 14, 2010,** the study's termination date.

If you have any questions, please contact me at (650)-604-5163 or by e-mail at Ralph.Pelligra-1@nasa.gov. Good luck in your research endeavors.

Ralph Pelligra, M.D.

cc: AF:243-1/T. Alderete

PROOF OF MIT COUHES APPROVAL

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Laurence Young 37-219
From:	Leigh Firn, Chair COUHES
Date:	10/15/2009
Committee Action:	Approval
Committee Action Date	10/15/2009
COUHES Protocol #	0909003430
Study Title	Spatial Orientation Estimation during Piloted Lunar Landing Terminal Descent Trajectories
Expiration Date	10/14/2010

The above-referenced protocol has been APPROVED following Full Board Review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospective new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

MOTION SICKNESS QUESTIONNAIRE

Pre-experimental questionnaire:

Subject #: ______________________________________

Please circle your responses.

How often do you do the following activities?:		How likely are you to become motion sick while doing these activities?:
Ride in a car	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride in a bus	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride in a train	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride on a large boat	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride on a small boat	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride in a large airplane	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5
Ride in a small airplane	Daily Weekly Monthly Yearly Rarely Never	Not likely 1 2 3 4 Very likely 5

How do you rate your motion sickness susceptibility? Not very susceptible 1 2 3 4 Highly susceptible 5

When wearing any glasses or contacts that you normally wear do you consider yourself to have normal visual acuity? Yes No

Are you wearing glasses for this experiment? Yes No

Table of Subject Information

Subject	Male/Female	Age	Piloting Experience (Y/N)
1	M	28	N
2	M	30	Y
3	M	32	N
4	M	27	N
5	M	31	N
6	F	32	N
7	M	29	N
8	F	26	N