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VISUALLY COUPLED SYSTEM - COMPUTER GENERATED IMAGERY (VCS-CGI) --ETC(U)

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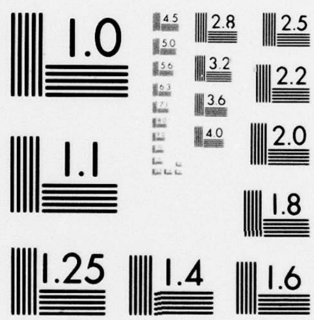

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VISUALLY COUPLED SYSTEM — COMPUTER GENERATED IMAGERY (VCS-CGI) ENGINEERING INTERFACE

SHELTON MACLEOD
AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
DAVID B. COBLINTZ
McDONNELL DOUGLAS ELECTRONICS COMPANY
DIVISION OF McDONNELL DOUGLAS CORPORATION
ST. CHARLES, MISSOURI 63301

NOVEMBER 1979

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AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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AMRL-TR-79-32

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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

FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
Air Force Aerospace Medical Research Laboratory

AIR FORCE/56780/1 February 1980 — 100

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Helmet-mounted sight and display hardware was interfaced with an advanced computer-generated imagery system. The system was then flown using a joystick in a tactical gunnery range data base simulation. Five presentation parameters (display update time, position update time, scene slew rate, head-position sensing precision and lag) were selected for experimental analysis. A subjective rating system of five levels for the first four parameters was devised. Five levels of lag were examined in a separate study using both a tracking and nontracking mode. Flight simulations were then carried out and each parameter

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20) was evaluated and the results analyzed.

PREFACE

This work was performed for the Visual Displays Systems Branch (HEA), Human Engineering Division, of the Aerospace Medical Research Laboratory (AMRL). The data analysis was performed by that laboratory, the experiments were designed jointly by that laboratory and the McDonnell Douglas Electronics Company (MDEC), and the hardware and software interfacing was performed by the MDEC. Dr. Shelton MacLeod was the technical monitor for AMRL. Key assistance is gratefully acknowledged to Milt Fulghum, Bernard Hanson, and Ernie Bynum of MDEC, respectively, for the computer programming, hardware interface design, and building of the interfaces. We wish also to thank Don Hauck, Joe Kosednar, and Darrell Lentsch of MDEC, and Dean Kocian, Shelton MacLeod, Master Sergeant Donald Smith, Major Michael Rundle, and John Bridenbaugh of AMRL for their participation as subjects in the experiments. Transformation mathematics for the project was provided by Dean Kocian. Finally, the assistance of Robert Mills in the response surface methodology analysis is gratefully acknowledged.

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SUMMARY

The Visually-Coupled System Computer-Generated Imagery (VCS-CGI) Interface program had two main phases. The objective for the first phase was to successfully interface the various subcomponents (helmet-mounted sight, helmet-mounted displays, and advanced computer-generated image system) and demonstrate their compatibility and feasibility for use in wide field of view, air-to-ground visual simulation. The objective for the second phase was to conduct a systematic exploration and evaluation of various system parameters that could affect display quality.

PHASE I

In the first phase a pair of Honeywell displays (Mod III) were integrated with a mechanical head position tracker and a VITAL IV computer generated image system. This effort involved the design and construction of the appropriate interface equipment as well as the modification of the computer program and data bases to permit both wide variation of experimental parameters required for the second phase studies as well as the demonstration of various techniques applicable to VCASS. One such technique was the masking of the terrain image by an occulting, computer generated silhouette of the pilot's cockpit. Parallax effects due to head motion and binocular effects were also represented. In this phase the system was flown using a joystick in a tactical gunnery range data base with a T-38 cockpit silhouette to occult the scene.

PHASE II

Five presentation parameters were selected for experimental analysis: Display Update Time, Position Update Time, Scene Slew Rate, Head Position Sensing Precision, and Lag. Effective ranges of each variable were determined by preliminary observation within equipment constraints. Five levels of the first four parameters were analyzed in a main experiment using a response surface statistical design with 31 presentations per subject. Five levels of lag were examined in a separate study.

Eight subjects were used, two of whom were pilots. All were familiar with the VCASS type of presentation. Subjects were given controlled monocular presentations of a night carrier scene with balanced combinations of all experimental parameters. Two kinds of judgments were made to assess the level or types of degradation associated each presentation:

a. An overall quality rating on a continuous scale from zero to four with the following numerical transition points: 0 (ideal); 1 (noticeable degradation); 2 (objectionable degradation); 3 (degradation expected to impair operator performance), and 4 (degradation expected to be extremely disruptive to operator performance).

b. A subjective analysis of discriminable kinds of degradation phenomena. These are described by the terms: Multiple Imaging, Jitter, Jumping, Flicker, Lag, Hard-to-track, and Blur.

Appropriate anchoring stimuli were selected to provide high and low quality end points for the rating scale. These produced both the highest (3.9) and the lowest (0.4) mean ratings obtained in the study.

Precision, which was varied from 6 to 14 bits, had a strong effect on display quality. For 9 presentations which included high levels of precision ($\geq$ 12 bits) and balanced variation of all other parameters, the mean rating was 1.7, indicating a quality level which was at worst mildly objectionable.

Moreover, for these high levels of precision, the only conditions under which mean quality ratings were greater than 2.0 occurred (for two presentations) where both Position Update Time and Scene Slew Rate were set at relatively high (degrading) levels.

At low Precision levels ($\leq$ 8 bits), on the other hand, the mean quality rating (again for nine presentations with balanced combinations of the other factors) was greater than 2.5, suggesting impairment to operator performance. Degradation effects for low precision (with the other parameters set at nondegrading levels) were also revealed by the relatively high rate of associated display anomalies. In particular, Jumping was perceived 94 percent of the time and Multiple Imaging also had a high rate of occurrence (82%).

Scene Slew Rate (varied over a range of 0-25^{o}/sec) was the only other parameter with an overall significant effect on display quality ratings. Averaged across all other parameters, this factor produced a mean rating of 2.5 (showing unacceptable quality) when its level equalled or exceeded 15^{o}/sec. Multiple imaging and tracking difficulty were the predominant forms of degradation associated with high slew rates.

Over balanced combinations of all other parameters, Position Update Time had no significant impact on quality judgment. However, when it was varied under conditions of high precision (12 bits), it became an effective determinant. The principal degradation responses associated with high Position Update Time ($\geq$ 70 msec) were Jitter and Multiple Imaging.

Display Update Time was varied from 25 to 45 msec. Within this somewhat restricted range it produced no measureable effects on display quality ratings and elicited relatively few degradation responses.

The effect of Lag on Display quality was the subject of a separate study in which four levels of this parameter were explored over a range of 45 to 495 msec. Quality ratings were provided by the subjects for two modes of viewing:

a. Tracking mode - where the subject attempted to maintain fixation on the aircraft carrier as it was slewed at 10^{o}/sec along a pseudo-random path.

b. Nontracking mode - where the subject alternated his fixations between two points in the display.

As in the case of Precision, Lag had a powerful effect on display quality which was evident for both modes of viewing. At the highest level of lag (495 msec) mean quality ratings for both viewing modes approached 3.5, indicative of an extremely disruptive display. Conversely, at the lowest Lag value (45 msec) mean ratings for both modes fell within a superior quality zone where degradation though noticeable was not objectionable. At the same time there was a consistent difference in ratings between the two viewing modes at the lower levels of Lag (45-75 msec), wherein better quality ratings were assigned in the case of the tracking mode.

In general, the results showed that Lags of less than 50 msec are required to produce displays of supperior quality, and Lags which exceed 200 msec are judged to impair operator performance.

VCS-CGI ENGINEERING INTERFACE

INTRODUCTION

In the past, air-to-air and air-to-ground combat visual simulation systems have been very expensive and complex while yielding only marginally acceptable imagery. This is largely due to the requirements for highly detailed imagery over an extremely wide field of view presented at very high rates. The Aerospace Medical Research Laboratory (AMRL) has been pursuing the development of Visually Coupled Systems (VCS) for many years. Currently, AMRL's Visually Coupled Airborne Systems Simulator (VCASS) Program is aimed at exploiting the unique capabilities of the VCS technology including Helmet Mounted Sights and Helmet Mounted Displays to solve some of the deficiencies of previous visual scene simulation techniques and extending these to the airborne environment. AMRL is developing advanced VCS components for this research program, but answers are required to fundamental questions before component specifications can be finalized. Experimental exploration of these questions requires the capability to vary the parameters involved over wide ranges. A low-cost computer generated imagery system (VITAL IV) provided imagery well suited to a VCASS research program, since it allows visual flight simulation while accepting a position update rate variable up to 100 Hz. A second field of view display scene was available to allow stereo or double field image generation. This system also provided high fidelity simulation of weather conditions as well as simulated cockpit occulsion of the external CGI scene.

OBJECTIVE

The objective for the first phase of this program was to accomplish the successful engineering interface of several subsystems integral to AMRL's Visually Coupled Airborne System Simulator (VCASS) Program. The specific subsystem capabilities to be interfaced were a government furnished Helmet Mounted Sight and Helmet Mounted Display with a computer generated imagery subsystem (VITAL IV) owned by McDonnell Douglas Electronics Company. The second phase objective was to systematically explore and evaluate various system parameters such as display and position update rate, display field of view, system throughput delay, and head-tracking precision.

APPARATUS

The effort included the design and fabrication of interfaces between Helmet Mounted Sight and Display subsystems provided as Government Furnished Equipment (GFE) and an existing contractor-owned computer generated imagery system (VITAL IV) at the contractor's facility.

Helmet Mounted Displays

AMRL provided two Helmet Mounted Display Systems consisting of display electronics unit, control panel, CRT assemblies and interconnecting cabling. Also included were two Honeywell MOD III 40° field of view display optical units, one mounted on each side of a helmet which was supplied with the mechanical Helmet Mounted Sight (See Figures 1, 2, and 3). The display electronics units were capable of being operated either in the direct draw or calligraphic mode. In accomplishing the interface no internal modifications were made to the HMD hardware.

Helmet Mounted Sight

The Government-Furnished Helmet Mounted Sight System consisted of a mechanical helmet tracker and associated electronics capable of providing essentially continuous output of helmet position and orientation information (6 degrees of freedom). The VITAL IV computer image generator converted this output to transformation matrices and hence to real time image motion corresponding to the measured helmet motion. The tracking mechanism consisted of five resolvers and one linear encoder. (See Figures 4 and 5.) Three of the resolvers measured helmet orientation, while the other two, together with the linear encoder, provided signals from which Cartesian position coordinates (XYZ) were derived. The head motion inputs were combined with simulated aircraft motion to arrive at the net transformation of the scene viewed by the pilot.

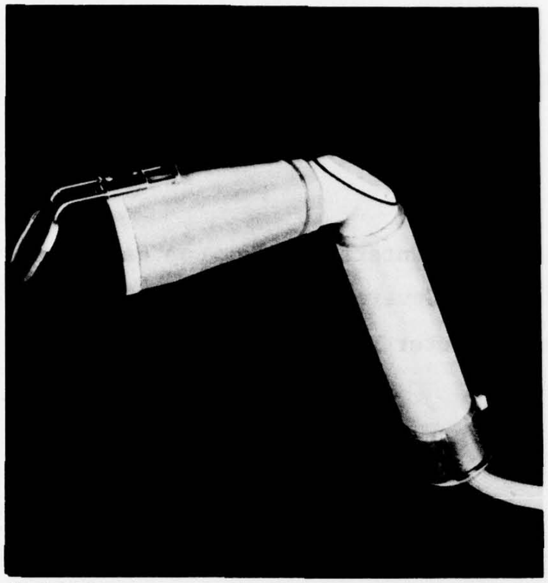

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Figure 1. Honeywell MOD III display

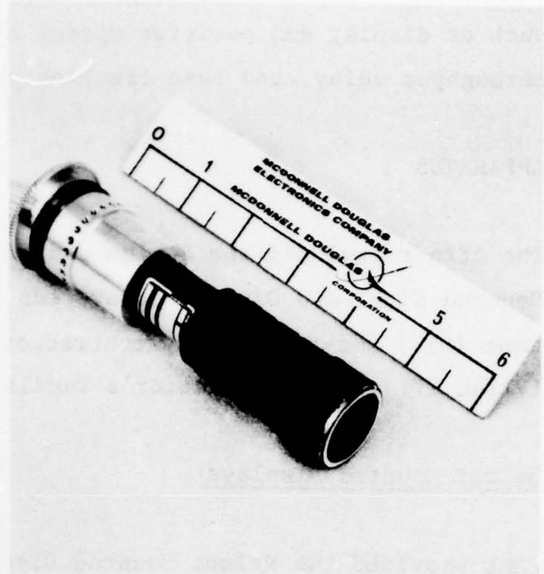

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Figure 2. Cathode-ray tube assembly

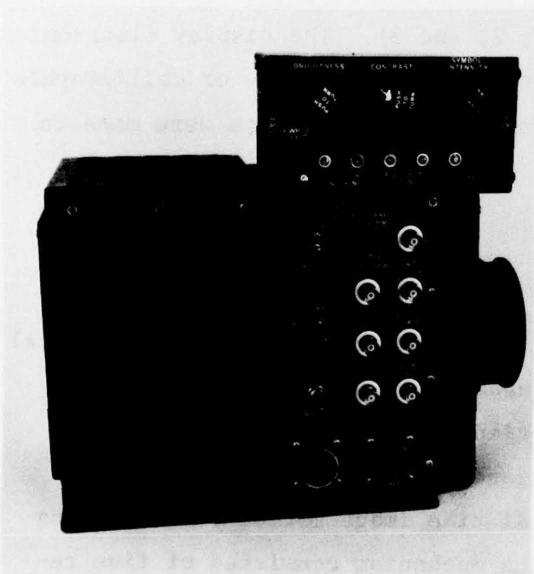

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Figure 3. Display electronics unit and control panel

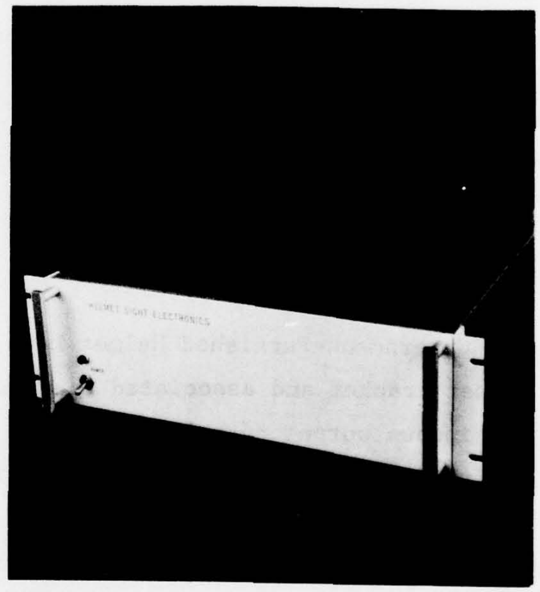

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Figure 4. Helmet sight electronics

Computer Generated Image (CGI) System

A standard VITAL IV CGI system was used (See Figure 6). This system comprises a calligraphic display controlled by a Varian 76 general purpose minicomputer and high speed special purpose hardware which transform a digitally stored data base, representing the outside environment, to a perspective view of this environment as seen from the pilot's eyepoint. The environment is made up of lightpoints and shapes to represent night, day, or twilight scenes. The basic CGI display environments for this effort were environments already in existence at MDEC including an air-to-ground environment, an aircraft carrier environment, and take-off/fly-over/landing environments. The VITAL IV system normally accepts inputs of aircraft state vectors and the coordinates of moving objects in the environment from a host aircraft simulator computer. From these it creates the matrices required to transform the various objects to eyepoint coordinates and performs the transformations required to create the new perspective views in real time. For this project a small joystick box was used instead of a host computer to allow one to "fly" the system. This joystick box was modified to increase its update rate and to allow the rate to be varied easily over a wide range. Modifications to the computer program were made to incorporate the additional transformations required by changes in head motion so that the displayed scene changed simultaneously as a function of flight and head motion. The allowable head motion range was ± 180 degrees in azimuth, ± 75 degrees in elevation, and ± 30 degrees roll. The operating program was also modified to permit independent variation of input sampling rate (head tracker and flight control inputs), system throughput delay, display frame time, and simulated display field of view. Single-eye or two-eye viewing in redundant biocular, variable overlap binocular, and stereo modes were provided. Update and refresh of the display could be based solely upon the most recent input or upon an interpolation from the most recent two inputs. Occulting was used to provide simulated masking of the displayed scene caused by the silhouette of the pilot's aircraft structure. Advantages of the VITAL IV Image Generator for this application were:

a. MDEC's patented calligraphic image generation technique which allowed updated rates to be readily traded for quantity of scene content with no loss

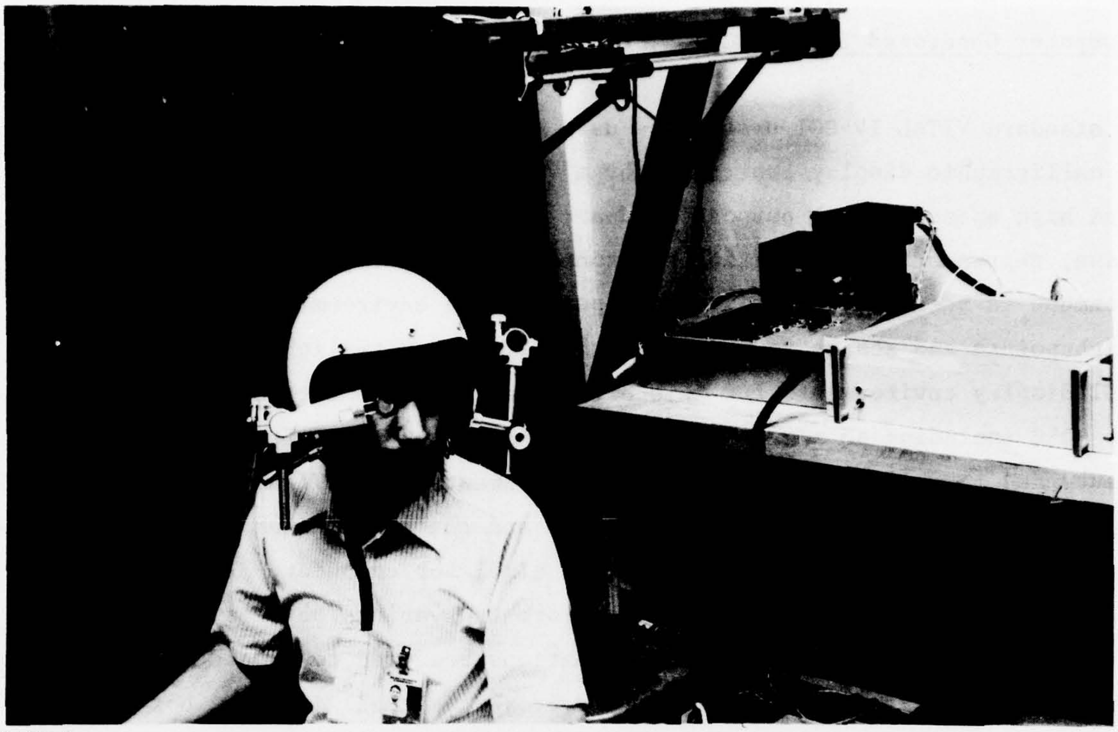

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Figure 5. Head position tracker and display system

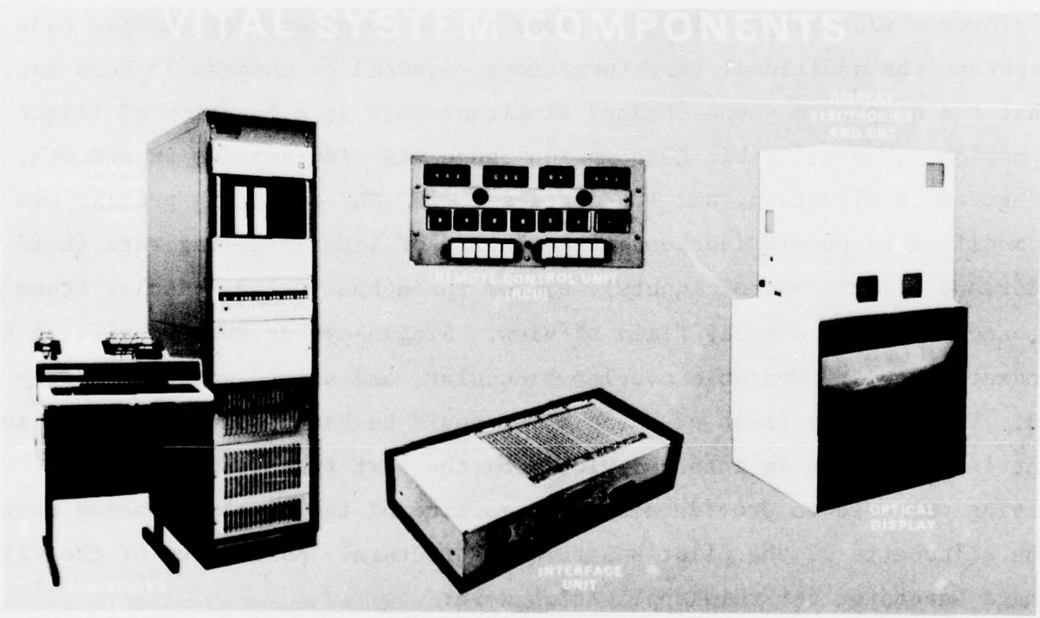

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Figure 6. VITAL IV computer generated image system

of image quality. This would have been much more difficult with a raster type system.

b. The fact that VITAL IV could readily be interfaced with the Honeywell display to yield image content comparable to that provided on normal VITAL display units.

Interfaces

Design and construction of the display interfaces (Figure 7) basically involved design of receivers for the analog deflection and intensity signals as well as the digital unblank and necessary control functions. Signal scaling and delay matching functions were also designed into the interface unit. The remote video blank circuits in the Honeywell Helmet Display Unit were found to be too slow for VITAL IV blanking. This resulted in intensity ringing at the edges of shape. Therefore, the intensity signal was blanked and unblanked at the input. This method eliminated the ringing but still allowed a brightening of intensity near the edges of shapes. It could readily be upgraded to provide a quite acceptable signal.

A standard host interface unit is normally used with the VITAL IV system. The vital interface unit was specifically designed so that the impact of the electronic interface on the Host Flight Simulator Computer would be minimized. The interface consists of a fully asynchronous bit parallel word serial digital data channel from the host computer to the VITAL IV interface unit. The output of the Helmet Mounted Sight and joystick were channeled into the standard VITAL interface unit. Provisions were made for supplying the appropriate control signals to the Helmet Mounted Sight, to sequence through the various input parameters.

In addition to driving two HMD systems, the standard VITAL IV system used in this effort included its own monitor displays on which the two HMD display scenes could be viewed by the experimenter at the same time as the subjects viewed them on the HMD. Upon completion, the various hardware subsystem, program, and environment modifications were integrated with the VCS hardware and VITAL IV to form a complete VCS-CGI system. A block diagram of the system is shown in Figure 8.

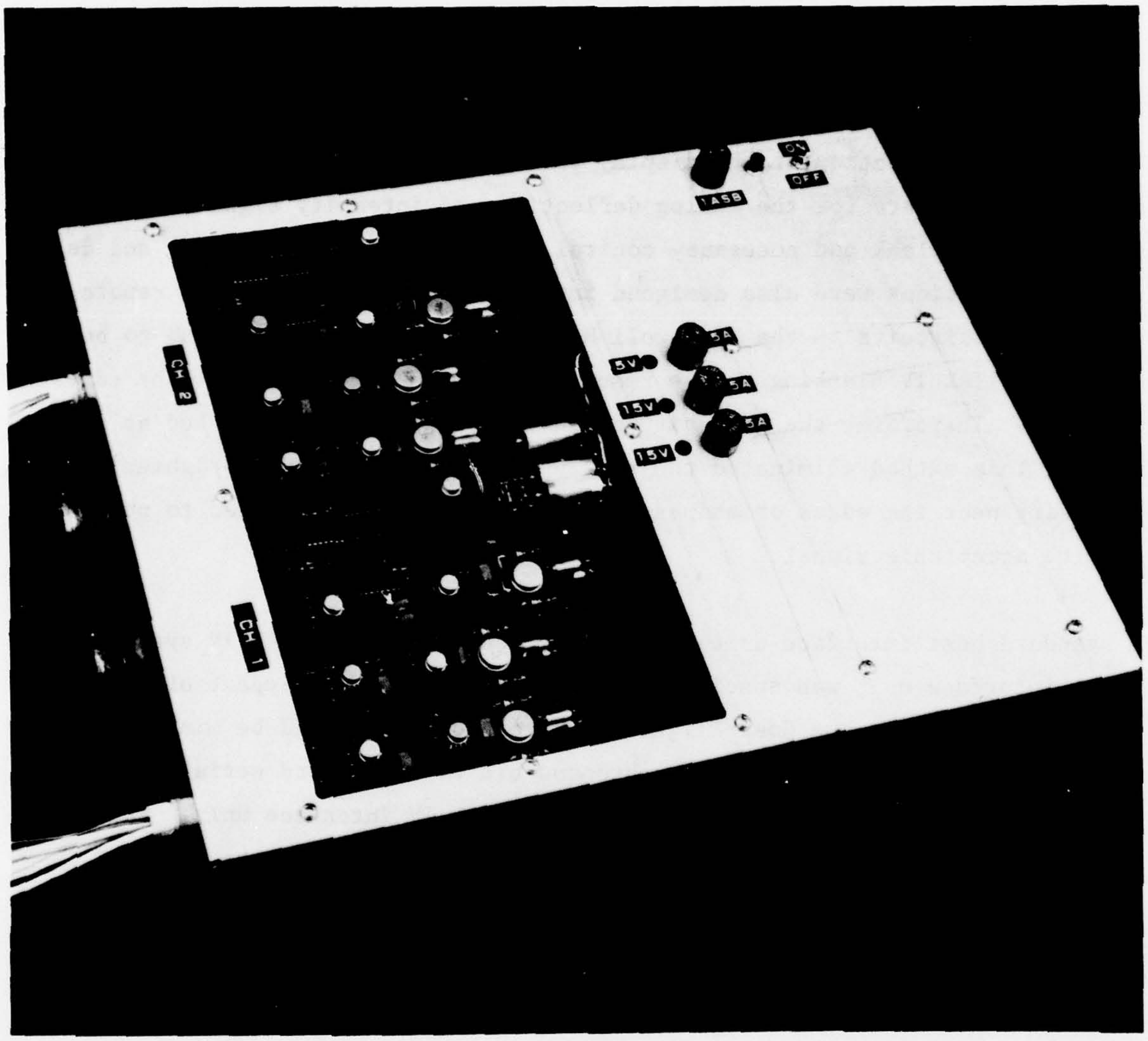

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Figure 7. Display interfaces

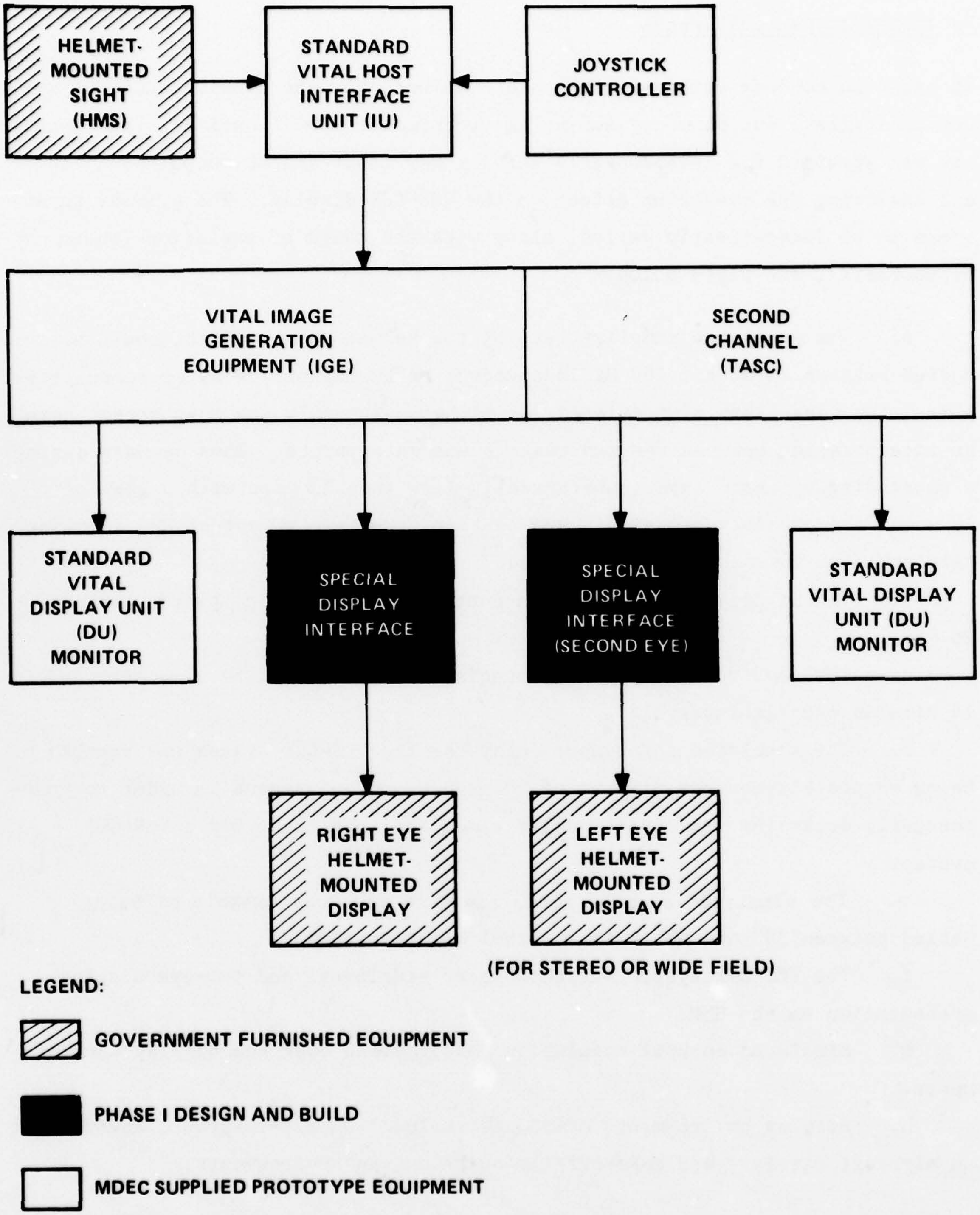

Figure 8. VCS-CGI system block diagram

Parameter Adjustment Ranges

In order to conduct critical evaluations of not only the combined VCS-CGI system capability, but also key subsystem performance specifications, the capability was provided for independently varying key input and/or output parameters and observing the resulting effect on the VCS-CGI display. The primary parameters to be independently varied, along with the range of variation (where appropriate), are given below:

a. The simulated sampling rate of the Helmet Mounted Sight could be varied between 20 Hz and 100 Hz independent of throughput delay or computation time. The capability also existed for either using only the most recent data or interpolating between the two most recent data inputs. Thus by maintaining a short display frame time (substantially less than 33 msec with a goal of 10 msec) and possibly reducing scene content, the true effect of HMS sampling rate could be independently determined.

b. The display update time was continuously variable upwards from 25 msec.

c. The head position sensing precision was variable between zero and 14 bits in one bit intervals.

d. The simulated throughput delay for the VCS-CGI system was capable of being varied between the minimum of 10 msec up to one second in order to independently determine what system delay times are acceptable for a VCS-CGI system.

e. The simulated display scene field of view was capable of being varied between 20° and 60° with a 1-to-1 magnification.

f. The VCS-CGI system was capable of single-eye and two-eye display presentation on the HMD.

g. Simulated cockpit occulation was provided over the display environments.

h. Display environments available included an air-to-ground environment, an aircraft carrier, and take-off/fly-over/landing environments.

The details of the mathematical transformations for converting the mechanical Helmet Sight outputs to helmet position and orientation are given in Appendix A.

EXPERIMENTATION USING THE VCS-CGI SYSTEM

EXPERIMENT OBJECTIVES

Given a successful engineering interface of the subsystems (helmet mounted sight, helmet mounted display, and computer generated imagery subsystem) which are integral to AMRL's Visually Coupled Airborne Systems Simulator (VCASS) program, the broad objective of the experimentation phase of this effort was to exercise the system and to evaluate the quality of displays produced by it under controlled experimental conditions.

By initial agreement, two important constraints were established for the type of display to be studied and the manner in which it was to be evaluated.

Binocular vs Monocular Displays

Although it had previously been planned to evaluate the system in terms of binocular presentations (with variable fields of view and amounts of overlap), equipment limitations made this plan unfeasible. The two available HMD's, when placed in the existing helmet mounts, failed to provide images which were compatible for proper optical fusing or which had sufficiently large fields of view and adjustment range for the proposed binocular research. Therefore, it was decided to restrict the system being evaluated to a single display channel utilizing a monocular right-eye presentation.

Performance Measures

Two broad choices for the kind of operator performance measures were considered as feasible alternatives for evaluating the monocular VCASS system. One of these was a subjective assessment technique wherein the operator provided numerical ratings to represent perceived differences in display quality. This kind of measure has the advantage of being easy to record, relatively reliable (as indicated by previous subjective scaling research) and obviously valid in the sense that no display should be developed for a user if its visual quality is judged to be unacceptable.

The other kind of performance measure considered was a real-time record of visual tracking which would indicate how accurately the head can follow and permit visual pursuit of moving targets. Given sufficient lead-time and resources for developing an effective means to record and analyze tracking data, with the available VCASS system, this approach had considerable appeal both from the point of view of face validity (pilots must track targets with the system) and objectivity. Moreover important differences may well exist between the type of independent variables that affect the appearance of the display and those that control tracking accuracy. "Double-dotting" for example might be judged as only a minor visual quality blemish, while representing a serious problem for tracking; or a blurred, low-contrast, or flickering image might represent very poor visual quality while having little or no effect on tracking accuracy.

Unfortunately, inclusion of even a relatively simple acceptable technique for correlating head tracking performance with presentation parameters proved to be beyond the scope of the present contract. Hence only the scaling approach was pursued.

EXPERIMENTAL METHOD

HMD Scene

A single scene was selected for experimental use from the numerous environments available within the VITAL IV system. This was a night aircraft carrier scene depicted in Figure 9. When viewing this scene the subject was instructed to maintain fixation at the junction of lines at the forward center of the landing strip and to judge the quality of the display in terms of visual elements associated with the carrier. Of primary importance, in this regard, were the dotted rows of landing lights which remained within a few degrees of foveal vision and lined the center and edges of the landing strip. The visual subtense of the carrier's longest dimension was about ten degrees. The luminance of the various parts of the image varied between 0.05 and 10 ft lamberts. This range of luminance provided adequate visual contrast with the much darker surrounds, while remaining dim enough to generally suppress visual flicker.

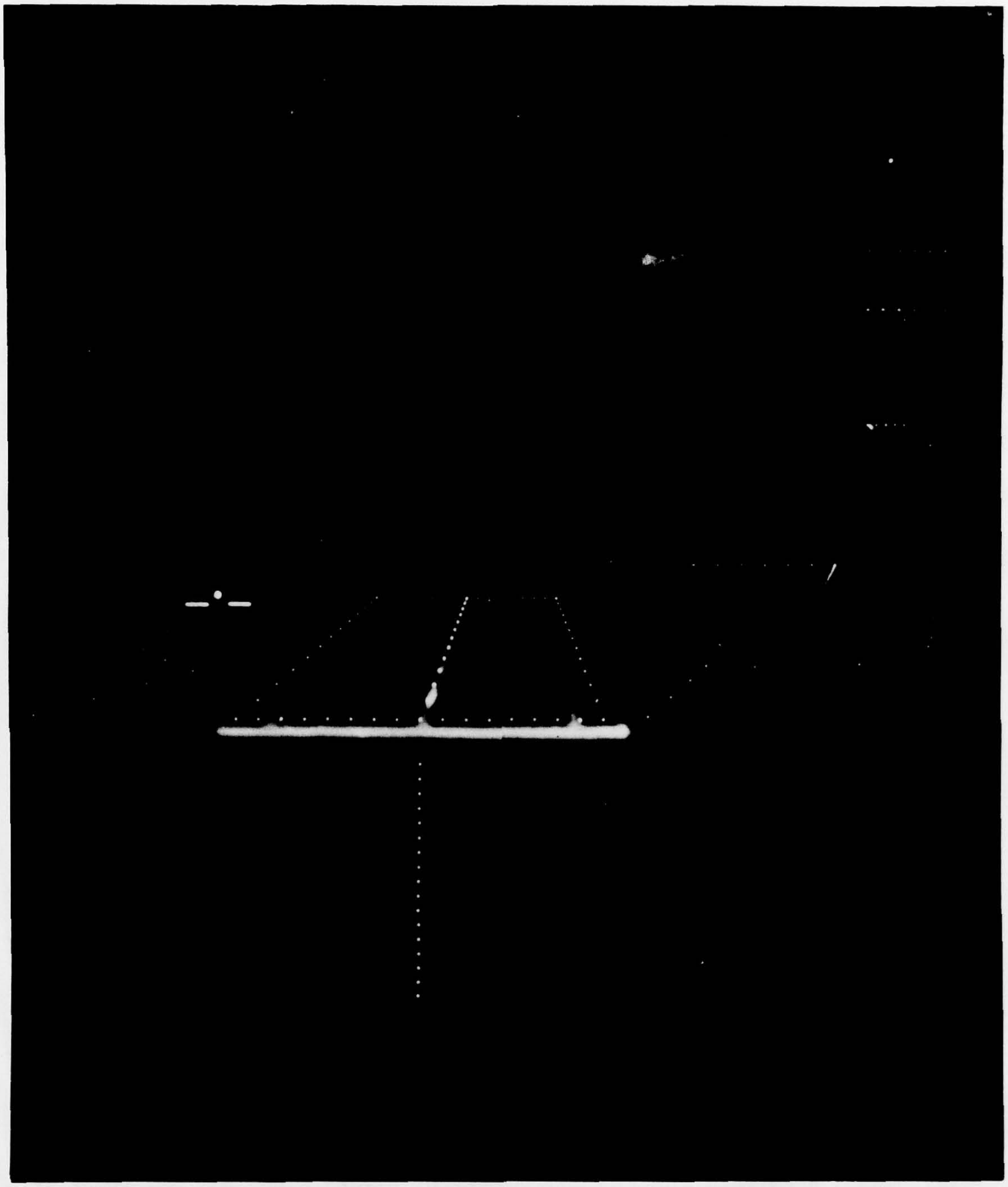

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Figure 9. Night aircraft carrier scene used in the present study.

Brightness was adjusted for each subject to eliminate any flicker at the 30 msec display update interval.

Once the scene had been initially presented to the right eye, its focus and orientation were adjusted until the sharpest possible, horizontally-aligned image of the carrier was registered in the center of the visual field.

Presentation Parameters

A fairly extensive set of parameters were identified as having a potentially degrading effect (over some portion of their range) on VCASS display quality. These are defined and their properties for degradation identified as follows. The first five parameters listed became independent variables in the experiments to follow, while the remaining factors were held constant at some relatively optimal level:

o Display Update Time (DUT). The interval in msec at which successive display frames are presented on the CRT. Excessively long durations of this parameter would degrade display quality by producing flicker or strobe effects.

o Position Update Time (PUT). The duration in msec between position samples, i.e., the interval between updates of the helmet position data. PUT can interact with DUT and Lag to produce various display perturbations.

o Scene Slew Rate (SSR). This is the rate, in degrees per second, at which the carrier scene is moved by a forcing function in pitch, roll, or yaw. Such functions available in the VITAL IV system driver cause the scene to travel linearly along one or more of these dimensions until it reaches one limit (typed in by the operator). It then moves linearly in the opposite direction until it arrives at the other limit. As the observer fixates the carrier, variations in slew rate simulate the effect of aircraft motion. In the present experiment slew occurred simultaneously in the pitch and yaw dimensions causing display movement to follow a pseudo-random path. Excursions of the moving display varied in extent from about ± 7 degrees for the slowest slew rate to about ± 26 degrees for the fastest in order to keep the time between direction changes roughly constant at about two and one half seconds. Sufficiently high scene slew rates would tend to impair head-tracking efficiency and otherwise adversely affect display quality.

o Precision (PRB). This parameter, specified in bits, represents the number of position steps available in the display which can be affected by head motion. With an insufficient number of such steps the image will move jerkily and undergo a number of other kinds of degradation in response to head motions.

o Lag or System Throughput Delay. This is defined as the delay in msec between the time upon which calculation of image position is based and the time at which it is used (i.e. in generating the displayed image). Lag differs from PUT in two ways: (a) PUT is only one of several factors that can affect Lag; (b) For a given PUT, the manner in which the position samples are used also affects Lag.

Excessive physical lag should introduce a corresponding degree of perceived temporal lag and make the image hard to track.

o Position Update Mode. Two modes of controlling displayed position were available:

a. one which involves linear interpolation of the two most recent position samples to estimate the position at time of display,

b. an uncorrected mode based only on the most recently sampled position. In the present experiments only the uncorrected mode was used.

o Display Luminance. The highest level of luminance was represented by the carrier lights. This was maintained at a relatively low photopic level.

o Display Contrast. This is the luminance ratio between the bright regions of the display and the dark background. Though not specified in this study, contrast was held relatively constant at a high level sufficient to provide clear visibility of the carrier lights.

• Field of View. The displayed field of view was decreased somewhat by adjusting the horizontal and vertical gain in the interface unit to eliminate unwanted optical distortion at its edges. It was rectangular in shape, 26 degrees along the vertical and 32 degrees along the horizontal dimension.

Experimental Facility

The observer was stationed in a small room with overhead (incandescent) lighting controlled by a rheostat. Before any data were taken, he was first fitted to a helmet which had been linked to the head-tracking system. The Helmet Mounted Display was then attached and its image (the night carrier scene) was properly aligned and focused. An extensive homogeneous dark visual background was provided by a black cloth fastened to a screen which curved from left to right around and in front of the subject at about a two-foot distance. All HMD images to be presented were contained within this background. Room illumination was held at a low level just sufficient to permit reading and manual recording by the subject.

The experimenter provided controlled inputs to the HMD from an adjoining room. A two-way voice-link between experimenter and subject was maintained through a small opening in a sliding partition separating the two rooms.

Display Quality Scoring Technique

The subject was trained to make and record two types of judgments immediately following each HMD presentation.

The first of these was an overall display quality categorization in which he assigned a numerical rating to the image (consisting primarily of the carrier lights). This rating fell somewhere along a scale having major divisions which are defined in terms of the following numerical categories:

0 - representing an ideal high quality display (the best that could be achieved with the present VCS-CGI system).

1 - representing a display which has noticeable degradation, but which would not be judged as objectionable by a display operator.

2 - representing a display for which the degradation has become objectionable, but which is unlikely to impair an operator's performance.

3 - representing a display for which the degradation has become severe enough to impair an operator's performance, but not to a degree that would be considered extremely disruptive.

4 - representing the worst possible display having a level of degradation which would seriously disrupt an operator's performance.

Ratings based on the above criteria were recorded by inserting an appropriate check mark along a 17-step, numerically graduated line consisting of the above five numerical divisions (0-4) with each division further separated into quarter-step intermediate positions.

The second type of judgment was more analytical and was used to identify the specific kind or kinds of quality degradation which were observed. Such assignments were based on a standard check-list of the following possible anomalies affecting the quality of the VCASS display:

a. Jitter. A tendency for portions of the image to produce small oscillating vibrations without positional displacement.

b. Multiple Imaging. The breaking up of images into two or more parts. The simplest case of this is double dotting, e.g., where a double line of lights appears along the carrier runway.

c. Jumping. Here the amplitude of apparent image motion has exceeded the jitter stage so that portions of the image abruptly change from one position to another.

d. Flickering. An alternating temporal change in the perceived brightness of an image.

e. Lag. A perceived lack of temporal correspondence between a particular head movement and associated image movement. Typically, the image movement will lag behind the head movement.

f. Hard-to-Track. Where a moving image being fixated is (for any reason) difficult to follow and visually track with the head moving.

g. Blur. An image which has the appearance of being out of focus or lacking sharp contours.

After each presentation a global quality judgment was made and recorded by marking the linear scale. Then all associated kinds of perceived degradation (if any) were recorded by writing one or more responses from the above checklist along side of the rating line.

Presentation Sequence

Each experimental presentation consisted of the following temporal sequence:

Event	Approximate Time Required	Explanation
1. Parameter set by operator	30 seconds to 2 minutes	The length of time depended on the types and levels of variables being combined in the presentation
2. Operator Command "Close your Eyes"	10 seconds	This prevented the subject from prematurely viewing a display being readied for presentation by the operator
3. Operator Command: "Ready" along with number of presentation	2 seconds	This prepared the subject to attend to upcoming presentation and to record his response at proper presentation number
4. Subject Response: "Ready" along with repetition of the same presentation number	5 seconds	This was given immediately after the display had been perceived and the subject's presentation number tallied with the one given by the operator

Event	Approximate Time Required	Explanation
5. Presentation - Recording Period	30 seconds	During this period the subject formed and recorded the two types of display quality judgments

From the above schedule one notes that total time for a single presentation varies from about one to three minutes.

Experimental Programs

Two experiments were run to evaluate the effects of VCASS presentation parameters upon quality judgments. The first and most extensive experiment (Main Experiment) dealt with four independent variables (Display Update Time, Position Update Time, Scene Slew Rate, and Precision). The second experiment concerned only Lag.

MAIN EXPERIMENT

Method

The main experiment was designed to explore the effects of four parameters, each being varied over physical ranges at five equally spaced intervals.

A recently developed and promising type of statistical analysis, known as Response Surface Methodology (RSM), enables one to make initial explorations of the type proposed here. Using RSM, one can uncover main effects and two-way interactions for a relatively large number of previously untested variables presented simultaneously and this can be done with only a very small fraction of the number of trials representing a complete factorial design. Using a central composite, rotatable, second-order RSM design in the case of the proposed experiment, only 31 presentations were required (Cochran and Cox 1957, p. 370) whereas a complete factorial design would have required 12,500.

The categories and levels of variables selected for the RSM analysis are listed in Table 1. Note that the five levels for each parameter correspond to the coded numbers: -2, -1, 0, +1, +2. All levels are at equal intervals and the values from -2 to +2 are selected to represent an hypothesized increasing effect of display degradation. The following considerations based on pilot studies also partially determined which particular values would be chosen:

a. The -2 values for both Display and Position Update Time were limited by equipment constraints, i.e., these variables could not be further decreased without program failure.

b. To the degree possible, parameter endpoints were also selected (as in the cases of System Slew Rate and Precision) to represent a range over which maximum effect on display quality might be expected.

The combinations making up the 31 RSM presentations for the four variables, each at five coded levels, are shown in Table 2. The model numbers (1-31) were presented in a fixed random order to all eight subjects during the experiment. Two additional presentations were given initially. The first of these was designed to elicit a very high quality anchoring stimulus and thus allow the subjects to appreciate the best possible display. Parameters for this high anchor were set as follows: DUT = 35 msec, PUT = 50 msec, SSR = 10^{o}/Sec and PRB = 10 bits. A contrasting low quality anchor occurred at the second presentation. This was intended to provide the worst possible quality rating at the opposite end of the scale. Parameters for this stimulus were: DUT = 40 msec, PUT = 70 msec, SSR = 15^{o}/sec and PRB = 8 bits.

Eight volunteer subjects with normal or corrected vision were run successively in the main experiment. One of these (MR) was a pilot from AMRL. Four others (SM, DK, JB & DS) were nonpilot AMRL personnel working on the FCASS system. The remaining three (DL, JK & DH) were engineers from MDEC who were also knowledgeable about VCASS. One of them (DH) was a commercial instructor pilot.

Table 1. Experimental parameters and levels selected for Response Surface Analysis. Numbers in columns represent the physical levels of each parameter which correspond with the five coded levels: -2, -1, 0, +1, +2.

	CODED PRESENTATION LEVEL				
	-2	-1	0	+1	+2
Display Update Time	25 msec	30 msec	35 msec	40 msec	45 msec
Position Update Time	10 msec	30 msec	50 msec	70 msec	90 msec
Scene Slew Rate	0 deg/sec	5 deg/sec	10 deg/sec	15 deg/sec	20 deg/sec
Precision	14 bits	12 bits	10 bits	8 bits	6 bits

Table 2. Coded values for Response Surface Analysis. Central composite rotatable second order design. Plan: 4 variables; N=31 treatment combinations; 2^4 factorial + star design + 7 points in the center.

Model No.	DUT 1	PUT 2	PRB 3	SSR 4	Model No.	DUT 1	PUT 2	PRB 3	SSR 4
1	-1	-1	-1	-1	17	-2	0	0	0
2	1	-1	-1	-1	18	2	0	0	0
3	-1	1	-1	-1	19	0	-2	0	0
4	1	1	-1	-1	20	0	2	0	0
5	-1	-1	1	-1	21	0	0	-2	0
6	1	-1	1	-1	22	0	0	2	0
7	-1	1	1	-1	23	0	0	0	-2
8	1	1	1	-1	24	0	0	0	2
9	-1	-1	-1	1	25	0	0	0	0
10	1	-1	-1	1	26	0	0	0	0
11	-1	1	-1	1	27	0	0	0	0
12	1	1	-1	1	28	0	0	0	0
13	-1	-1	1	1	29	0	0	0	0
14	1	-1	1	1	30	0	0	0	0
15	-1	1	1	1	31	0	0	0	0
16	1	1	1	1					

DUT = Display Update Time
PUT = Position Update Time
PRB = Precision
SSR = Scene Slew Rate

Results and Conclusions from Main Experiment

• Frequency Distribution for Subjects' Ratings. Figure 10 consists of eight arrays of frequency distributions for the thirty-one display quality ratings on a subject-by-subject basis. Inspection of these distributions reveals intersubject differences with respect to ranges, frequencies and distributions of the numerical ratings. Total frequencies at the foot of the table show that all 17-scale values were used and that the overall distribution is bimodal for numerical ratings 2 and 3.

It is important to note that no subject restricted his judgments to a very narrow range. All portions of the scale were used by all subjects.

• Analysis of Variance. A regression Analysis of Variance was applied to the data (based on the model shown in Table 2) to show possible main effects and two-way interactions for the four independent variables. Using the Residual (Lack of Fit plus Replications) as an Error Term, the following sources of variance were found to be significant at p values beyond the 0.01 level:

System Slew Rate: $F(1, 16) = 23$

Precision: $F(1, 16) = 99$

Position Update Time x Precision:
$F(1, 16) = 10$

No other sources of variance were significant at or beyond the 0.05 level.

• Effects of the Presentation Parameters on Display Quality Ratings. A result of immediate interest concerned the effectiveness of the high and low anchor points for establishing opposite extremes of the rating scale. The mean rating for the high anchor presentation was only 0.47 with a SD of 0.37. It clearly represented the highest quality reference point where degradation was no more than barely noticeable. The low quality anchor proved to be equally effective in representing the opposite end of the scale where quality was judged to be extremely disruptive. It had a mean rating of 3.6 (higher than any other presentation) with an SD of 0.40 and elicited a total of 25 degradation terms including every category but blur.

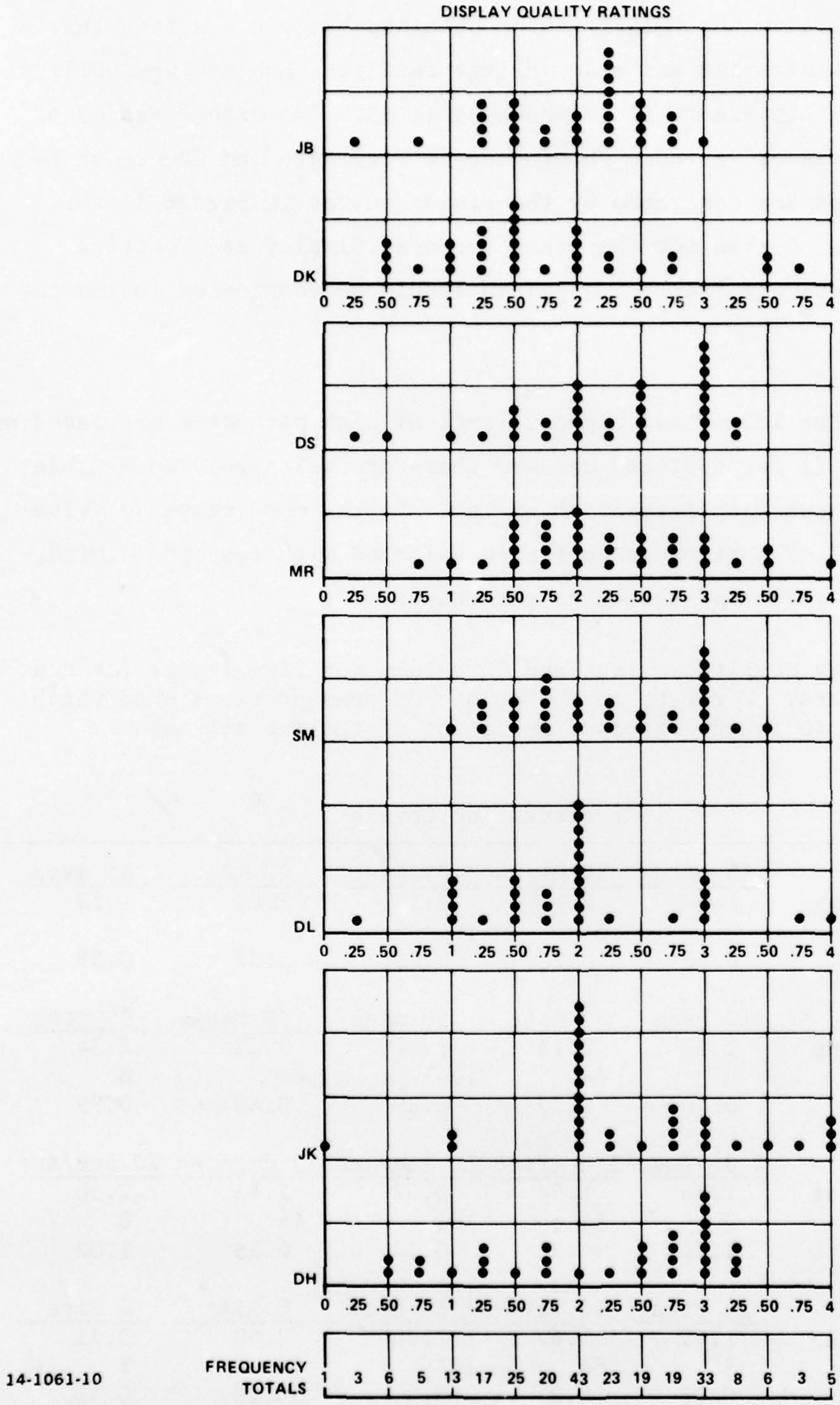

Figure 10. Frequency distributions of display quality ratings for eight subjects in the main experiment.

Table 3 and Figure 11 show the relationships obtained between the five levels of each presentation parameter and mean quality ratings. Subject variability around each data point in Figure 11 is shown as ±1 SD. The high F ratios of the regression analysis of variance showing Scene Slew Rate and Precision to be significant factors are confirmed by the rising curves in Figure 11 for these two parameters. Curves for the other factors, Display and Position Update Time, are relatively flat. Two points should be considered in looking at these data:

a. Means for the lowest and highest level of each parameter are based on only 8 presentations (1 per subject) and are therefore relatively unreliable;

b. As can be seen from inspection of Table 2, the mean response value plotted at each level of a given parameter is balanced with respect to high, low, or intermediate levels of the other parameters.

Table 3. Mean display quality ratings and SD values for five levels for four experimental parameters. N refers to the number of presentations upon which each mean is based. SD is the standard deviation of the subject means.

		Presentation Levels				
		25 msec	30 msec	35 msec	40 msec	45 msec
Display Update Time	Mean Rating	1.84	2.12	2.13	2.26	1.53
	N	8	64	104	64	8
	SD	0.46	0.22	0.22	0.32	0.59
		10 msec	30 msec	50 msec	70 msec	90 msec
Position Update Time	Mean Rating	1.88	2.14	2.04	2.22	2.34
	N	8	64	104	64	8
	SD	0.40	0.27	0.20	0.48	0.99
		0 deg/sec	5 deg/sec	10 deg/sec	15 deg/sec	20 deg/sec
Scene Slew Rate	Mean Rating	1.66	1.94	2.07	2.43	2.50
	N	8	64	104	64	8
	SD	1.26	0.26	0.20	0.25	1.02
		14 Bits	12 Bits	10 Bits	8 Bits	6 Bits
Precision	Mean Rating	1.69	1.67	2.00	2.69	3.31
	N	8	64	104	64	8
	SD	0.75	0.24	0.21	0.30	0.46

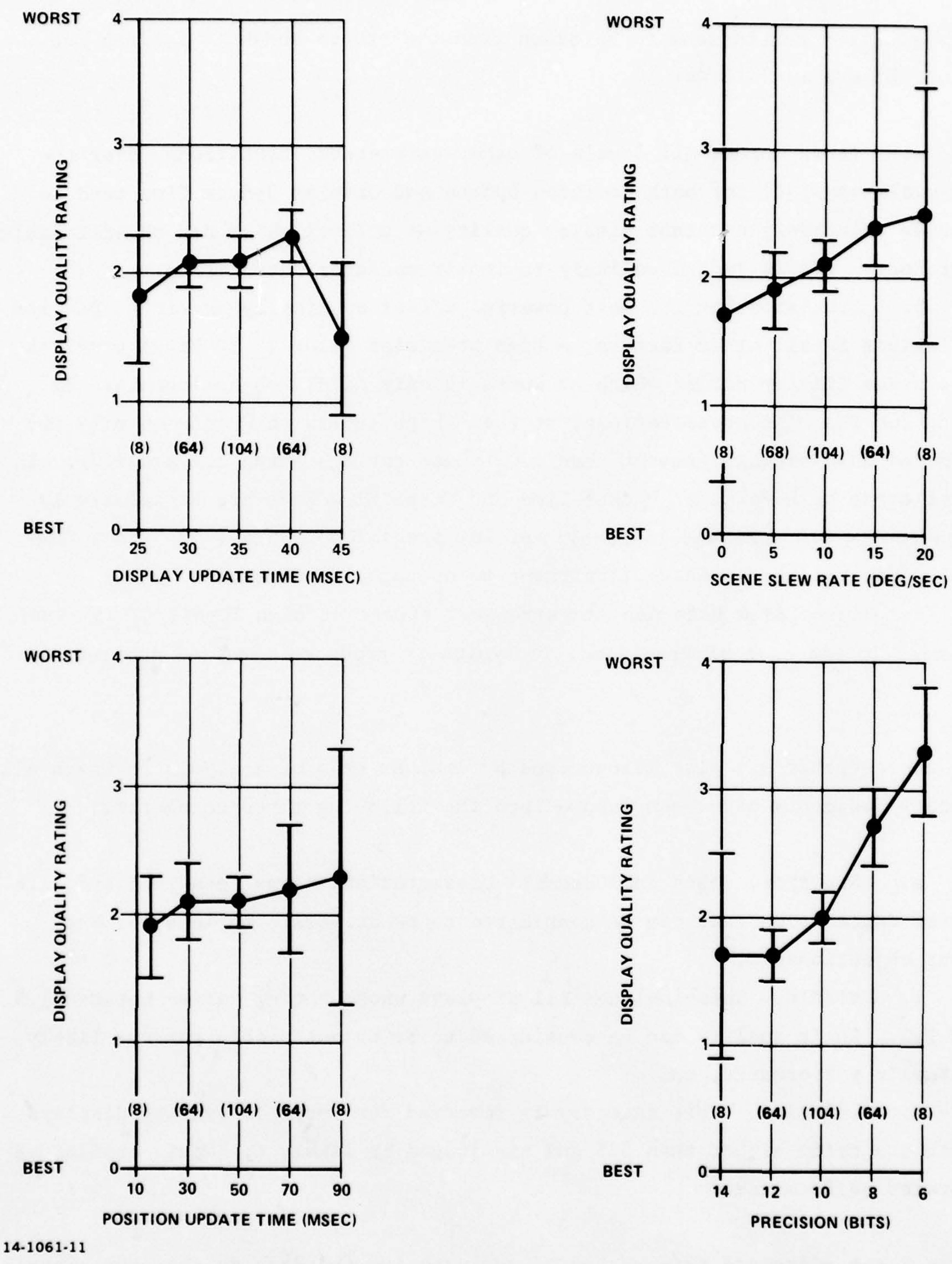

Figure 11. Graphs showing the effect of presentation level upon mean quality ratings for the four experimental parameters. Bands of variability show ± 1 SD for subject means. Means are based on the numbers in parentheses.

The principal conclusions to be drawn from the trends shown in Table 3 and Figure 11 are as follows:

a. Taken across all levels of other parameters, variations (over the intervals sampled) for both Position Update and Display Update Time tend to provide relatively constant display quality at a level which has ob ectionable degradation but is judged unlikely to impair operator performance.

b. Precision has the most powerful effect on display quality. Despite variations in all other factors, a high precision value ($\geq$ 12 bits) provides an average display rating which at worst is only mildly objectionable. In fact, for the nine presentations, at these high levels of Precision only two produced mean ratings greater than 2.0 (these ratings being 2.4 and 2.2). In these cases both Position Update Time and Scene Slew Rate are at relatively high levels (70 msec and 15°/sec). At low precision levels ($\leq$ 8 bits), however, mean ratings indicate impairment to operator performance.

c. Scene Slew Rate has its strongest effect at high levels ($\geq$ 15°/sec), whereas in the case of Precision, it typically produces impaired judgments.

The above trends are also illustrated by another type of analysis in which all quality judgments have been lumped into the following three categories:

a. Superior. This includes all presentations rated less than 1.5, i.e., having degradation that can be considered to be at worst, noticeable, but never objectionable.

b. Middle. This includes all displays whose rating varies between 1.5 and 2.5. Their quality can be considered to be objectionable but not likely to impair performance, and

c. Inferior. This category is reserved for very low quality displays which are rated higher than 2.5 and are judged as likely to impair or disrupt operator performance.

Table 4 has addressed this method of representing the data to the four experimental parameters. Note that the two lowest and two highest coded presentations levels have in each case been lumped together. Percentages of responses comprising the three categories of display quality are entries in the table. This analysis shows that over 30 percent of the responses for coded presentations levels -1 and -2 of Scene Slew Rate (0-5°/sec) and Precision (14-12 bits) are in the superior category. However, at the other end of the scale, where SSR is 15 or 20°/sec and PRB is 8 or 6 bits, no more than 11 percent of the judgments for either of these parameters show superior quality, and most of the judgments now fall into the inferior category.

Table 4. Percentages of responses falling into three categories of judged display quality (Superior, Middle, and Inferior) for three presentation levels of Display Update Time, Position Update Time, Scene Slew Rate, and Precision. Percentages are based on the numbers in parentheses. Quality categories are defined in the text.

	Presentation Levels								
	25-30 msec			35 msec			40-45 msec		
Display Update Time	Sup	Mid	Inf	Sup	Mid	Inf	Sup	Mid	Inf
	19%	44%	36%	16%	64%	20%	19%	43%	38%
	(14)	(32)	(26)	(17)	(66)	(21)	(14)	(31)	(27)
	10-30 msec			50 msec			70-90 msec		
Position Update Time	Sup	Mid	Inf	Sup	Mid	Inf	Sup	Mid	Inf
	19%	45%	35%	18%	62%	20%	15%	44%	40%
	(14)	(33)	(25)	(19)	(64)	(21)	(11)	(32)	(29)
	0-5 Deg/Sec			10 Deg/Sec			15-20 Deg/Sec		
Scene Slew Rate	Sup	Mid	Inf	Sup	Mid	Inf	Sup	Mid	Inf
	31%	40%	29%	14%	68%	18%	11%	40%	49%
	(22)	(29)	(21)	(14)	(71)	(19)	(8)	(29)	(35)
	14-12 Bits			10 Bits			8-6 Bits		
Precision	Sup	Mid	Inf	Sup	Mid	Inf	Sup	Mid	Inf
	35%	50%	15%	16%	69%	14%	3%	29%	68%
	(25)	(36)	(11)	(17)	(72)	(15)	(2)	(21)	(49)

Note: Superior Rating < 1.5
Middle = 1.5 thru 2.5
Inferior > 2.5

The potency of Precision as a determinant of display quality is revealed by the data of Table 5, Figure 12 and Table 6. In these analyses the data have been segregated for two contrasting levels of Precision (Coded levels -1 and +1) representing, respectively, 12 and 8 bits. For each of these PRB values there are an equal number of judgments (4 per subject) made at similarly contrasting coded levels (-1 and +1) for each of the other display parameters. These levels are, respectively: 30 and 40 msec for DUT, 30 and 70 msec for PUT, and 5 and 15°/sec for SSR. Table 5 shows mean quality ratings (each based on 32 responses) and SD's (intersubject variability) for the 12 combinations of parameters. Figure 12 provides a graphic portrayal of the same data and Table 6 presents the data as percentages of responses falling into the three previously defined categories (Superior, Middle, and Inferior) of display quality.

Table 5. Mean quality ratings and intersubject standard deviations (SD's) for 2 levels of precision (8 and 12 bits) at each of two levels of Display Update Time, Position Update Time, and Scene Slew Rate. All means are based on 32 responses.

			Precision	
			8 bits	12 bits
Display Update Time	30 msec	M	2.61	1.63
		SD	0.38	0.22
	40 msec	M	2.78	1.74
		SD	0.34	0.39
Position Update Time	30 msec	M	2.80	1.48
		SD	0.31	0.41
	70 msec	M	2.56	1.91
		SD	0.46	0.59
Scene Slew Rate	5°/sec	M	2.57	1.31
		SD	0.39	0.21
	15°/sec	M	2.81	2.04
		SD	0.32	0.30

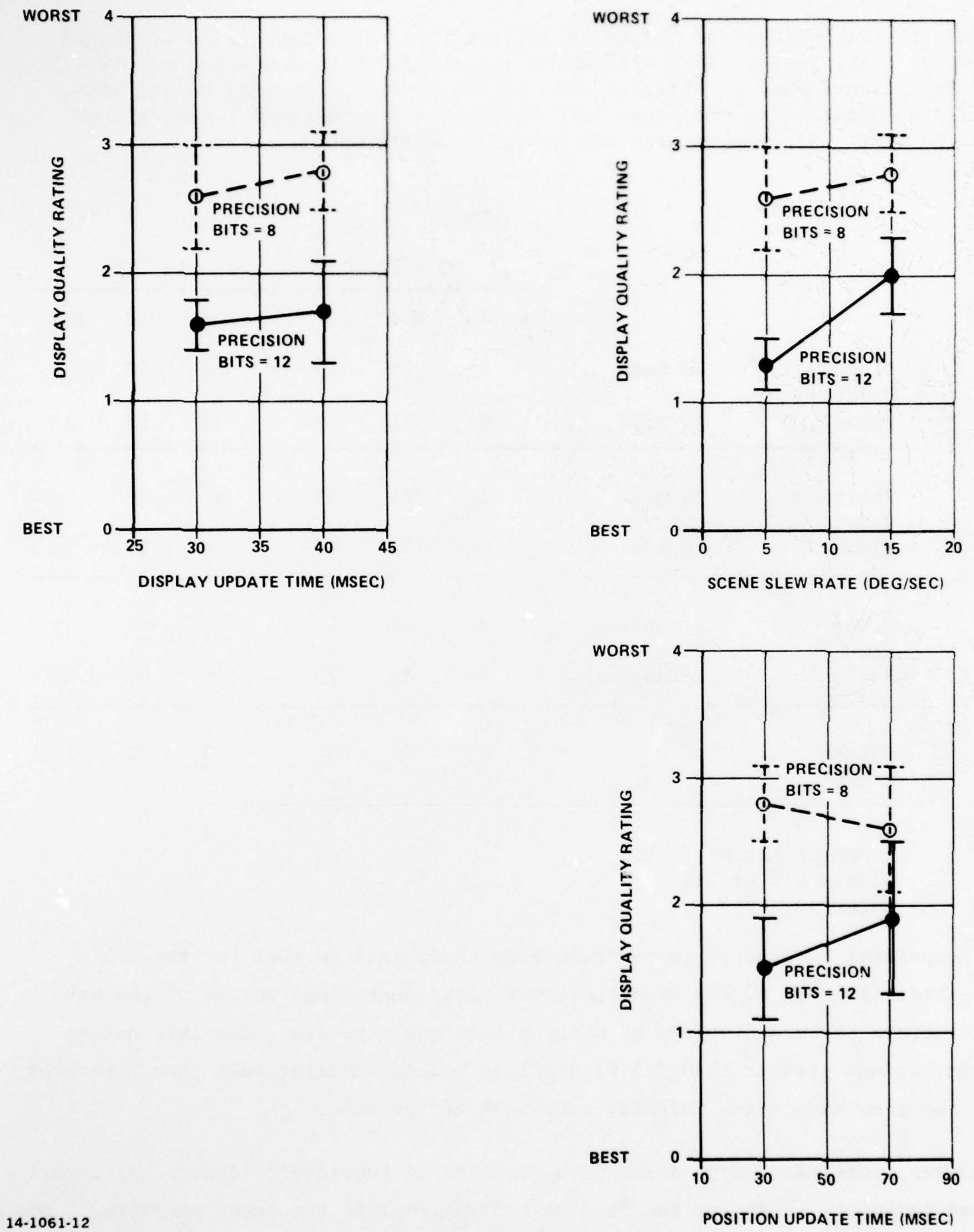

Figure 12. Graphs of mean quality ratings at contrasting levels of Display Update Time, Position Update Time and Scene Slew Rate. Separate relationships are shown at both 8 and 12 bit levels of Precision. All means are based on a total of 32 responses. Bands of intersubject variability are ± 1 SD.

Table 6. Percentages of responses falling into three categories of judged display quality (Superior, Middle and Inferior). Data represent two levels of Precision (8 and 12 bits) at each of two levels of Display Update Time, Position Update Time and Scene Slew Rate. Quality categories are defined in the text. All percentages are based on 32 responses.

		Precision					
		8 bits			12 bits		
		Sup	Mid	Inf	Sup	Mid	Inf
Display Update Time	30 msec	6	34	59	34	47	19
	40 msec	0	31	69	31	56	13
Position Update Time	30 msec	0	25	75	41	56	3
	70 msec	6	41	53	25	47	28
Scene Slew Rate	5 deg/sec	3	44	56	50	47	1
	15 deg/sec	3	25	72	16	56	28
Column Means		3	33	64	33	52	15

Superior Rating < 1.5
Middle 1.5 to 2.5
Inferior > 2.5

A compelling conclusion to be drawn from these data is that for the 8-bit (degrading) level of PRB even the lower (less degrading) values of the other parameters produce displays of unacceptable quality, i.e., displays having mean ratings greater than 2.5 or displays judged superior less than 7 percent of the time and judged inferior over half of the time.

However, note what happens for presentations at the 12-bit (enhancing) level. Mean judgments, even for the more degrading level of the other parameters, now fall within the high quality half of the scale (i.e. ≤ 2). Superior quality judgments occur across all other conditions about one third of the time and the average rate of inferior judgments is only 15 percent.

Of some interest is the fact that, given sufficiently high precision (12 bits), increasing the level of PUT now has a significant effect on display quality (as shown by the Walsh test (Siegel 1956) $p=0.05$). In fact, both the effects of PUT and SSR appear to be more pronounced at the 12-bit level of PRB as can be seen by the more steeply rising slopes of the lower graphs in Figure 12. From the Table 6 data these steepened effects for the 12-bit precision value can be stated in practical terms. In the case of PUT, changing the level from 70 to 30 msec causes the percentage of superior quality displays to increase from 25 to 41 and the inferior category to drop from 28 percent to only 3 percent. Even more strikingly in the case of SSR, changing the level from 15 to 5^{o}/ sec increases superior ratings from 16 to 50 percent where decreasing the inferior quality ratings from 28 to only 1 percent.

• Types of Display Quality Degradation Associated with the Presentation Parameters. As previously stated, the subject was instructed to provide one or more descriptive response terms from a standard check list in order to indicate the kind or kinds of perceived effects associated with the severity of degradation for each presentation. These terms (defined earlier in the report) include: Multiple Imaging, Jitter, Jumping, Flicker, Lag, Hard-to-Track and Blur.

A relatively high rank-order correlation coefficient (RHO) of +0.79 was established between mean quality ratings for the 31 presentations and the total number of degradation responses assigned to each. Thus the total number of perceived anomalies associated with any VCASS presentation proved to be a reasonably good indication of its overall quality rating.

It was also of interest to characterize and differentiate the four presentation parameters (DUT, PUT, SSR and PRB) with respect to frequency and types of associated degradation responses. This was done by selecting all presentation configurations where only one of four parameters could be considered to be potentially degrading. Specifically, two presentations having such combinations were possible for each variable, where its coded value was $\geq +1$ and the coded values of the other variables were ≤ 0 (See Table 1 for the physical levels associated with these coded values).

Table 7 shows the percentage of occurrence of the various degradation responses for those instances (determined in the manner described above) where each of the four parameters will have both an isolated and maximum potential for degradation. Percentages of occurrence for each category of response for all 248 presentations (31 presentations times 8 subjects) have also been included (along the bottom row) to provide a baseline of comparison. Row means show the percentage occurrence for all degradation responses with each type of presentation. Note that the row mean for a given parameter can be compared to the row mean for all presentations (25.7%) to determine the relative effectiveness of that factor for eliciting degradation responses. Comparison of data within each of the four top rows shows how rates of occurrence among degradation responses are distributed for a given parameter; while comparison of data within columns shows how rates of occurrence for each kind of degradation vary across the four parameters.

Inspection of the percentage of occurrence for all presentations along the bottom row of Table 7 shows that the responses of Lag and Blur occur to a negligible degree (< 10% of the time). Multiple Imaging, Jitter, and Jumping (with rates of 51%, 39% and 38%) occur most often; while Flicker and Hard-to-Track responses have intermediate rates (15% and 24%).

For Display Update Times greater than or equal to 40 msec the mean rate (14%) for eliciting degradation responses is far less than the overall rate (26%). Here is an additional indication that this parameter has little effect in impairing display quality. Note that the rates for each degradation category associated with DUT never exceed 25%.

Position Update Time ($\geq$ 70 msec) has considerably more effect (26% mean occurrence), but its rate of elicitation is still no more than the mean for all presentations. Jitter, which occurs fifty percent of the time for this parameter is the only anomaly occurring at an above-average rate.

Scene Slew Rate ($\geq 15^{o}$/sec) provides a mean degradation response rate of 28% which is slightly above average. In particular, this parameter has the potential for producing hard-to-track responses at a rate of 62% (which is 2 1/2

Table 7. Percentage occurrence for various kinds of degradation responses for presentations where the coded level of one parameter (DUT, PUT, SSR, or PRB) has been selected to maximize its degradation potential. Percentage of occurrence for all presentations have been included for comparison.

	Type of Response Degradation							
	MI	JI	JU	FL	LG	HT	BL	Row Means
DUT $\geq$ 40 msec	12.5%	25.0%	12.5%	18.8%	18.8%	12.5%	0%	14.3%*
PUT $\geq$ 70 ms	43.8%	50.0%	31.3%	6.3%	18.8%	25.0%	7.5%	26.0%*
SSR $\geq$ 15^{o}/sec	62.5%	37.5%	25.0%	6.3%	0%	62.5%	0%	27.7%*
PRB $\leq$ 8 bits	62.5%	31.3%	93.8%	12.8%	0%	37.5%	0%	33.9%*
All Presentations	51.3%**	38.8%**	37.5%**	15.0%**	7.5%**	23.8%**	6.3%**	25.7%***

DUT = Display Update Time
PUT = Position Update Time
SSR = Scene Slew Rate
PRB = Position Sensing Precision

MI = Multiple Imaging
JI = Jitter
JU = Jumping
FL = Flicker
LG = Lag
HT = Hard-to-Track
BL = Blur

NOTES:

1. The coded levels of all the other parameters were held to less degrading coded levels (-1 or 0).
2. All percentages except those followed by asterisks are based on an n of 16 (8 subjects x 2 presentations).

* n=112 (8 subjects x 2 presentations x 7 types of degradation)
** n=248 (8 subjects x 31 presentations)
*** n=1736 (8 subjects x 31 presentations x 7 types of degradation)

times the average for this type of degradation). Multiple imaging also occurs for this factor at the same high rate (62%).

One can easily see that Precision at levels less than or equal to 8 bits (in addition to producing the most defective quality ratings) evokes by far the greatest percentage of degradation responses (34%). Three kinds of responses predominate: Jumping, which is reported at the extremely high rate of 94 percent and appears to be an inescapable consequence of low PRB; Multiple Imaging with a rate of 62%; and Hard-to-Track with a rate of 38%.

LAG-EXPERIMENT

In order not to overcomplicate the Response Surface Methodology design, the effects of a single factor, Lag (System Throughput Delay), were studied in a second, relatively simple experiment.

Method

The experiment was run in two ways:

a. In the first, so-called tracking mode, four subjects (MR, DL, DH and JK) performed the same task called for in the main experiment, i.e., they fixated the forward center point on the carrier runway and attempted to hold this fixation as the target was slewed at a constant rate (10^{o}/sec);

b. In the second, so-called nontracking mode, another four subjects (JB, DS, MR and SM) were shown a motionless scene. Their task was to alternate fixations between the same point on the carrier runway and the center of a simulated moon along a diagonal line of about 20 degrees above and to the right of the carrier. This alternation was accomplished by repeated obliquely-directed head movements. The rate of alternation was left unspecified, each subject being allowed to establish his own rhythm.

For both experimental modes, five Lag times (45, 75, 135, 255 and 495 milliseconds) were presented four times in random order. Thus each subject received a total of 20 presentations. Quality judgments were made and recorded as in the main experiment. In both versions of the Lag study Display and Position Update Times were held constant at 30 msec, while Precision remained at 14 bits. High and low quality anchors were again given on the first two trials, where respective Lags of 15 and 1005 msec were inserted.

Results and Conclusions from Lag Experiment

The high and low anchoring presentations were again effective in producing quality judgments at opposite ends of the scale. For the nontracking task the mean quality rating was only 0.69 for the high and moved up to 3.81 for the low anchor. For the tracking situation the anchored ratings were pushed even farther apart, down to 0.44 for the high and up to 3.94 for the low anchor.

Subjects in the abbreviated study were not required to report types of degradation effects as in the main experiment. However, two subjects, one from each experimental subgroup, elected to provide this information. One of these subjects (MR) from the tracking group made use of four response categories, reporting Multiple Imaging and Jitter in 19 of his 20 trials, Lag on 16 occasions, and Hard-to-Track in 11 instances. The other subject (SM), who performed in the Head-Oscillating condition used only two categories, reporting Multiple Imaging 15 times and Lag on 16 occasions.

Analysis of quality ratings resulting from the experimental presentations are summarized in Table 8, Table 9 and Figure 13. Table 8 shows mean quality ratings and intersubject SDs associated with the different levels of Lag for both the tracking and nontracking modes of response. Figure 13 is a graphic representation of the same data with Lag plotted on a logarithmic scale. Table 9 shows the percentage of judgments for each amount of Lag and for both response modes which fall into categories of Superior (rating < 1.5), Middle (rating 1.5 - 2.5) and Inferior (rating > 2.5).

Both semilog plots in Figure 13 appear to be roughly linear, with the plot representing the tracking task having the steeper slope. The effects of Lag

Table 8. Means and intersubject standard deviations (SD's) for display quality ratings associated with different amounts of Lag. Both Tracking and Nontracking modes of response are represented.

		LAG msec				
		45	75	135	255	495
Tracking	MEAN RATING	1.12	1.36	2.17	2.94	3.25
	SD	0.05	0.20	0.33	0.09	0.10
Nontracking	MEAN RATING	1.47	1.97	2.23	2.90	3.41
	SD	0.04	0.21	0.21	0.16	0.26

Table 9. Percentages of responses falling into three categories of judged display quality (Superior, Middle, and Inferior) for five presentation levels of Lag. Both tracking and nontracking tasks are represented. Percentages are based on totals of 16 responses.

	Quality	LAG msec				
	Category	45	75	135	255	495
	Superior	69	50	12	0	0
Tracking	Middle	31	44	56	19	25
	Inferior	0	6	31	81	75
	Superior	40	16	0	0	0
Nontracking	Middle	60	88	81	33	12
	Inferior	0	6	19	67	88

Superior Rating < 1.5
Middle 1.5 thru 2.5
Inferior > 2.5

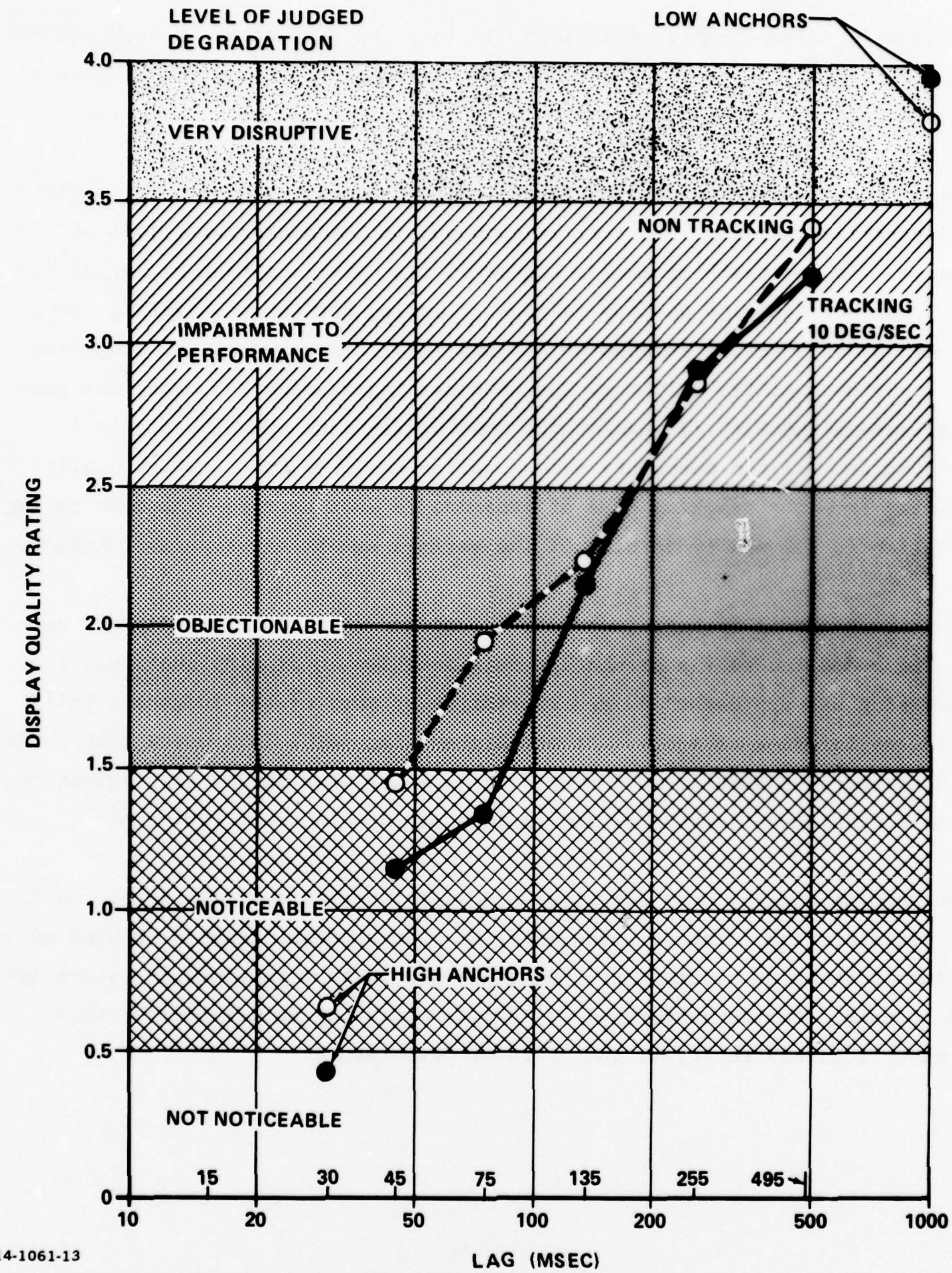

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Figure 13. Effect of Lag on mean quality ratings. Data associated with the tracking mode of response are represented by solid circles and solid lines. Nontracking data are represented by open circles and dashed lines. Data points can be related to the degradation level bands shown.

are, in both cases, highly significant as shown by respective one-way analyses of variance yielding F ratios greater than 9, which (at 4 and 13 DF) have p values less than 0.005.

All the data indicate that the shorter Lags (45 and 75 msec) provide higher quality ratings for the tracking, as compared to the nontracking mode of response. In the tracking case a Lag of 75 msec yields a mean rating of 1.4 and 50 percent superior quality judgments; while, for the nontracking task, the mean quality rating remains at 2.0 and only 16 percent of the judgments show superior quality. Although the shortest Lag studied (45 msec) now provides improved quality ratings in the nontracking case (Mean rating is 1.5 and 40 percent of the responses show superior quality), the display quality resulting from the tracking mode of response is even better. The mean rating has fallen to 1.1 and 69 percent of the ratings are in the superior category.

At the fourth level of Lag, judgments associated with both tracking and nontracking modes indicate a pronounced deterioration in display quality. The mean rating has approached 3, and two-thirds or more of the judgments fall within the inferior category. At the highest Lag value (495 msec) mean ratings for both response modes show a very high level of degradation (approximating 3.5) and more than three-fourths of the ratings are now in the inferior class.

These results clearly show Lag to be a powerful variable in its effect on display quality. According to these data, to insure VCASS displays of high quality the duration of system throughput time should be maintained at values less than 50 msec. On the other hand any display with Lag values greater than 200 msec is likely to impair the operator performance.

APPENDIX A

DESCRIPTION OF MECHANICAL HELMET MOUNTED SIGHT AND MATHEMATICS TO TRANSFORM LINE-OF-SIGHT FROM HEAD TO AIRCRAFT COORDINATES.

This note describes the Mechanical Helmet Mounted Sight (MHMS) which will be used in VCASS at AMRL/HEA in terms of the computations necessary to transform line-of-sight fixed with respect to the head to a vector measurable with respect to the frame on which the sight is mounted. No attempt is made to do error analysis, nor are the actual measurements themselves and instrument calibrations discussed.

The MHMS (Figure A-1) consists of a helmet rigidly attached to a linkage on one end. Angular motion from link to link is measured through to the point of joining to a fixed frame. This note defines a 3-dimensional coordinate system at each joining point of MHMS and also defines the axes of each coordinate system and the mathematics to travel from one coordinate system to another. The coordinate systems are arranged so that if all angular sensors are set to zero simultaneously, all the coordinate systems are parallel with the X-axis pointing to the front, Y-axis to the right, and Z-axis up. All coordinate systems in this note are left-handed systems.

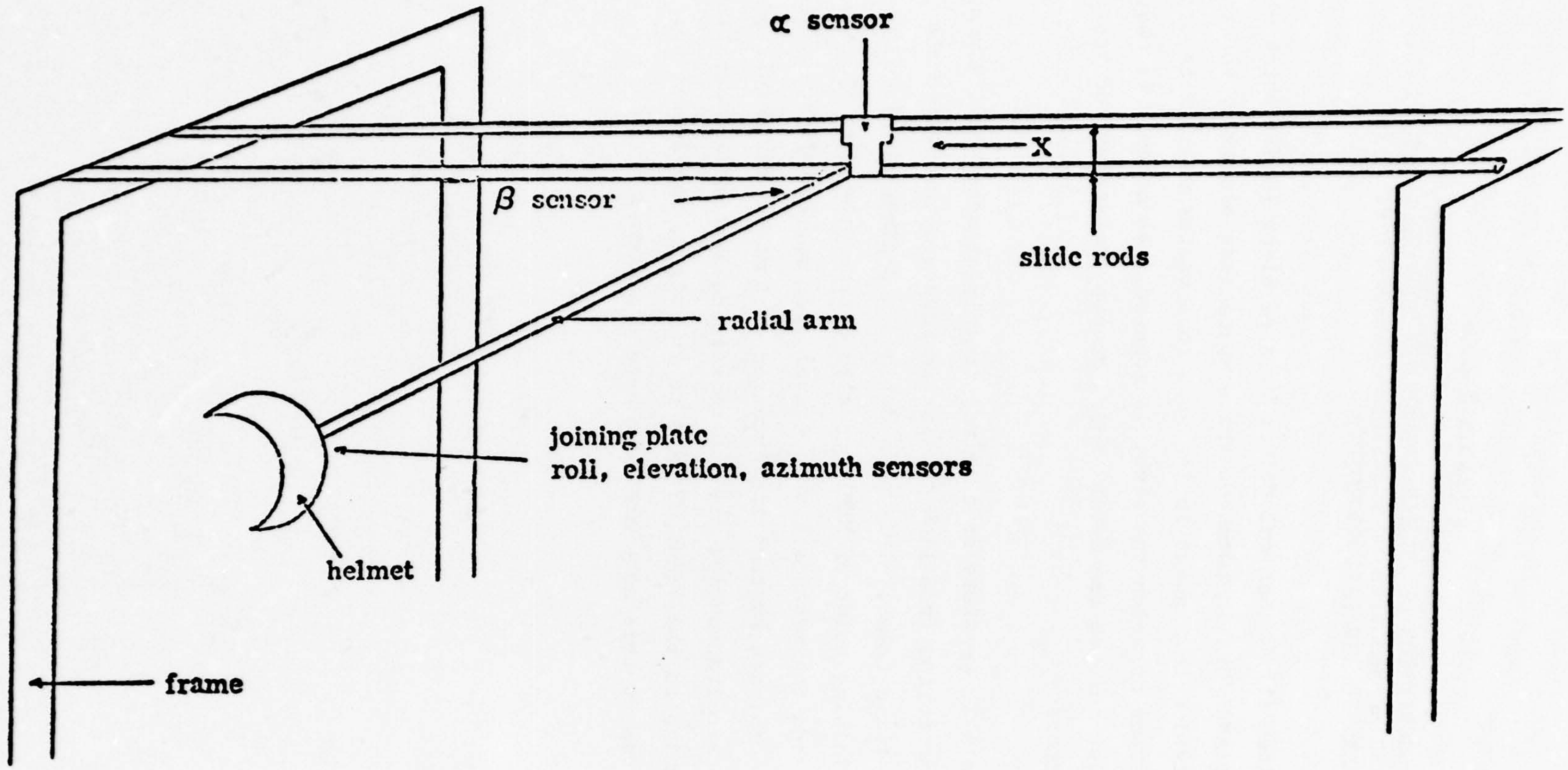
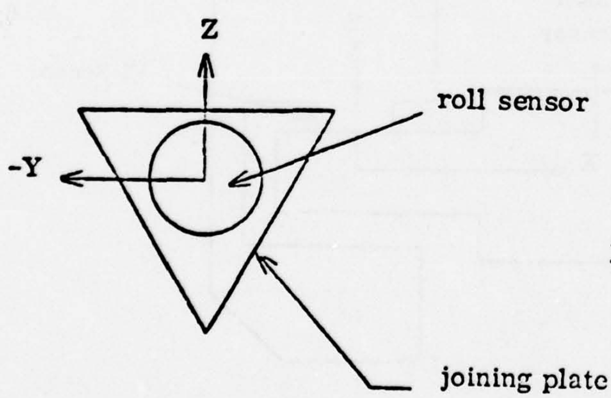

α sensor
X
slide rods
β sensor
radial arm
joining plate
roll, elevation, azimuth sensors
helmet
frame

Figure A1

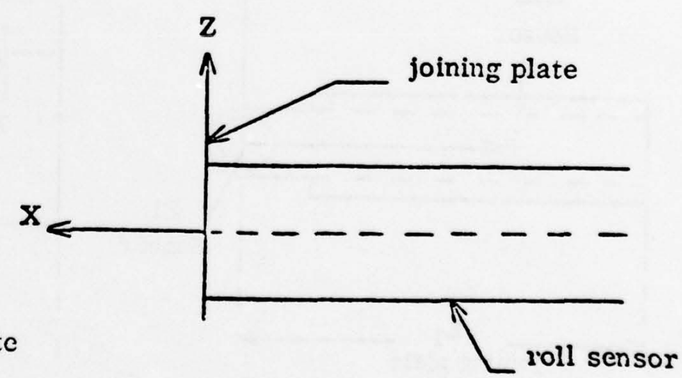
Coordinate System 1: Fixed with respect to the helmet.

X-axis:	Along roll sensor line directed away from roll sensor
Y-axis:	On plane of joining plate perpendicular to Z.
Z-axis:	On joining plate along center line of back of helmet.
Center:	Intersection of joining plate with center line of roll sensor.

Θ_1 (Roll Sensor) = Measured from +Z to +Y as positive angle



View from back of helmet

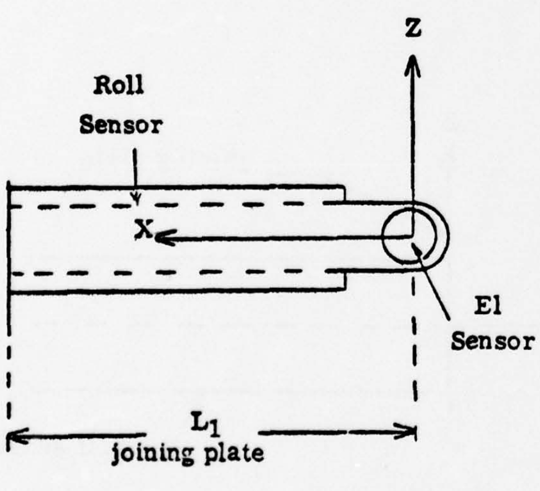


View from left side of helmet

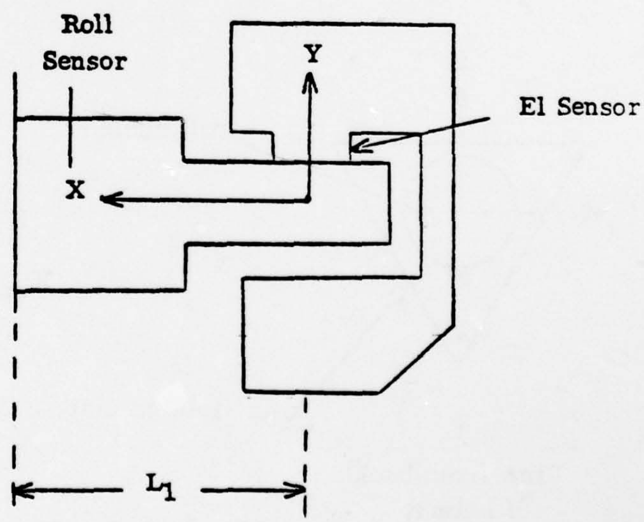
Coordinate System 2: Coordinate system 1 fixed after roll to El joining bracket.

X-axis:	**Along center line of roll sensor toward joining plate.**
Y-axis:	**Along center line of El sensor directed away from Az sensor.**
Z-axis:	**Perpendicular to X, Y at center directed toward up side of El sensor.**
Center:	**Intersection of roll sensor center line and El sensor center line.**
L_1 =	**2.108"**

Θ_2 (El sensor) = Measurement from +X to +Z as positive angle.



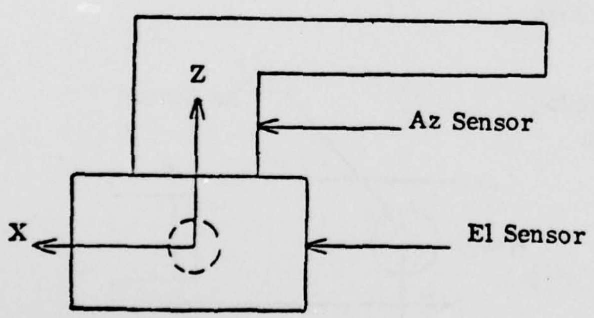
View from left side of helmet



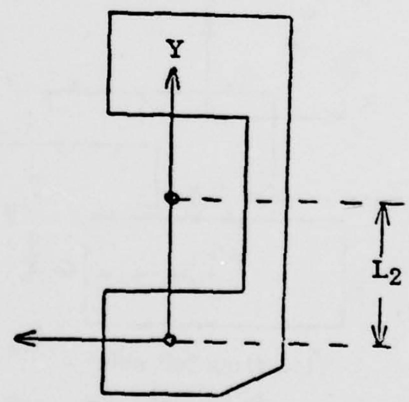
View from top of helmet

Coordinate System 3: Coordinate system 2 after El, fixed on El sensor.

Y-axis:	Along center line of El sensor toward roll/El joining.
X-axis:	Perpendicular to Y, Z directed toward joining plate.
Z-axis:	Along center line of Az sensor directed toward Az sensor bracket.
Center:	Intersection of center line of El sensor with center line of Az sensor.
L_2 =	.63"
Θ_3 (Az sensor) =	Measured from +X to +Y as positive angle.



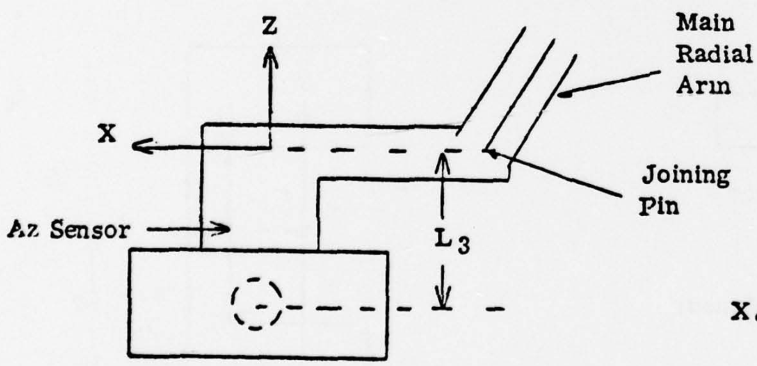
View from left side of helmet



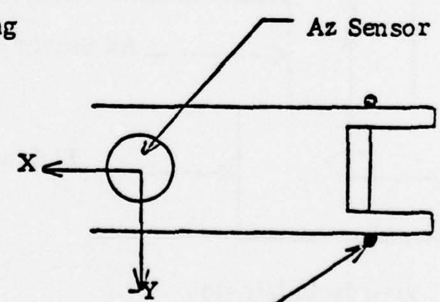
View from top of helmet

Coordinate System 4: Coordinate system 3 after Az, fixed on Az sensor bracket.

X-axis:	Parallel to edges of the bracket which joins the radial arm and intersecting center of joining pin.
Y-axis:	Perpendicular to X axis at center directed toward right of bracket.
Z-axis:	Along center line of Az sensor to center directed up on the Az bracket.
Center:	Intersection of Az sensor center line with a line parallel to the edges of the bracket for joining to the radial arm and intersecting the center of the main radial arm.
L_3 =	.94"



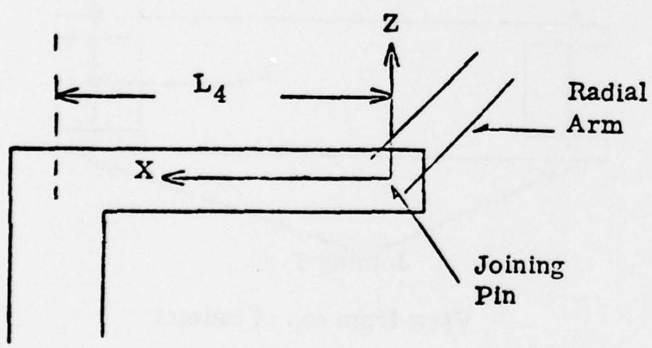
View from left side of helmet



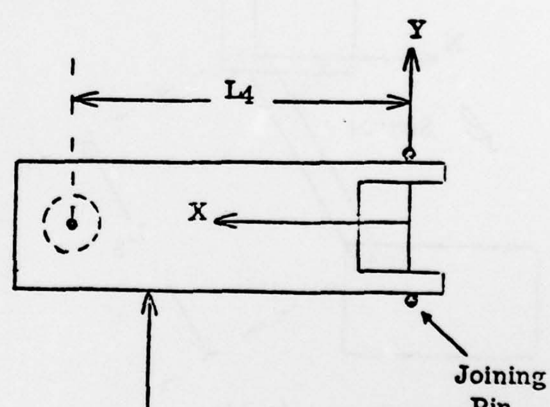
View from top or helmet

Coordinate System 5: Coordinate system 4 translated to the joining point of the radial arm with the Az bracket.

X-axis:	Along center line of Az bracket as defined in coordinate system 4.
Y-axis:	Along center line of joining pin directed toward right.
Z-axis:	Perpendicular to X-Y plane at center directed up.
Center:	At intersection of X-axis of coordinate system 5 with joining pin.
L_4 =	1.25"



View from left side of helmet



View from top of helmet

Coordinate System 6: Coordinate system 5 translated to top of radial arm.

X-axis: Directed toward radial arm and on a plane parallel to the slide bar plane intersecting the joining pin.

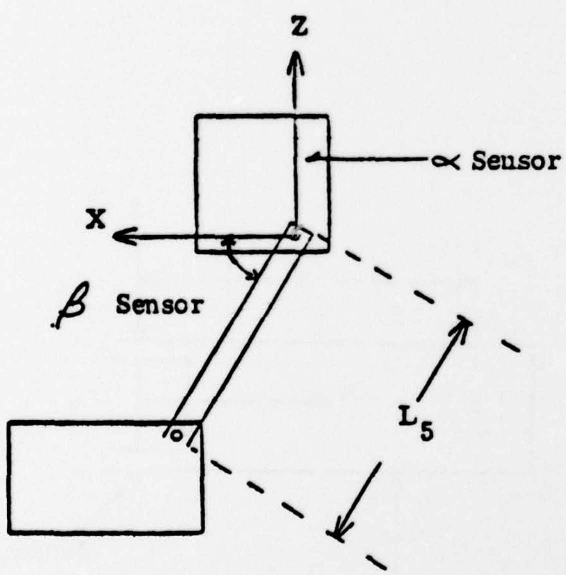
Y-axis: Along center line of upper joining pin directed toward right.

Z-axis: Directed up along center line of α sensor.

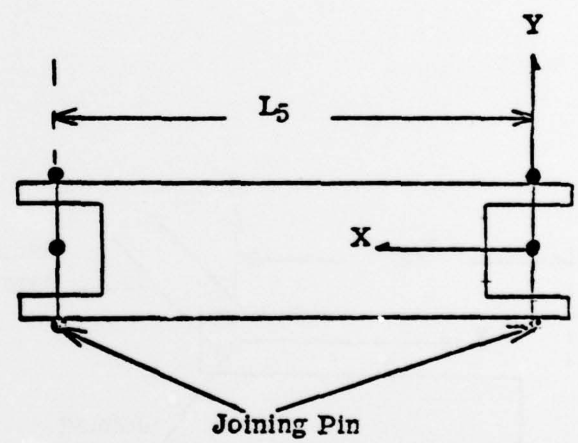
Center: Middle of upper joining pin.

L_5 = 23.62"

Θ_4 (β Sensor) = Measured from +X to -Z as negative angle.



View from left side of helmet

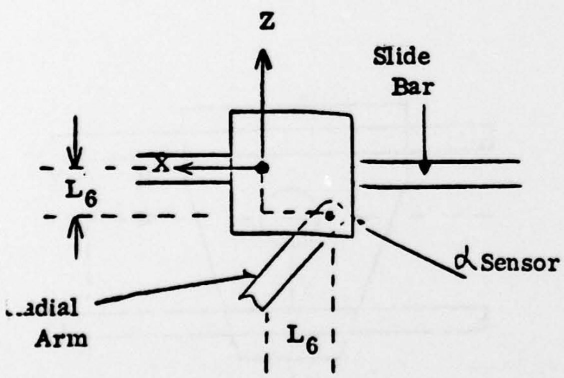


View from top of helmet

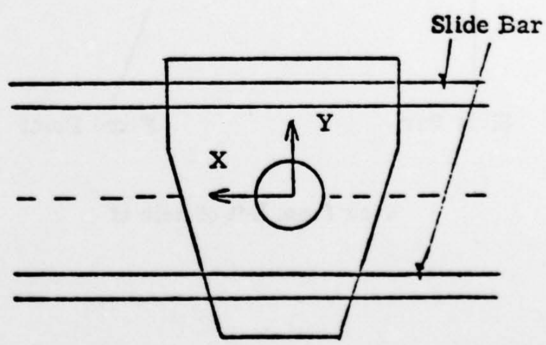
Coordinate System 7: Coordinate system 6 transformed onto slide bar plane.

X-axis:	On plane containing the center line of the two slide bars, parallel to the bars, intersecting the α sensor center line and directed toward helmet.
Y-axis:	On plane of the center lines of the two slide bars perpendicular to X-axis and directed toward the right.
Z-axis:	Along center line of the α sensor directed up.
Center:	Intersection of center line of α sensor with plane containing center lines of the two slide bars.
L_6 =	1.498"
L'_6 =	.25"

Θ_5 (α sensor) = Measured from +X to +Y as positive angle



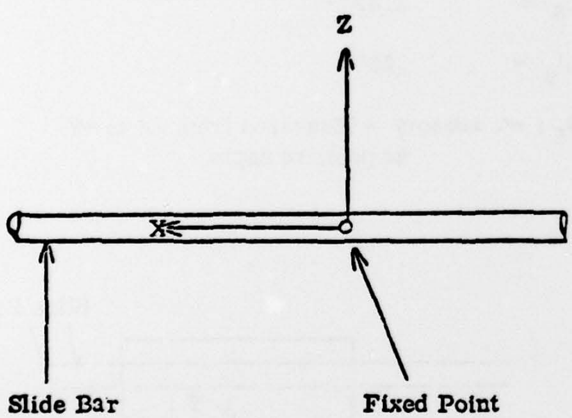
View from left side of helmet



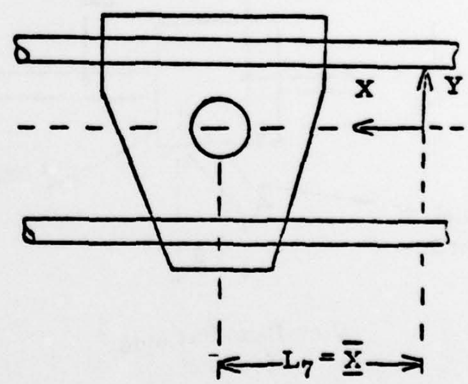
View from top of helmet

Coordinate System 8: The coordinate system fixed with reference to a point on the slide bar system.

X-axis:	Along coordinate system 7 X-axis directed toward helmet.
Y-axis:	Perpendicular to X-axis directed toward right.
Z-axis:	Up with respect to frame.
Center:	At a fixed point along coordinate system 7 X-axis.
$\overline{X}$ =	Undefined



View from left of helmet



View from top of helmet

Now, let us take a look at the transformations from one coordinate system to the next and then all the way to the coordinate system 8.

Let C_i = Represent coordinate system i

$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix}$ = A vector in coordinate system C_i

L_i = Represent measured distance along the fixed axis from C_i to C_{i+1} on MHMS

Θ_1 = Roll sensor

Θ_2 = Elevation sensor

Θ_3 = Azimuth Sensor

These readings are measured with respect to Coordinate System 1 (joining plate).

Θ_4 = β Sensor

Θ_5 = $\propto$ Sensor

From C_1 to C_2

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \text{Cos } \Theta_1 & \text{Sin } \Theta_1 \\ 0 & -\text{Sin } \Theta_1 & \text{Cos } \Theta_1 \end{pmatrix} \begin{pmatrix} X_1 + L_1 \\ Y_1 \\ Z_1 \end{pmatrix}$$

From C_2 to C_3

$$\begin{pmatrix} X_3 \\ Y_3 \\ Z_3 \end{pmatrix} = \begin{pmatrix} \text{Cos } \Theta_2 & 0 & -\text{Sin } \Theta_2 \\ 0 & 1 & 0 \\ \text{Sin } \Theta_2 & 0 & \text{Cos } \Theta_2 \end{pmatrix} \begin{pmatrix} X_2 \\ Y_2 + L_2 \\ Z_2 \end{pmatrix}$$

From C_3 to C_4

$$\begin{pmatrix} X_4 \\ Y_4 \\ Z_4 \end{pmatrix} = \begin{pmatrix} \cos\theta_3 & -\sin\theta_3 & 0 \\ \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_3 \\ Y_3 \\ Z_3 - L_3 \end{pmatrix}$$

From C_4 to C_5

$$\begin{pmatrix} X_5 \\ Y_5 \\ Z_5 \end{pmatrix} = \begin{pmatrix} X_4 + L_4 \\ Y_4 \\ Z_4 \end{pmatrix}$$

From C_5 to C_6

$$\begin{pmatrix} X_6 \\ Y_6 \\ Z_6 \end{pmatrix} = \begin{pmatrix} X_5 + L_5 \cdot \cos\theta_4 \\ Y_5 \\ Z_5 + L_5 \cdot \sin\theta_4 \end{pmatrix}$$

From C_6 to C_7

$$\begin{pmatrix} X_7 \\ Y_7 \\ Z_7 \end{pmatrix} = \begin{pmatrix} \cos\theta_5 & -\sin\theta_5 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_6 - L'_6 \\ Y_6 \\ Z_6 - L_6 \end{pmatrix}$$

From C_7 to C_8

$$\begin{pmatrix} X_8 \\ Y_8 \\ Z_8 \end{pmatrix} = \begin{pmatrix} X_7 + \underline{\overline{X}} \\ Y_7 \\ Z_7 \end{pmatrix}$$

A much more concise statement is available:

Let M_i be the rotation matrix from C_i to C_{i+1}

Let t_i be the translation vector and

V_i be any arbitrary vector in C_i

Then

$$V_8 = M_6(M_3(M_2(M_1(V_1 + t_1) + t_2) + t_3) + t_4 + t_5 + t_6) + t_7$$

Therefore, given a vector (X, Y, Z) in C_1 and all sensor measurements, Θ_1, Θ_2, Θ_3, Θ_4, Θ_5 we can compute the corresponding coordinate, say(X_8, Y_8, Z_8), in C_8 by the following:

(I) $$X_8 = \text{Cos}\,\Theta_5\,(\text{Cos}\,\Theta_3(\text{Cos}\,\Theta_2(X_1 + L_1) - \text{Sin}\,\Theta_2\,(-Y_1\text{Sin}\,\Theta_1 + Z_1\,\text{Cos}\,\Theta_1)) - \text{Sin}\,\Theta_3\,(Y_1\,\text{Cos}\,\Theta_1 + Z_1\,\text{Sin}\,\Theta_1 + L_2) + L_4 + L_5\,\text{Cos}\,\Theta_4 - L_6') - \text{Sin}\,\Theta_5\,(\text{Sin}\,\Theta_3\,(\text{Cos}\,\Theta_2\,(X_1 + L_1) - \text{Sin}\,\Theta_2\,(-Y_1\,\text{Sin}\,\Theta_1 + Z_1\,\text{Cos}\,\Theta_1)) + \text{Cos}\,\Theta_3\,(Y_1\,\text{Cos}\,\Theta_1 + Z_1\,\text{Sin}\,\Theta_1 + L_2)) + \underline{\overline{X}}$$

(II) $$Y_8 = \text{Sin}\,\Theta_5\,(\text{Cos}\,\Theta_3\,(\,\text{Cos}\,\Theta_2\,(X_1 + L_1) - \text{Sin}\,\Theta_2\,(-Y_1\,\text{Sin}\,\Theta_1 + Z_1\,\text{Cos}\,\Theta_1)) - \text{Sin}\,\Theta_3\,(Y_1\,\text{Cos}\,\Theta_1 + Z_1\,\text{Sin}\,\Theta_1 + L_2) + L_4 + L_5\,\text{Cos}\,\Theta_4 - L_6') + \text{Cos}\,\Theta_5\,(\text{Sin}\,\Theta_3\,(\text{Cos}\,\Theta_2\,(X_1 + L_1) - \text{Sin}\,\Theta_2\,(-Y_1\,\text{Sin}\,\Theta_1 + Z_1\,\text{Cos}\,\Theta_1)) + \text{Cos}\,\Theta_3\,(Y_1\,\text{Cos}\,\Theta_1 + Z_1\,\text{Sin}\,\Theta_1 + L_2))$$

$$\text{(III)} \quad Z_8 = \sin\Theta_2 (X_1 + L_1) + \cos\Theta_2 (-Y_1 \sin\Theta_1 + Z_1 \cos\Theta_1) - L_3 + L_5 \sin\Theta_4 - L_6$$

All the matrix operations described above are for a left-handed coordinate system. If we want the final coordinate system to be a right-handed coordinate system rather than a left-handed system, we simply change $+Z_8$ to $-Z_8$.

COMPUTATION OF AZ, EL & ROLL

Given the measurements and the transformation described it is now required to determine the azimuth, elevation and roll in the fixed coordinate system C_8 of a vector, $V = (X, Y, Z)$ fixed in the helmet coordinate system C_1.

:Let $V_1 = (1, 0, 0)$ and $O_1 = (0, 0, 0)$ in C_1.

Through the transformation (I), (II), (III), we get

$$V_8 = (X_8, Y_8, Z_8) \text{ and } O_8 = (X'_8, Y'_8, Z'_8)$$

Then

$$S_8 = V_8 - O_8 = (k, m, n),$$

Where

$$k = X_8 - X'_8, \; m = Y_8 - Y'_8, \; n = Z_8 - Z'_8,$$

is the direction cosines of S_8, since

$$k^2 + m^2 + n^2 = 1.$$

The elevation of S is

(IV) $$EL = \sin^{-1}(n)$$

The azimuth of S is

(V) $$AZ = \begin{cases} \cos^{-1}\left(\dfrac{k}{\sqrt{1 - n^2}}\right) & \text{if } m \geq 0 \\ -\cos^{-1}\left(\dfrac{k}{\sqrt{1 - n^2}}\right) & \text{if } m < 0 \end{cases}$$

To compute the roll, we need to take a vector perpendicular to V_1, say $U_1 = (0, 1, 0)$, the Y-axis unit vector in C_1 and transform it to C_8 using the transformations (I), (II), (III), called U_8.

Let $U_8 = (a_8, b_8, C_8)$ and then

$T_8 = U_8 - O_8 = (k', m', n')$, where

$k' = a_8 - X'_8$, $m' = b_8 - Y'_8$, $n' = C_8 - Z'_8$, is the

direction cosines of T_8 since $k'^2 + m'^2 + n'^2 = 1$.

Apply two rotational transformations to eliminate the azimuth and elevation variables on T_8 in C_8. We rotate fixed coordinate system C_8 by AZ and EL in terms of U_8 coordinate system. So we get T'_8 after the rotation of U_8. T'_8 is the new coordinate vector with respect to U_8 coordinate system. We have

$$M = \begin{pmatrix} \text{Cos El} & 0 & +\text{Sin El} \\ 0 & 1 & 0 \\ -\text{Sin El} & 0 & \text{Cos El} \end{pmatrix} \begin{pmatrix} \text{Cos Az} & +\text{Sin Az} & 0 \\ -\text{Sin Az} & \text{Cos Az} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Then

$$\text{(VI)} \quad T'_8 = \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} = M \cdot \begin{pmatrix} k' \\ m' \\ n' \end{pmatrix}$$

Therefore, the roll is

$$RL = -\text{Sin}^{-1}(t_z)$$

Remark: The outcomes of the azimuth, elevation, and roll are based on a left-handed coordinate system. One should not change $+Z_8$ to $-Z_8$ in this series of computations.

Refer to Appendix II

APPENDIX I

L_1 = Horizontal distance from the center of the joining plate to the intersection of roll axis and El axis.

Value = 2.108"

L_2 = Horizontal distance from the intersection of roll axis and El axis to the intersection of El axis and Az axis.

Value = 0.63"

L_3 = Vertical distance from the intersection of El axis and Az axis to the horizontal line through the joining pin of the radial arm.

Value = 0.94"

L_4 = Horizontal distance from the joining pin of the radial arm to the vertical line through the intersection of El axis and Az axis.

Value = 1.25"

L_5 = Length of the radial arm between two end joining pins.

Value = 23.62"

L_6 = Vertical distance from the joining pin of the radial arm to the center of the slide bar.

Value = 1.498"

L'_6 = Horizontal distance from the joining pin of the radial arm to the vertical line through the intersection of Az axis and X-axis (slide bar).

Value = 0.25"

APPENDIX II

Since all the coordinate systems are parallel to each other and Θ_1, Θ_2 and Θ_3 are the roll, elevation and azimuth angles measured at the joining plate located on the helmet and Θ_4 and Θ_5 are the elevation and azimuth angles measured at the main frame. Therefore, the true roll, elevation and azimuth angles with respect to the final coordinate system, C_8, are

$$RL = \Theta_1$$

$$EL = \Theta_2$$

$$AZ = \Theta_3 + \Theta_5$$

<u>Proof:</u>

Let $U = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad V = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \qquad O = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$

Then we get

$$U_x = \text{Cos } \Theta_5 \, (\text{Cos } \Theta_3 \cdot \text{Cos } \Theta_2 \cdot (1 + L_1) - \text{Sin } \Theta_3 \, (L_2) + L_4 + L_5 \text{ Cos } \Theta_4 - L'_6)$$
$$- \text{Sin } \Theta_5 \, (\text{Sin } \Theta_3 \text{ Cos } \Theta_2 \, (1 + L_1) + L_2 \text{ Cos } \Theta_3) + \overline{X}$$

$$U_y = \text{Sin } \Theta_5 \, ((1 + L_1) \text{ Cos } \Theta_2 \text{ Cos } \Theta_3 - L_2 \text{ Sin } \Theta_3 + L_4 + L_5 \text{ Cos } \Theta_4$$
$$- L'_6) + \text{Cos } \Theta_5 \, ((1 + L_1) \text{ Cos } \Theta_2 \text{ Sin } \Theta_3 + L_2 \text{ Cos } \Theta_3)$$

$$U_z = (1 + L_1) \text{ Sin } \Theta_2 - L_3 + L_5 \text{ Sin } \Theta_4 - L_6$$

$$V_x = \text{Cos } \Theta_5 \, (L_1 \cdot \text{Cos } \Theta_2 \text{ Cos } \Theta_3 + \text{Sin } \Theta_1 \text{ Sin } \Theta_2 \text{ Cos } \Theta_3 - \text{Cos } \Theta_1 \text{ Sin } \Theta_3$$
$$- L_2 \text{ Sin } \Theta_3 + L_4 + L_5 \text{ Cos } \Theta_4 - L'_6)$$
$$- \text{Sin } \Theta_5 \, (L_1 \text{ Cos } \Theta_2 \text{ Sin } \Theta_3 + \text{Sin } \Theta_1 \text{ Sin } \Theta_2 \text{ Sin } \Theta_3 + \text{Cos } \Theta_1 \text{ Cos } \Theta_3$$
$$+ L_2 \text{ Cos } \Theta_3) + \overline{X}$$

$$V_y = \sin\Theta_5 \;(L_1 \cos\Theta_2 \cos\Theta_3 + \sin\Theta_1 \sin\Theta_2 \cos\Theta_3 - \cos\Theta_1 \sin\Theta_3$$
$$- L_2 \sin\Theta_3 + L_4 + L_5 \cos\Theta_4 - L'_6)$$
$$+ \cos\Theta_5 \;(L_1 \cos\Theta_2 \sin\Theta_3 + \sin\Theta_1 \sin\Theta_2 \sin\Theta_3 + \cos\Theta_1 \cos\Theta_3$$
$$+ L_2 \cos\Theta_3)$$

$$V_z = L_1 \sin\Theta_2 - \sin\Theta_1 \cos\Theta_2 - L_3 + L_5 \sin\Theta_4 - L_6$$

$$O_x = \cos\Theta_5 \;(L_1 \cos\Theta_2 \cos\Theta_3 - L_2 \sin\Theta_3 + L_4 + L_5 \cos\Theta_4 - L'_6)$$
$$-\sin\Theta_5 \;(L_1 \cos\Theta_2 \sin\Theta_3 + L_2 \cos\Theta_3) + \overline{\underline{X}}$$

$$O_y = \sin\Theta_5 \;(L_1 \cos\Theta_2 \cos\Theta_3 - L_2 \sin\Theta_3 + L_4 + L_5 \cos\Theta_4 - L'_6)$$
$$+ \cos\Theta_5 \;(L_1 \cos\Theta_2 \sin\Theta_3 + L_2 \cos\Theta_3)$$

$$O_z = L_1 \sin\Theta_2 - L_3 + L_5 \sin\Theta_4 - L_6$$

by applying formulas (I), (II), and (III) on U, V and O.

To compute elevation:

Let $n = U_z - O_z = \sin\Theta_2$

Then, by (IV), we have

$$EL \;=\; \sin^{-1}(n) = \sin^{-1}(\sin\Theta_2)$$
$$= \Theta_2$$

To compute azimuth:

Let $k = U_x - O_x = \cos\Theta_2 \cos\Theta_3 \cos\Theta_5 - \cos\Theta_2 \sin\Theta_3 \sin\Theta_5$

$$= \cos\Theta_2 \;(\cos\Theta_3 \cos\Theta_5 - \sin\Theta_3 \sin\Theta_5)$$
$$= \cos\Theta_2 \;\cos(\Theta_3 + \Theta_5)$$

$$m = U_y - O_y = \cos\Theta_2 \cos\Theta_3 \sin\Theta_5 + \cos\Theta_2 \sin\Theta_3 \cos\Theta_5$$

$$= \cos\Theta_2 \cdot \sin(\Theta_3 + \Theta_5)$$

$$1 - n^2 = k^2 + m^2 = \cos^2\Theta_2 \cdot \cos^2(\Theta_3 + \Theta_5) + \cos^2\Theta_2 \sin^2(\Theta_3 + \Theta_5)$$

$$= \cos^2\Theta_2$$

Then, by (V), we have

$$AZ = \cos^{-1}\left(\frac{k}{\sqrt{k^2 + m^2}}\right)$$

$$= \cos^{-1}\left(\frac{\cos\Theta_2 \cdot \cos(\Theta_3 + \Theta_5)}{\sqrt{\cos^2\Theta_2}}\right)$$

$$= \cos^{-1}\left(\frac{\cos\Theta_2 \cdot \cos(\Theta_3 + \Theta_5)}{\cos\Theta_2}\right)$$

$$= \cos^{-1}(\cos(\Theta_3 + \Theta_5)) \qquad \text{if } \cos\Theta_2 \neq 0$$

$$= \Theta_3 + \Theta_5$$

To compute roll:

Let $k' = V_x - O_x = \sin\Theta_1 \sin\Theta_2 \cos(\Theta_3 + \Theta_5) - \sin\Theta_1 \sin(\Theta_3 + \Theta_5)$

$m' = V_y - O_y = \sin\Theta_1 \sin\Theta_2 \sin(\Theta_3 + \Theta_5) + \cos\Theta_1 \cos(\Theta_3 + \Theta_5)$

$n' = V_z - O_z = -\sin\Theta_1 \cos\Theta_2$

Now, we apply the transformation matrix.

$$m = \begin{pmatrix} \cos EL & 0 & \sin EL \\ 0 & 1 & 0 \\ -\sin EL & 0 & \cos EL \end{pmatrix} \begin{pmatrix} \cos AZ & \sin AZ & 0 \\ -\sin AZ & \cos AZ & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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